Smart Resource Control in Distribution Network to Improve the Integration level of PV

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Abstract

Widespread penetration of Renewable Energy (RE) sources in distribution networks may introduce new technical challenges for the distribution network. These issues include voltage rise, voltage unbalancing, voltage regulation problem, thermal overloading, frequency fluctuation, flicker and harmonics. Consequently, the traditional operation of distribution networks limits the penetration level of RE sources and need to be revised to incorporate new control and protection strategies.

In this PhD research project, novel smart strategies have been proposed to coordinate energy resources and deal with voltage and loading issues as the main power quality challenges in distribution networks. In this work, PV is considered as the RE source. As the layout of energy resources in the electricity network will be a mixture of both concentrated and distributed, the research is conducted at two steps. Firstly, the distributed energy resources are considered which are popular for residential customers in Low Voltage (LV) networks. In this voltage level, the main goal is to use distributed customers' resources to deal with voltage and loading issues. Medium Voltage (MV) network is also considered in the second step in which resources are concentrated and installed by utilities.

In Chapter 2, voltage rise problem is considered and a novel smart approach is proposed to deal with this issue in LV network. A mixed localized-distributed control strategy is proposed to coordinate the resources and avoid overvoltages.

It is worth noting that unbalancing between the generated power and load, in high generation period, causes the voltage and loading issues. As a result, Chapter 3 proposes a new distributed load leveling approach in LV network to coordinate distributed customers' ESUs and improve the balancing of generation and load.

Direct local power injection to AC line causes power quality issues. Therefore, one promising approach to avoid these concerns is to avoid injection to AC grid. Chapter 4 proposed the utilization of an auxiliary DC link in which all customers' DC links are connected together. This can be as an alternative approach to resolve the AC power quality problems, while providing additional advantages such as higher level of redundancy and a pathway to the future DC network.

In Chapters 2, 3 and 4, only PV inverter and ESU are considered as the distributed resources for coordination and control. However, future LV network will see widespread use of smart devices including dishwasher, washing machine, cooling load, etc. which can be used to deal with power quality challenges. Therefore, in Chapter 5 these devices are coordinated to avoid overvoltages.

The noted approaches in Chapter 2-5 are applied in LV network based on coordination of distributed resources. In Chapter 6, a new distributed control approach based on consensus algorithm is proposed to coordinate PV plant in MV network and deal with overvoltages and overloading. The main aim here is to have a fair sharing among PVs in period of high generation.

However, as the voltage rise is a local problem rather than wide area problem, fair sharing in reactive power may not be effective for voltage support. Therefore, to avoid this problem, a new distributed control approach is proposed in Chapter 7 to regulate PV reactive power in most efficient manner. Additionally, the effect of other voltage support strategies such as Automatic Voltage Regulation (AVR) loop on this voltage support strategy is studied as well.

Concentrated ESU is considered as the last resource in MV network and Chapter 8 proposes an effective and robust approach which can coordinate multiple ESUs to manage and control voltage and loading in distribution networks.

Finally, the conclusions and possible future works are given in Chapter 9.

Keywords

Controllable Load
Consensus Algorithm
Communication
DC Link
Distributed Control
Distributed Energy Resources
ESU
Information State
Localized Control
LV Network
MV Network
PV
Robust Control
Storage
Smart Meter
Thermal Overloading
Voltage Drop
Voltage Rise

List of principle symbols and abbreviations

AC	Alternating Current
ANN	Artificial Neural Network
AVR	Automatic Voltage Regulation
DC	Direct Current
DMS	Distribution Management System
DSTATCOM	Distribution Static Compensator
EMS	Energy Management System
ESU	Energy Storage Unit
GA	Genetic Algorithm
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
OLTC	On-Load Tap Changer
PCC	Point of Common Coupling
RE	Renewable Energy
SC	Switching Capacitor
SOC	State of Charge
THD	Total Harmonic Distortion
LV	Low Voltage

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Contributions

- **Smart Resources Control in LV network to Deal with Voltage Rise Issue**

    - Allowing every owner of renewable energy resources to utilize all available resources (e.g. ESU, inverter active and reactive power) for voltage rise control.
    - Design a new internal ESU control to adapt for consensus algorithm.
    - Design a method using combined localized and distributed algorithms to achieve a robust and efficient voltage reduction.

- **Developing a new Load Leveling approach in LV Network Using Coordinated ESUs**

    - Proposing a new distributed load leveling approach based on consensus algorithm to coordinate distributed ESUs in an LV network.
    - Avoiding network overloading in both high generation and high demand periods.
    - Avoiding overvoltages in high generation period.
    - Avoiding undervoltages in peak load period.

- **Proposing the use of an auxiliary DC link to accommodate more RE sources**
    - Allowing customers to inject their surplus power that otherwise would be limited due to AC power quality issues.
    - Avoiding the problem associated with increased RE generation.
    - Improving the local supply-demand matching and reduce the network losses.
    - Improving load balancing among the phases.
    - Improving the redundancy in the LV network.

- **Developing a robust and effective control approach for customers' controllable load and manage voltage rise in residential LV**

    - A new communication structure for smart meters in LV network
    - Avoiding permissible upper voltage limit violation.
    - Keeping robustness of voltage rise control even with communication drop.
    - Improving the efficiency of RE energy utilization in LV network comparing to other traditional approaches.

- **Developing a new distributed coordination approach to PV plants within a MV network and deal with voltage rise and network overloading**

  - Utilization of PV active power curtailment for network loading control.
  - Utilization of PV reactive power for voltage rise control.
  - Sharing the required contribution fairly among PVs.

- **Proposing a robust distributed approach to manage multiple PV reactive power for voltage support**

  - Robust overvoltage and undervoltage prevention in MV network using PV reactive power.
  - Efficient overvoltage and undervoltage prevention in MV network using PV reactive power.
  - Studying the effect of other voltage support equipment such as AVR control loop on this control approach.

- **Proposing a distributed control approach to coordinate multiple ESUs in MV network to avoid violation of voltage and thermal constraints**

  - Utilization of ESUs' reactive power for voltage support.
  - Utilization of ESUs' active power for network loading management.
  - Effective voltage support strategy.
  - Sharing the required active power for loading reduction with respect to ESU SOC.

List of Publications

The Queensland University of Technology (QUT) allows the presentation of a thesis for the degree of Doctor of Philosophy in the format of published or submitted papers, where such papers have been published, accepted or submitted during the period of candidature. This thesis is composed of seven published/submitted papers, of which five have been published and two are under review. Note that each paper is selected for the thesis as one chapter.

- *Chapter 2:* G. Mokhtari, A. Ghosh, G. Nourbakhsh, G. Ledwich “Smart Robust Resources Control in LV network to Deal with Voltage Rise Issue,” *Sustainable Energy, IEEE Transactions on, vol. 4, pp. 1043-1050, 2013.*
- *Chapter 3:* G. Mokhtari, G. Nourbakhsh, and A. Ghosh, "Load leveling in LV network using coordinated Energy Storage Units," *in Power Engineering Conference (AUPEC), 2013 Australasian Universities, 2013, pp. 1-5.*
- *Chapter 4:* G. Mokhtari, G. Nourbakhsh, F. Zare, and A. Ghosh, "Improving the penetration level of PVs using DC link for residential buildings," *Energy and Buildings, vol. 72, pp. 80-86, 2014.*
- *Chapter 5:* G. Mokhtari, G. Nourbakhsh, F. Zare, and A. Ghosh, “Overvoltage Prevention in LV Smart Grid Using Customer Resources Coordination,” *Energy and Buildings, vol. 61, pp. 387-395, 2013.*
- *Chapter 6:* G. Mokhtari, G. Nourbakhsh, A. Ghosh, ‘Overvoltage and Overloading Prevention Using Coordinated PV Inverters in Distribution Network’ to be *submitted to IEEE IECON 2014.*
- *Chapter 7:* G. Mokhtari, G. Nourbakhsh, A. Ghosh, G. Ledwich “A New PV Reactive Power Control to Improve Voltage Profile of Distribution Network,” *submitted to IET Generation, Transmission & Distribution.*
- *Chapter 8:* G. Mokhtari, G. Nourbakhsh, and A. Ghosh, “Smart Coordination of Energy Storage Units (ESUs) for Voltage and Thermal Constraints Management in Distribution Networks,” *Power Systems, IEEE Transactions on,* vol. 28, pp. 4812-4820, 2013.

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Statement of Original Authorship

I declare that the work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belied, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Ghassem Mokhtari Date: 21 May 2014

Chapter 1

Introduction

1.1. Definition of the Research Problem

There is a considerable increase in the penetration of RE generators like PV, wind turbine and fuel cell in distribution networks in response to the climate change. In particular, distributed RE sources with ranging from 1 kW-10 MW are gaining popularity in LV and MW networks. According to Australian energy target released in March 2010, electricity generation is predicted to increase at approximately 48% between 2007 (247 TWh) and 2030 (366 TWh) [1]. It has been anticipated that the share of renewable energy will increase to 19% in which PV systems will contribute a large part of the total produced renewable energy [2].

Distribution networks with high penetration of PVs can encounter two main challenges. A typical load curve for NSW in Australia [3] shows that during the peak load period, generation is normally low or zero. This will cause two main power quality problems including voltage drop and network overloading [4]. On the other hand, in peak generation period, when generated power exceeds the load, surplus power is injected to the grid. This will cause reverse power flow and hence may result in power quality issues such as voltage rise [5-11], voltage unbalancing [12], thermal overloading [5, 13-18], flicker and harmonics [19].

Voltage fluctuation (including voltage rise and drop) and network overloading will be the main challenges for future distribution networks [20]. These may have damaging effect on customer electric appliances and sensitive electronic equipment [21]. In addition, loss of RE supply may become inevitable if the voltage violates stationary limits. Therefore, avoiding these two main challenges are the focus of this research which leads to two main specific research problems:

Problem # 1: What are the main resources that can be used to avoid these problems?

Based on the type and voltage level in which PVs are installed, different resources are proposed to be used to deal with the noted issues. After comprehensive literature review, the main resources which are found suitable in this research project are listed below:

In LV networks, there is an increased interest to use the resources in customer side [22]. As a result, most resources can be used by customers to avoid the problems. These resources include:

1- PV inverter active power [23-25]

2- PV inverter reactive power [26-30]

3- Distributed ESU [31-41]

4- Customer's controllable load such as:

- dishwasher,
- washing machine,
- cooling load
- electric vehicle, etc.

In MV network, the resources are more concentrated and installed by utilities. These resources include:

5- PV plant active power [23-25]

6- PV plant reactive power [26-30]

7- ESU [42]

8- DSTATCOM [43]

The resources can be utilized in the period of high generation or peak load and avoid voltage or loading problems. However, the main challenge is to determine a coordination strategy for these resources, from which arises the second research problem.

Problem # 2: In what way, these resources can be coordinated?

There are three types of coordination strategies that can be implemented to coordinate the resources. The first strategy is a centralized control in which the central controller coordinates various resources in the distribution network. This approach is the most efficient way to coordinate the resources. However, the drawback of this approach is that it would require extensive database with high speed and fast calculating computers, along with broadband networks. This can be too expensive for the current state of art. This can also be less reliable due to communication failure and computer freezing [44]. The second strategy is a localized control which is based on local measurements only, such as the ones proposed in [23] and [45]. This control approach is robust as it only utilizes local information [44]. However, it cannot effectively utilize all the available resources. The third approach involves distributed control. This approach can have the effectiveness of centralized approach while avoiding its complexity. However, the robustness of this approach still depends on the communication links.

Based on advantages and disadvantages of the noted three coordination strategies, this research project has focused on localized and distributed control approaches to have robust control while improving efficiency which is important for future smart gird.

1.2. Literature Review

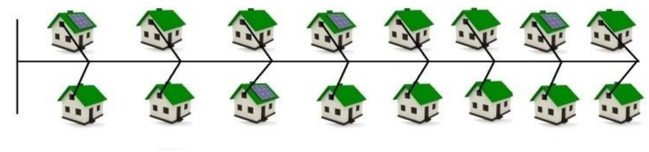
1.2.1. Grid-connected PVs

In future, the layout of grid-connected PVs in the electricity network will be a mixture of both concentrated and distributed. The choice will depend on many factors such as geographic location, load diversity, network configuration, population density etc. Loads in distribution network are normally residential and commercial which constitute a greater portion of most electricity systems [20]. For example, in the US, domestic loads consume nearly 40 percent of national electricity generation [46]. In France, buildings consumes nearly 45% of primary energy [20]. Generally, it is desirable to have electric energy generation close to the loads. This approach can help in avoiding long distance transmission of electric energy that can be associated with cost and energy losses [47], improving the supply security and reducing the electricity bill for customers [48]. Consequently, it makes sense to encourage customers in residential/commercial buildings to install PV. This way, the customers can generate electricity for their own consumption and export the surplus power to the grid. As a result, it is anticipated that future distribution networks with residential and commercial buildings will see a widespread use of grid-connected PVs.

The active power generation of PV is based on Maximum Power Point Tracking (MPPT) algorithm which is recommended to be in unity power factor by IEEE recommended practice for utility interface of PV systems [49].

1.2.2. The potential impacts of grid-connected PVs in distribution networks

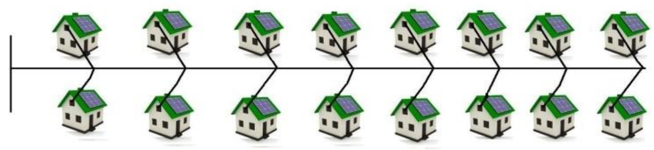
Fig. 1.1 illustrates a residential feeder with low to high density penetration of roof-top PVs, exemplifying the progression into the future. Case 1 and 2 can represent some of the current situations around the world, where PVs can inject their surplus power to the network without any limitation. For these cases, it is assumed that no power quality constraints are violated. However, by increasing the penetration level of PVs (cases 3 and 4 in Fig. 1.1), at noon in which the network is in off-peak load, PVs generate their maximum power and this result in different power quality problems along the feeder.



Case 1: 25% penetration

Case 2: 50% penetration

Case 3: 75% penetration



Case 4: 100% penetration

Fig. 1.1 Residential PV development.

Considering the provided example of the PV progress in distribution network, different power quality issues have been anticipated for future distribution network with high penetration of PVs. These issues can be summarized as follows:

A. Voltage fluctuation

Voltage fluctuation includes both voltage rise and voltage drop in distribution networks which usually are the main power quality concerns due to high penetration of PVs. During the high PV generation, the power flows reversely and the node voltages rise [23]. There is a possibility of losing renewable energy when the upper permissible voltage limit is violated. In addition, there is a potential of voltage drop during peak load period when the generation is zero [4].

Electricity standard around the world usually allows a maximum of ±6% voltage tolerance from transformer secondary to the last customer. Therefore, the transformer tap is usually set in the range of 1.02-1.05 to fulfil this standard in peak load period. However, when the PV penetration increases, distribution network may face voltage rise in high generation period.

To show the problem, consider the system as shown in Fig. 1.2 where V_t and $Z_t = R_t + j.X_t$ are the equivalent circuit at the left of Point of Common Coupling (PCC) node. The voltage at PCC bus voltage can be approximated as follow [23]:

$$V_i = V_t + \frac{P_i.R_t + Q_i.X_t}{V_{PCCi}} \quad (1\text{-}1)$$

where

$$P_i = P_{PVi} - P_{li} \quad (1\text{-}2)$$

$$Q_i = Q_{PVi} - Q_{li} \quad (1\text{-}3)$$

As it can be seen from these equations, when the PV active power (Q_{PV} is equal to zero based on standards) is more than the load, the PCC voltage will increase which may cause voltage limit violation.

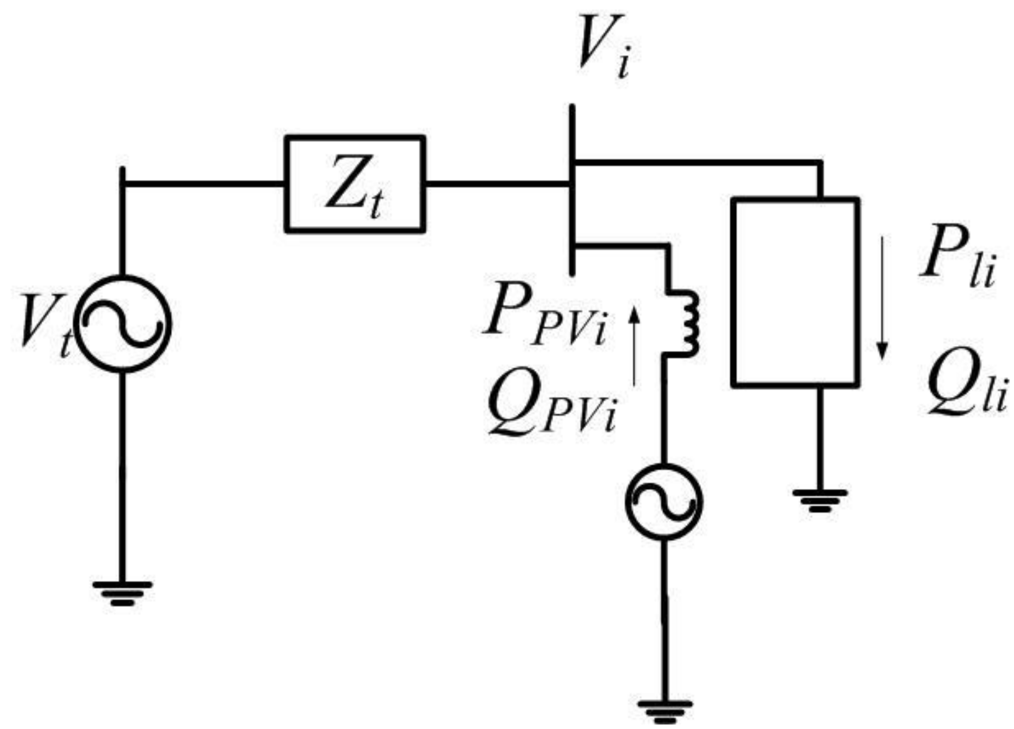


Fig. 1.2 Circuit Equivalent.

B. Voltage unbalancing

Voltage unbalancing occurs whenever there is a difference in the voltage amplitude or whenever the angle difference is not 120° [18]. Using Single-phase PVs, in random fashion, in distribution network may cause voltage unbalancing. Based on electricity standard, A maximum of 2% voltage unbalancing factor is usually allowed for different nodes of distribution network [51]. Voltage unbalancing has unacceptable influences on operation of motors and power electronic devices [18].

C. Harmonics

All power electronic converters generate harmonics. Current standard allows the inverters to inject current with Total Harmonic Distortion (THD) less than 5% [18]. In reference [18], it has been referred that the harmonics, caused by PV inverters, do not make significant impact on distribution network.

D. Thermal constraints violation

Thermal constraints violation is another limiting factor for high utilization of PVs in distribution network. Thermal constraints for lines or power transformers may be violated due to high penetration of PVs [17].

E. Frequency variation

The unbalancing between the generated power of PVs and load causes the power quality concerns and challenges. This demand-supply unbalancing causes also frequency fluctuation. If supply is more than demand, the frequency rise and vice versa. The increase in penetration level of uncertain sources such as PV makes the frequency control more difficult [18]. For example, as shown in reference [52], when the penetration level of PV increase from 10% to 30, the frequency control needs to increase from 2.5 % to 10 %.

F. Other potential impacts

The other power quality challenges such as flicker and DC injection can be anticipated for distribution network with high PV penetration [18]. However, these issues are not so important compared with those mentioned earlier.

1.2.3. Strategies to deal with the power quality problems

Different strategies have been suggested by researchers to deal with noted power quality concerns caused by high penetration of PVs. As this research project is focused on two main concerns, voltage fluctuation and network overloading, the solution suggested to deal with these two issues are addressed here. Three main strategies can be applied to deal with these concerns:

A. Network upgrading

The first strategy to deal with noted issues include the reinforcing the network. For instance, new component such as capacitor can be installed to deal with voltage issue [51]. This approach needs new investment cost for utilities for upgrading their networks and hence is not attractive [53-55].

B. Changing network static set points

In this strategy, the idea is based on working with static set points of network such as LV transformer tap. Considering the uncertainty in PV power and customer load, the main issue of this strategy is that the set points would have to change every time that load and generation change [54, 56]. These frequent changes are not acceptable for static set point.

C. Smart control of energy resources

This approach seems a promising concept for future smart grid [57]. This concept includes smart control of energy resources to deal with the technical impact of PVs on distribution networks. These strategies for coordination depend on the voltage level in which PVs are located.

- **Strategies in MV network**

In MV networks, the solutions which are studied in literatures are most based on centralized (supervisory) control where a centre such as Distribution Management System (DMS) decides the system operation. Different algorithms have been proposed to be utilized to determine the contribution of different resources in MV network [4, 47, 58-66]. In [59], Genetic Algorithm (GA) has been used to coordinate the operation of On-Load Tap Changer (OLTC) of transformer, Active Voltage Regulator (AVR) and SC (Switching Capacitor) in MV network to minimize the voltage fluctuation. Reference [58] uses an ordinal optimization based method to minimize the total power losses on network while keeping the node voltage close to the voltage rating. Reference [60] uses a linear programming formulation to find the optimal power factor of PV generator and the tap setting of transformer to prevent voltage violation. Other algorithms such as Artificial Neural Network

(ANR) [63], Fuzzy logic [4], State Machine concept [65] and multifrontal algorithm [67] are also utilized to coordinate different components in MV network in optimal way.

- **Strategies in LV network**

Strategies applied in LV networks are based on customers' resources. Considering the vastness and complexity of LV networks, the supervisory control is not so attractive to coordinate customer resources [30]. Instead, localized approaches which use the customer local information is popular in the literature. These approaches are based on the controlling of injected active or reactive power of customers. However, for this control, smart inverter is required for each of the customers. Smart inverter can actively detect local power quality issues such as voltage rise and react to that [30]. The block diagram of a smart PV inverter based on localized control is shown in Fig. 1.3. The main strategies based on this control mode and contributing by smart inverter are discussed as follows:

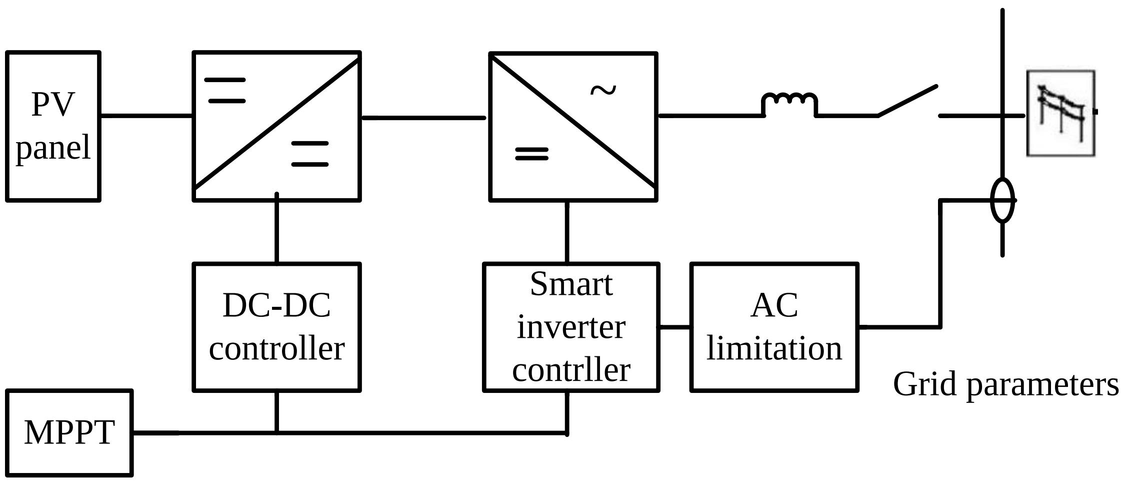


Fig. 1.3 Smart PV inverter [30].

- *Active Power Curtailment (APC) of PV output power [23-25]*

This method is based on droop control, which is usually used in power sharing among parallel generators. Considering the highly resistive line characteristics [56, 68], the relationship between voltage and active power is strong. As a result, in [23], it is proposed that the power injected by the inverter can be as a function of the PCC bus voltage according to the equation (1-4). The control Structure of this strategy for each inverter has been shown in Fig. 1.4.

$$\begin{cases} P_{inv} = P_{MPPT} & V_{PCC} < V_{cri} \\ P_{inv} = P_{MPPT} - m(V_{PCC} - V_{cri}) & V_{PCC} > V_{cri} \end{cases} \quad (1\text{-}4)$$

where P_{inv} is the injected active power to the network, P_{MPPT} is the maximum available power for PV panel, m is the droop factor (kW/V), V_{PCC} is the voltage of PCC bus and V_{cri} is the critical limit above which the injected power should be curtailed.

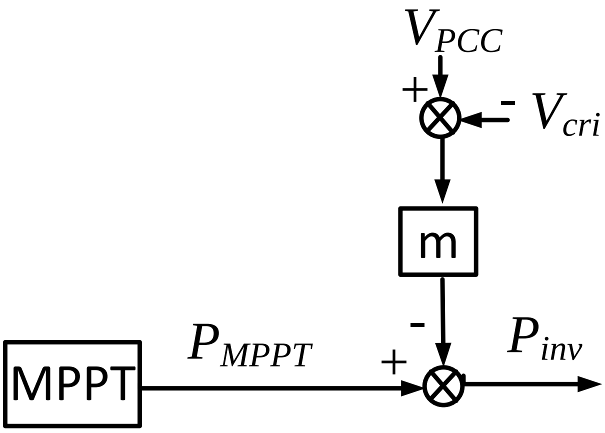


Fig. 1.4 APC control diagram [23].

To select droop factor (m) and critical voltage limit (V_{cri}), two methods have been proposed in [23].

The first one is to introduce the same droop factor and critical voltage for all inverters in a network with the following equation:

$$m_i = \frac{rating_i}{V_{\max} - V_{cri}} \quad (1\text{-}5)$$

where $rating_i$ is the rating of ith inverter in kVA and V_{max} is the maximum voltage in which the inverter should stop injecting power to the grid.

The second method tries to share the required power curtailment among the inverters fairly. The details of this method has been addressed in [23].

The main advantage of this strategy is that there is no need for any investment cost for customers. The only required thing is to modify the control of inverter to operate with regard to the PCC bus voltage. However, this method causes renewable energy losses, considering the curtailment of power in high generation mode. In addition, the inverters in this method operate based on a voltage feedback of the AC system. Considering the noises and harmonics in AC system, this strategy may be subjected to oscillation and unacceptable operation.

- *Contribution of PV inverter in reactive power [26-30]*

The strategies for voltage support based on reactive power control are popular in literatures [28-30, 47, 60, 64, 69-71]. The strategies that can be applied in customer side in LV network are summarized in following parts. In the following strategies, it is assumed that the PV inverter rating has been increased by 10% which can give the ability of reactive power control around 0.48×P_{PVmax}, even when the maximum active power is injected by the inverter (P_{PVmax} is the maximum power that can be drawn from PV). The strategies based on reactive power contribution of PV inverter can be classified into three main categories as follow:

Strategy-1: Reactive power control as a function of the injected active power [30]

In this strategy, the inverter power factor changes based on the injected active power. The characteristic of this strategy has been shown in Fig. 1.5. In this figure, PF_{cri} is the critical power factor for the customer in LV network which depends on the standard (for instance 0.95), and P_{cri} is the critical power of PV inverter from which the inverter start to absorb reactive power for voltage control.

This strategy does not get any feedback from AC grid. This means that this method is not subject to unacceptable operation [30].

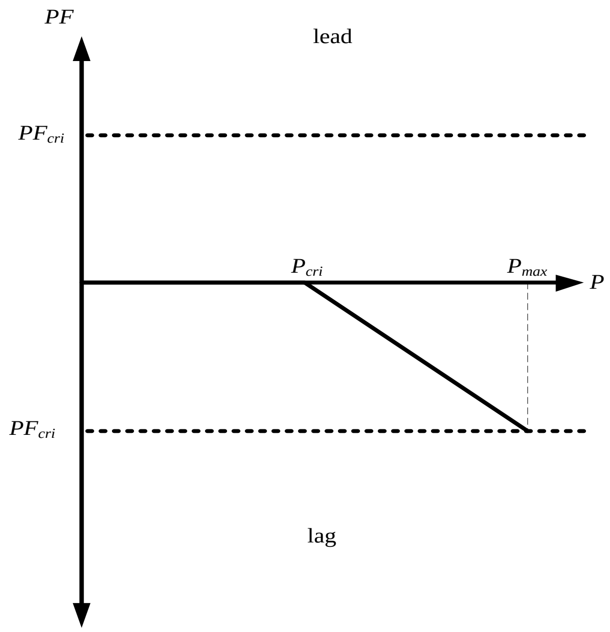


Fig. 1.5 Voltage control through PF (P) characteristic.

Strategy-2: Fixed reactive power control [30]

In this strategy, the PCC bus voltage is monitored. If the bus voltage goes above the critical limit, the smart inverter starts to absorb a constant reactive power. The characteristic of this strategy has been shown in Fig. 1.6. In this strategy, the feedback from AC network may cause unacceptable operation for the inverter.

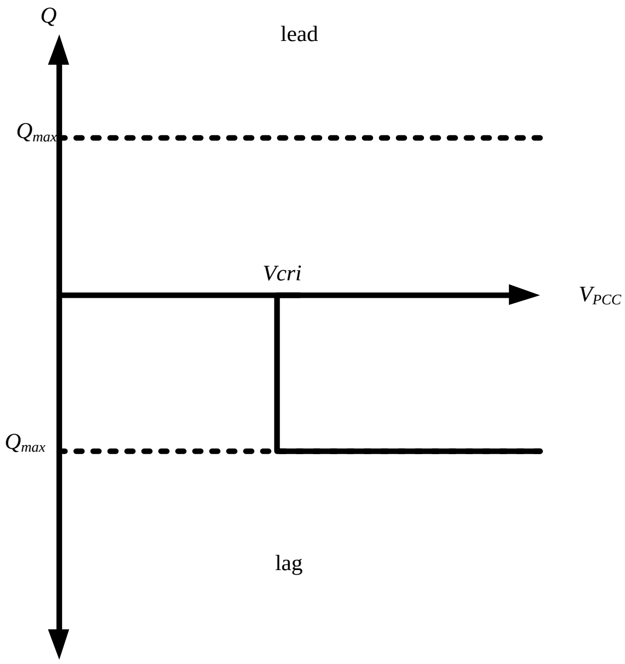


Fig. 1.6 Voltage control through fixed reactive power absorption.

Strategy-3: Reactive power control as a function of the bus voltage [30]

This strategy is based on fixing the bus voltage of each customer to a desired value by absorption of reactive power. The voltage of each bus is fixed based on droop control as shown in Fig. 1.7. If the voltage goes above the desired value (usually in high generation period), inverter absorb some reactive power to reduce the voltage. This strategy also needs feedback from AC network which may cause stability issues.

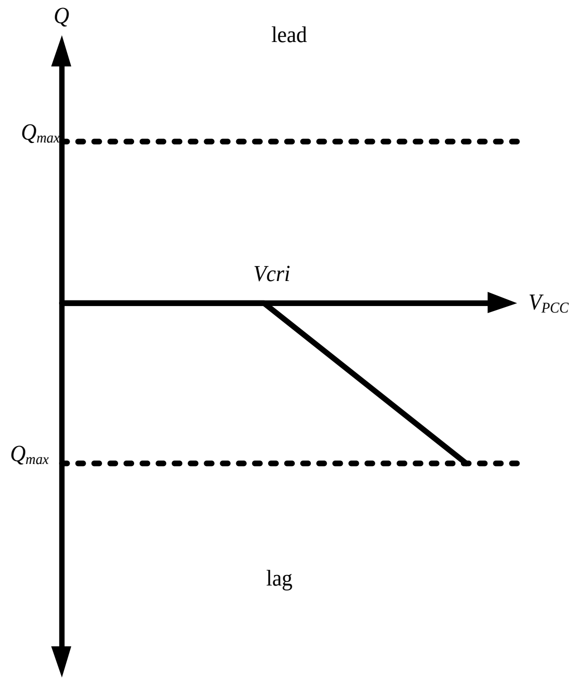


Fig. 1.7 Voltage control through *Q (V)* characteristic.

The strategies based on reactive power control have the same advantages and disadvantages. As noted before, to apply these strategies, the inverter rating need to be increased which means investment cost for customers. In addition, considering the reactive power absorption, the added losses to the network is unavoidable.

❖ *Combined PV- ESU configuration [31-41]*

It is noted before that the unbalancing between the PV generated power and load, in high generation period, causes the power quality concerns. Therefore, the introduction of ESU at every household with a PV can store surplus power in high generation period. To prevent any power quality issue, the LV network regulation can limit the maximum power injection of each customer. This limitation could be a fixed power level. As a result, the customer needs to charge their ESU in high generation mode and recharge it in peak load period (load leveling).

Although the usage of storage unit could be beneficial for grid voltage support, load leveling, peak shaving, power quality, reliability and so on [37], there are some critical factors and challenges which make the usage of storage for residential households unattractive.

The first factor is the investment cost. Storage is currently much expensive which is the key reason that the customers and utilities are reluctant to use them [31].

The second factor is the smoothness effect. Considering no smoothness effect for one customer [42], if the utility want to put an ESU for each customer, the sizing of whole storage in residential network will be high.

Moreover, considering different parameters which influence the efficiency and operation of storage, the usage of storage in residential household cannot guarantee the optimal utilization of storage units. Consequently, it results in low efficiency operation which causes least efficient operation and more renewable energy losses for the customer and network [37].

Finally, considering the low market prices, revenues from discharging the storage device might not cover the cost of charging energy that includes.

- *Utilization of controllable devices*

It has been estimated that nearly 33% of customer's demand including, dishwasher, washing machine, cooling load, storage units and electric vehicle, can be considered as controllable loads [72]. Therefore, in period of high generation or peak load, these resources can be utilized to deal with power quality issues.

1.3. Account of Research Progress Linking the Research Papers

This research project focuses on new coordination approaches for resources in distribution networks to avoid unacceptable impacts of high penetration of PVs. From the literatures, impacts including power quality issues are studied. Based on comprehensive literature review, the two main aspects have been identified - voltage and loading effects. To avoid these two problems, different solutions have been proposed and their advantages and disadvantages have been studied. These solution strategies are categorized based on voltage level in which PV is installed. LV and MV, as the main location for PVs, are considered in this research project. The main resources which can be used in LV networks are identified as follows:

1- PV inverter active power
2- PV inverter reactive power
3- Distributed customer ESUs

4- Customers' controllable loads

Considering the high number of these resources, proposed coordination strategies in literature are more in localized manner, which is not efficient. In following parts, the new approaches are introduced based on both localized and distributed to make their coordination efficient while keeping the robustness.

In MV network, the main resources which are considered for coordination are as follows:

1- PV plant active power
2- PV plant reactive power
3- ESUs

In MV network, the main strategies proposed in literature are based on centralized control. However, it would require extensive database with high speed and fast calculating computers, along with broadband networks. These approaches can also be less reliable due to communication failure and computer freezing [44]. Therefore, the new approaches are introduced based on distributed control to avoid the noted disadvantages.

1.3.1. Novel approaches to coordinate resources in LV network

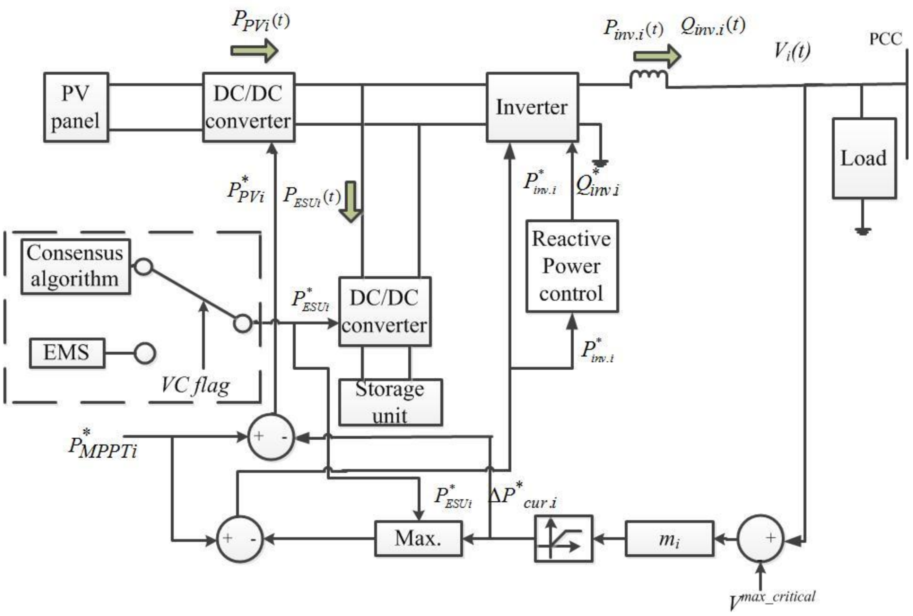
As noted before, the main resources for LV network are PV active and reactive power control, customer ESU and customer controllable loads. Since all of these resources are single-phase rather than three-phase, the proposed algorithms are applied in per phase basis. These approaches are discussed below:

A. Smart resources Control in LV network with distributed ESUs to avoid voltage rise

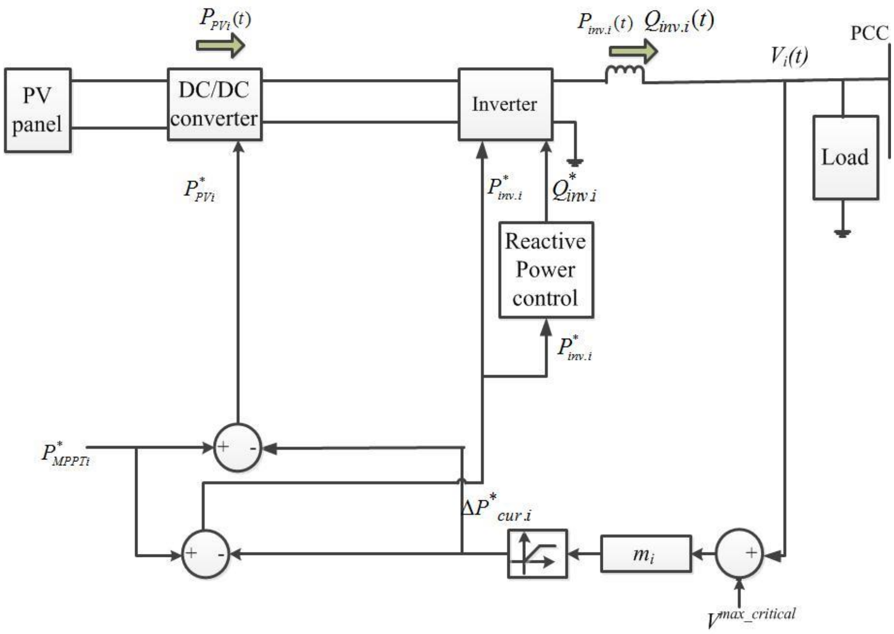
In the first step of this research, an LV network which is supported by distributed ESUs for customers is considered. In this network, for each customer, three main resources can be identified. PV inverter active and reactive power are the first and second resources which all customers, who contribute in voltage rise, have as an asset to use for avoiding voltage rise. However, the utilization of these resources results in increasing the renewable energy losses. In addition, some customers may be provided with ESUs which can be used for voltage support.

To use these resources, a new RE system is proposed for a customer in an LV network as shown in Fig. 1-8. Depending on availability of ESU, structure (a) or (b) can be used. Each

PV is connected through a DC-DC converter to a DC link. The DC link also includes the all available customer ESUs, which can be charged or discharged through the DC link. In addition, the inverter injects the surplus active power in the DC link to the AC grid.



(a)



(b)

Fig. 1.8 Proposed RE system for a customer (a) with ESU, (b) without ESU.

In the proposed RE system structure, there are three main resources which can be used by customer to deal with voltage rise. These resources include PV inverter active ($P_{inv.i}$) and reactive ($Q_{inv.i}$) power and ESU active power (P_{ESUi}). The proposed coordination approach uses these three resources to manage voltage rise. In the proposed coordination strategy, the first and second resources are coordinated by a localized control strategy to have a robust voltage reduction. However, to make the voltage reduction more efficient, the charging of distributed ESUs along the network will be coordinated using a distributed control strategy based on consensus algorithm. The details of these two control strategies are explained in Chapter 2.

In order to determine the contribution of each inverter in voltage support using active power, an upper critical voltage limit ($V^{max\_critical}$) is defined, which is less than upper permissible voltage limit ($V^{max\_permissible}$). If the voltage of any PV inverter bus passes this limit, PV inverter start to curtail its active power with a droop factor. In addition, reactive power of each PV inverter is set as a function of inverter active power. Finally, to coordinate ESUs power, critical node voltage is considered as the controllable variable and a leader is responsible to initiate and coordinate ESUs power for voltage rise control. Fig. 1-9 shows different operation modes of the proposed approach. The sequence of events is as follows:

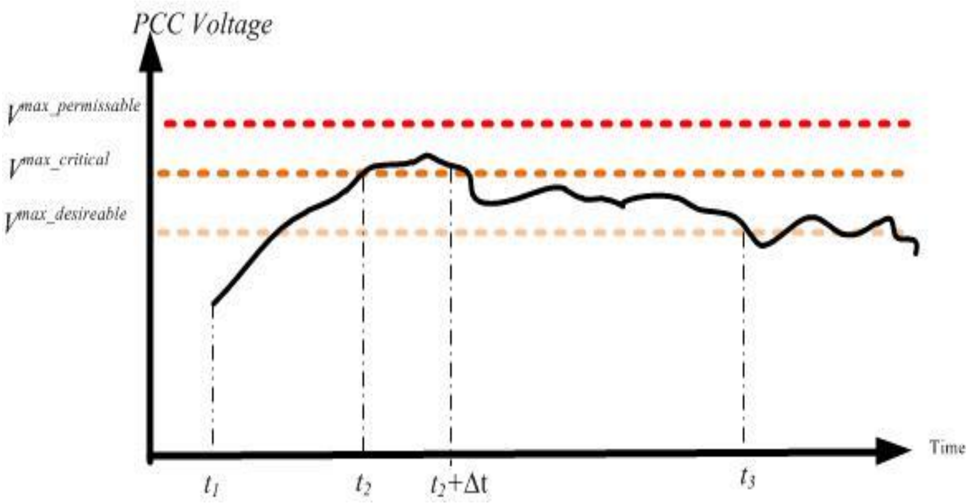


Fig. 1.9 Different operation modes of a radial LV network based on critical node voltage.

- Between t=t_1 and t=t_2, the critical node voltage is within desirable voltage range. Consequently, the network is in normal operation condition. In this situation, all PV inverters inject maximum available active power and their reactive power is as a function of their active power. Moreover, ESUs are controlled by customers Energy Management System (EMS).

- At t=t_2, the upper critical voltage limit is violated in the critical node. Therefore, PV inverters, whose bus voltages pass this, start to curtail their active power. In addition, the leader initiates the communication among ESUs to find their contribution for voltage reduction.
- Depending on the communication speed, at $t_3+\Delta t$, the ESUs reduce the voltage of critical node below the upper critical limit, which results in preventing RE curtailment.
- At t=t_4, voltage of the critical node falls back in the desirable range which means the voltage of all nodes is in desirable range. As a result, ESU control strategy is changed back to function based on customer's EMS commend.

The proposed approach here is just beneficial for voltage rise control. However, there is no control on network loading. In order to control network loading in different time period (high generation and peak load), load leveling is proposed in this research project. In other words, it is proposed that distributed customer's ESU can be coordinated to act as a buffer and charge during high generation period and recharge back to the network during peak load period. With this strategy, both network overloading and voltage fluctuation can be solved. A new distributed load leveling approach is proposed to coordinate multiple distributed ESUs in LV network and deal with voltage and loading issues as shown in following part.

B. A novel distributed approach for load leveling in LV network

In this part, to have control on network loading as well as voltage, load leveling is proposed to be used in LV network. Let us consider phase *X* that has *n* distributed ESUs. The proposed distributed control structure for this network is shown in Fig. 1.10. In this structure, a higher control level as leader is defined as the one who is responsible to initiate the coordination among ESUs. $S(t)$, which is the drawn power from or injected power to the higher voltage level network, is considered as the controllable variable for load leveling. For both peak generation and peak load periods, two threshold limits have been defined to determine the operation mode of network. In peak load period, the value of $S(t)$ is positive and if $S(t)$ is less than $S^{load\_desirable}$, network is in normal operation mode and ESUs coordination is not needed. However, if the $S(t)$ violates $S^{load\_critical}$, ESUs coordination is initiated by leader and the coordination will continue until the value of $S(t)$ becomes less than $S^{load\_desirable}$. The same procedure is applied for peak generation period in which $S(t)$ is negative and $S^{gen\_critical}$ and

$S^{gen\_desirable}$ determine the operation of the network . The details of this approach are given in Chapter 3.

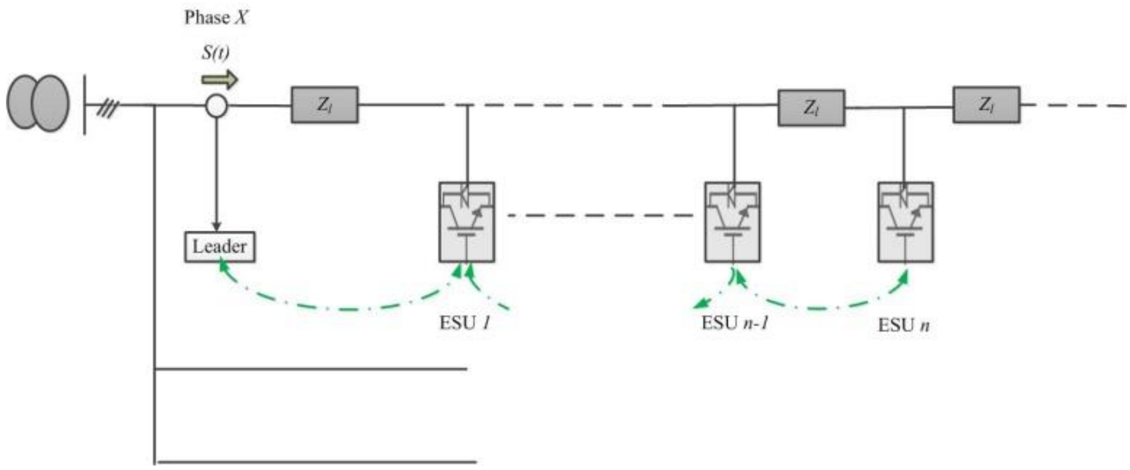


Fig. 1.10 Proposed distributed control structure.

The proposed load leveling approach is applied to a typical LV network with 12 customers (six nodes) as shown in Fig. 1-11. This network includes 4 distributed ESUs. The same load and generation is considered for all customers as shown in Fig. 1-12. The results when there is no ESU coordination, is shown in Fig. 1-13. It can be seen that nodes 5 and 6 voltage violate the upper permissible limit between t =12s to t=14s; in addition, node 6 voltage violates the lower permissible limit during t=21s to t=22s.

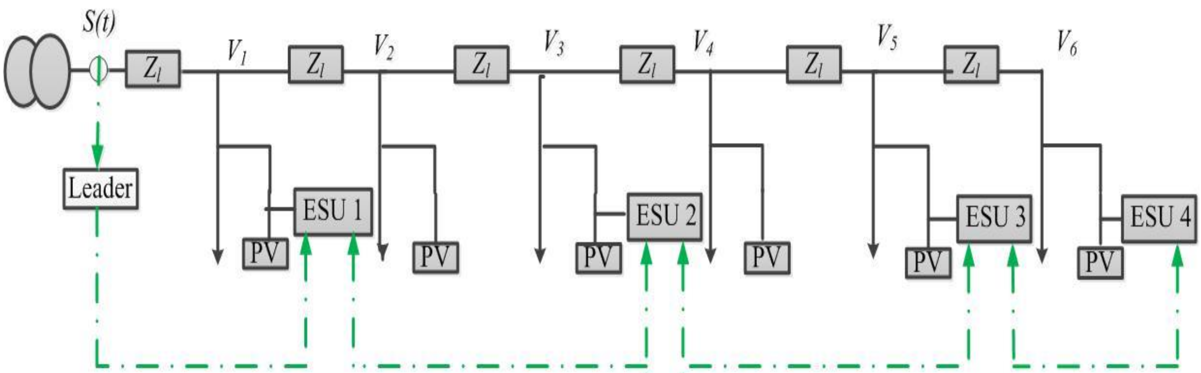


Fig. 1.11 Case study.

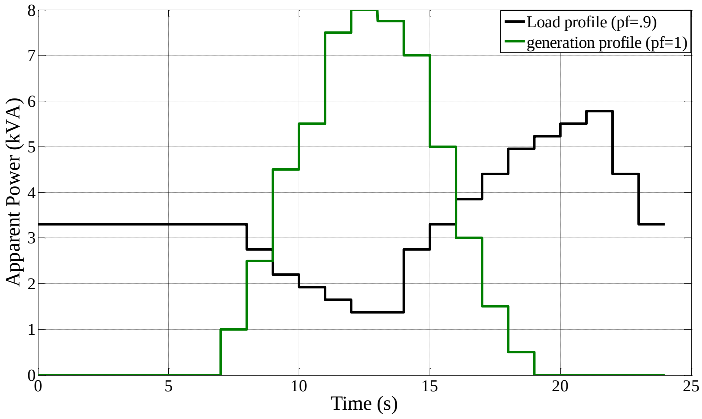
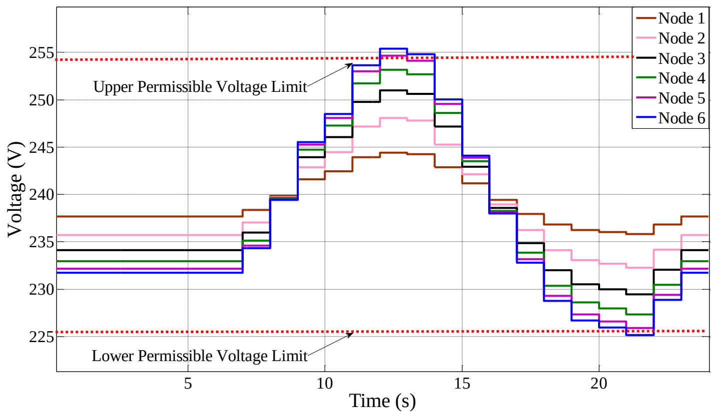
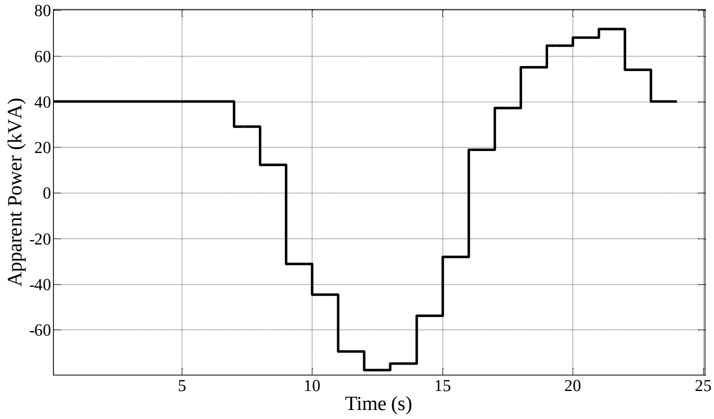


Fig. 1.12 Load and generation profile for customers.

In the second case, the proposed approach is applied for operation of this network. It can be seen that both undervoltage and overvoltage issues are resolved while the network loading is reduced to 60 kVA.

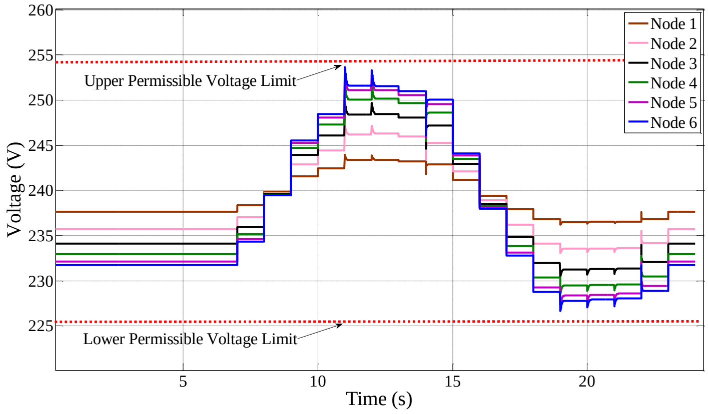


(a)

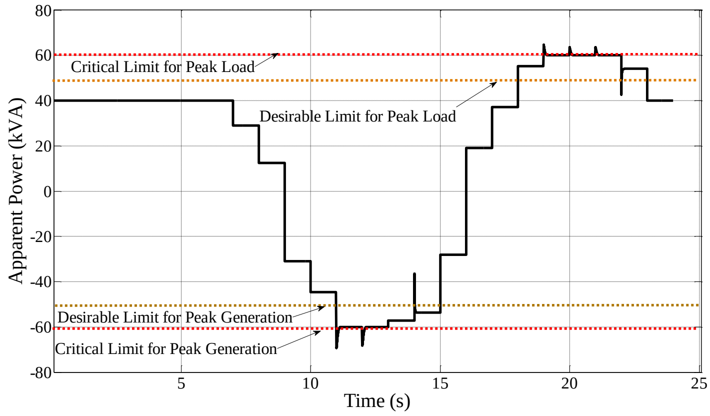


(b)

Fig. 1.13 No ESUs coordination (a) voltage profile of critical buses, (b) Network apparent power.



(a)



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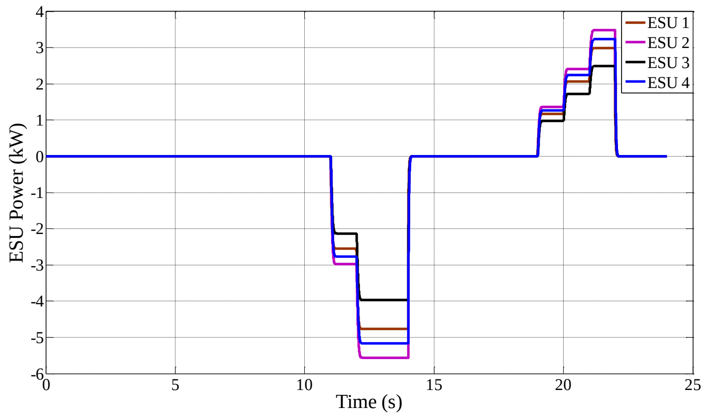


(c)

Fig. 1.14 Proposed control approach (a) Nodes voltage, (b) Network apparent power, (c) ESUs power.

Until now, the proposed approaches are just considered for customers who have their own DC link. However, if their DC links are connected together, they can exchange their power through this DC link. In following part, common DC link is proposed to be installed in LV network to accommodate customer injection while providing a pathway to future DC network. The details of this approach are as follows.

C. Common DC link in LV network to avoid AC power quality issues

The maximum desirable penetration level of PVs with “plug-and-play” functionality can be achieved using a common DC link with associated auxiliaries. This method gives suitable solution for the unbalancing between generation and load. In traditional structure, any surplus power is injected to the AC line. However, as noted earlier, direct local power injection to AC line may cause power quality problems. The utilization of an auxiliary DC link as an alternative approach is proposed to resolve the AC power quality issues, while providing additional advantages such as higher level of redundancy and a pathway to the future LV DC network. This system can efficiently provide supply to the AC loads, while the PVs surplus power can be injected into the common DC link. As a result, the problems associated with local surplus power injection to the LV AC lines will be resolved, while great deal of flexibility and redundancy are achieved.

The network shown in Fig. 1-11 is used to assess this upgrading approach as well. A 4-second study is utilized to show how this approach can improve the efficiency in LV network. The details are provided in Chapter 4. Four types of scenarios, including no control, overvoltage protection and active power curtailment are considered to compare with this approach. The total energy injected to the upstream network in period of study is shown in Table 1-1. It can be seen that this approach has the maximum injected energy to the upstream network.

Table 1.1 Energy injected to the upstream network.

Strategy	value
No control	0.0489 kWh
Overvoltage protection	0.0336 kWh
Active power curtailment	0.0367 kWh
Proposed approach	0.0522 kWh

Until now, PV inverter active power, PV inverter reactive power, customer DC link and customer ESU are used as the resources and new coordination approaches are proposed to coordinate these resources to avoid voltage and loading issues. However, future electricity grid will include widespread use of smart controllable devices such as electric vehicle, dishwasher, air conditioner and so on. These resources can be useful asset to deal with noted problems. In the following part, a new communication structure is proposed to be used for smart meters and coordinate these resources for voltage rise mitigation.

D. Smart voltage rise control using customers controllable loads

The schematic layout of the proposed structure is shown in Fig. 1-15. The dashed arrows show the information flow. As shown in this figure, individual customers are controlled by their own EMS. There is a communication link between EMS and customers' resources. The EMS receives the resources' information and sends back required command, taking into account each customer's objective or any external command.

In addition, there are communication link between EMSs of adjacent customers through their smart meters. This functionality can give customers the ability to collaborate with each other for different operational goals such as voltage support using their controllable load.

Two voltage limits have been defined for operation of network. Based on these limits, the operating state of individual customers can be determined by their own PCC voltage (*Vi*) as shown in Table 1-2.

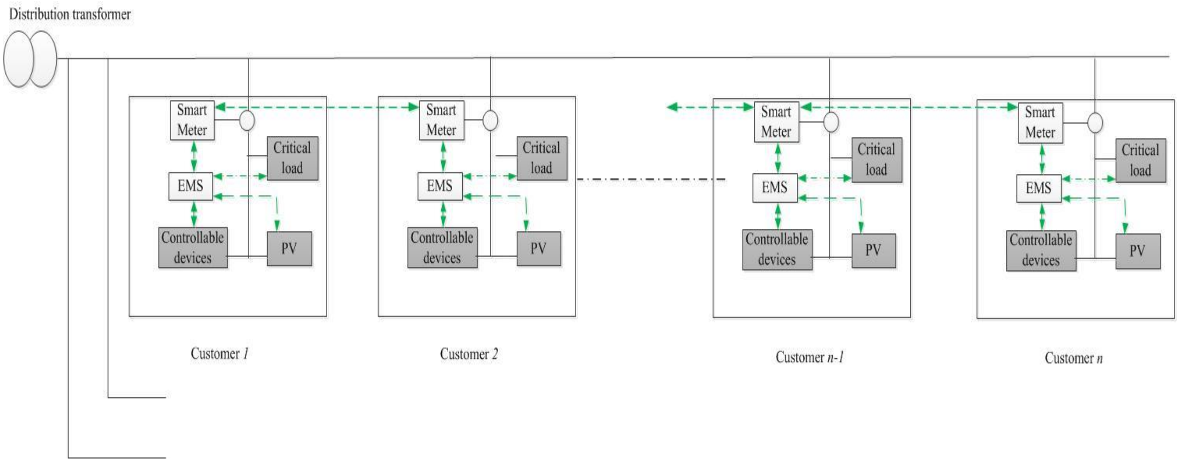


Fig. 1.15 Proposed structure for residential LV network.

Table 1.2 Customer operation states.

State	Definition
Normal	$V_i \leq V^{\max\_desirabele}$
Alert	$V^{\max\_desirabele} \leq V_i \leq V^{\max\_critical}$
Emergency	$V^{\max\_critical} \leq V_i$

The network operating mode is defined based on the operating state of all customers. If all customers are in normal state, the LV network is in normal operating mode. In this operating mode, there is no need for voltage support and all customers are free to maximize their injection to the grid.

However, if there is any customer in emergency state, network goes to the voltage control mode. Consequently, two control strategies (localized and distributed) will be used to prevent permissible voltage limit violation. The details of these strategies are explained in Chapter 5.

The same LV network is considered to study this approach. A 12-second simulation is applied to four types of scenario. In the first scenario, it is assumed that overvoltage would not pose any problem and PVs can generate power without voltage control. Although this situation is not realistic, it is only included for comparison purpose. Let us assume the efficiency of PV inverters is equal to 0.95. If the energy yield defined to be as the value of PV inverters injected power to the value of available PVs power, the yield for this scenario is equal to 0.9394 for the period of study.

For the second scenario, it is assumed that overvoltage protection is applied for each inverter and whenever the inverter bus voltage violates the upper permissible limit, the PV inverter will trip and reclose after 5 s, that is if the PCC voltage is in permissible range [49]. With this strategy, the energy yield is reduced to 0.7481 for the period of study.

Finally, in the third scenario, the proposed operation approach is used. Application of the proposed method in Chapter 5 can provide an energy yield of 0.9357. This approximately increases the energy yield by 20% compared to the case with overvoltage protection, thereby saving large amount energy on a large scale.

In addition, the effect of communication drop is also studied on the proposed approach. The energy yield for this case is equal to 0.9331. The result of this scenario shows that the communication problem can only affect the efficiency of voltage reduction and robustness of the proposed control approach does not depend solely on communication availability.

1.3.2. Novel approaches to coordinate resources in MV network

As noted before, the challenge in MV network is the coordination among concentrated resources. The resources which are identified in this project include:

1- PV plant active power
2- PV plant reactive power
3- ESU

These resources are installed in three-phase layout. As a result, the proposed approaches are considered in three-phase base. For the sake of simplicity, balanced network are considered for the case studies.

A. Distributed Coordination Approach for Multiple PVs in MV Networks

The proposed distributed control structure for coordination of PVs in distribution network is shown in Fig. 1-16. In this structure, the neighbouring PVs are communicated to coordinate their operation. A higher control level, named the leader, is responsible to initiate the coordination. Both voltage rise and network loading are considered to be controlled by the PV coordination. To keep all voltages in permissible range, the critical bus voltage ($V_c(t)$) is proposed to be the controlling variable. Two voltage limits, $V^{desirable}$ and $V^{critical}$, are defined to determine the network operation modes. If the critical bus voltage is less than $V^{critical}$, coordination of PV inverters for voltage support is not needed. However, if the critical bus voltage violates this limit, leader initiates the distributed algorithm to regulate PV inverters reactive power and reduce the voltage, as will be discussed in Chapter 6. The coordination will continue until the critical bus voltage is reduced to less than $V^{desirable}$. In this situation, all PV inverters decrease their reactive power to zero, step by step.

For network loading management, the network loading ($S(t)$) is considered as the controlling variable and $S^{desirable}$ and $S^{critical}$ determine the network operation. If the network loading passes $S^{critical}$, leader initiates consensus algorithm to share the required active power curtailment among the PVs.

The main objective in this part is to design a control for each PV inverter in such a way that at equilibrium point, the required active and reactive power is shared with the same ratio among PV inverters.

A typical distribution network is used in Chapter 6 to show the effectiveness of the proposed approach. The network parameters can be found in Reference [44]. The network structure with its communication topology is shown in Fig. 1-16.There are 5 PVs and 6 loads connected in this network. The value of load in each node is as listed in Table 1-3. To study the operation of network in different modes, it is assumed that PVs have the generation profiles as shown in Fig. 1-17.

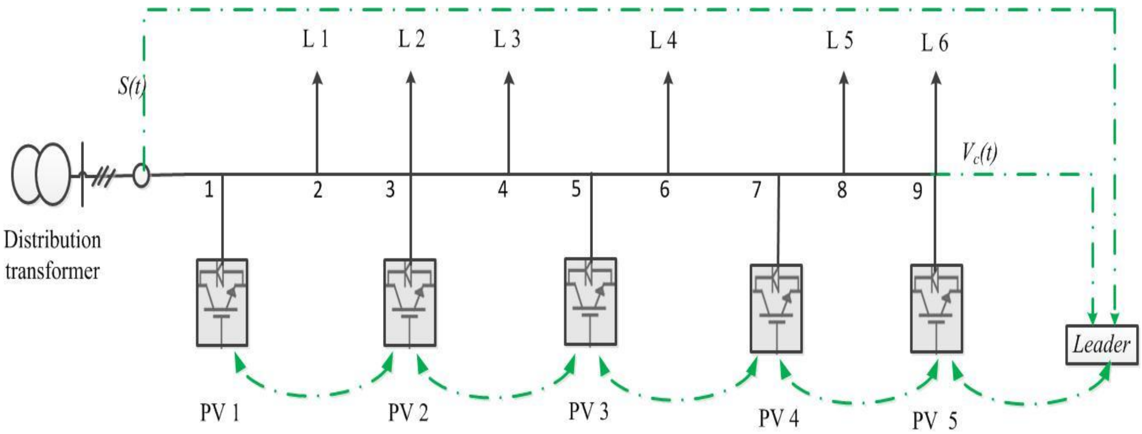


Fig. 1.16 Case study.

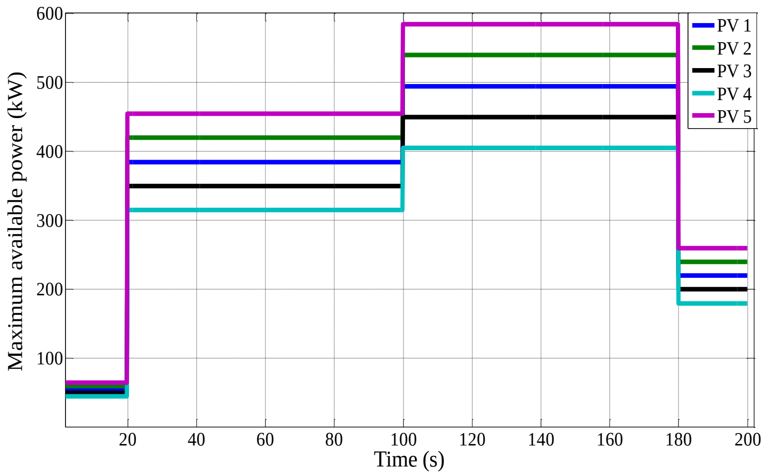


Fig. 1.17 PVs Generation profile.

Table 1.3 Load information.

Load	L1	L2	L3	L4	L5	L6
Active power (kW)	34.6	36.5	47.4	39.5	41.3	27.3
Reactive power (kVAR)	9.2	5.8	9.7	6.3	12.2	7.8

The results in Fig. 1-18 show the bus voltages, network loading, PVs active power, PVs reactive power in different time steps, using the proposed control approach. Time sequence of this operation process is described as follows:

1- Between 0 s and 20 s, all voltages are in the desirable range and PVs inject their maximum active power and no coordination is needed.

2- At 20 s, the PVs injection increases while the critical bus voltage passes $V^{critical}$. As a result, leader initiates the coordination of PV inverters reactive power to reduce the voltage. At t=68 s, the critical bus voltage become less than $V^{critical}$ (the first objective is achieved). At equilibrium point, the contributions of PVs in reactive power are listed in Table 1-4. It can be seen that they contribute with same ratio with respect to their ratings.

3- At 100 s, the critical limit of both voltage and network loading is violated. As a result, the leader initiates to coordinate PVs active and reactive power. The contributions of PVs at equilibrium point are listed in Table 1-4 and 1-5. It can be seen for both active and reactive power that PVs contribute with the same ratio. Consequently, both aims for voltage rise control and network loading management are achieved by the proposed distributed control approach.

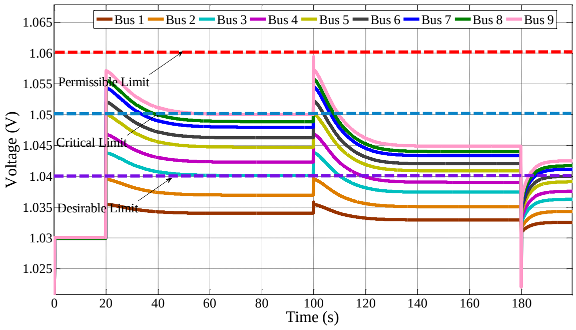
4- At 180 s, the injection to the network is reduced which causes the voltages and network loading go to the desirable range. From this point, PV units again maximize their active power injection with no reactive power contribution.

Table 1.4 PVs reactive power in different time interval.

Time interval	PV1	PV2	PV3	PV4	PV5	$\frac{Q_{PVi}}{Q_{PVi}^{\max.}}$
0-20s	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0*
20-100s	*-130.45*	*-142.32*	*-118.61*	*-106.74*	*-154.17*	*-0.47*
100-180s	*-240.67*	*-262.55*	*-218.79*	*-196.91*	*-284.43*	*-0.87*
180-200s	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0*

Table 1.5 PVs active power in different time interval.

Time interval	PV1	PV2	PV3	PV4	PV5	$\frac{P_{PV1}}{P_{PV1}^{\max.}}$
0-20s	*55.00*	*60.00*	*50.00*	*45.00*	*65.00*	*1.00*
20-100s	*385.00*	*420.00*	*350.00*	*315.00*	*455.00*	*1.00*
100-180s	*397.23*	*433.34*	*361.12*	*325.00*	*469.46*	*0.80*
180-200s	*220.00*	*240.00*	*200.00*	*180.00*	*260.00*	*1.00*



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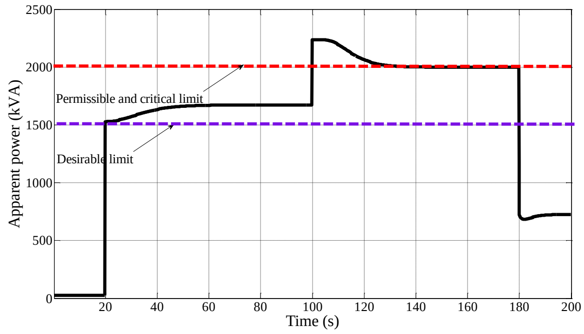

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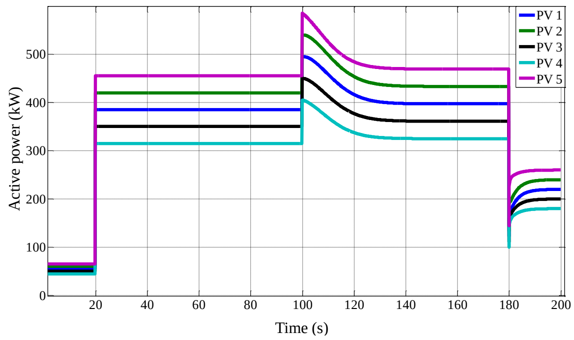

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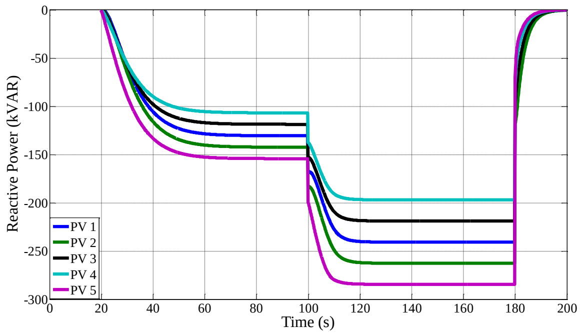


(d)

Fig. 1.18 Proposed control approach, (a) bus voltages, (b) network loading, (c) PVs active power, (d) PVs reactive power.

As shown in this part, the coordination strategy shares the required reactive power with the same ratio among PV inverters. However, voltage limit violation is a local problem, not a network wide area issue. Therefore, it is well suited to design a distributed control such that the most effective PVs on the violated voltage(s), should contribute more in the reactive power sharing. This strategy is expected to provide the efficient voltage support mechanism. To achieve this objective, a new mixed localized-distributed control strategy is proposed to coordinate PVs reactive power in efficient way as shown in following part.

B. Efficient Distributed Voltage Support Approach for Distribution Networks with Multiple PVs

The idea in this approach is to keep the PV bus voltage in an acceptable range (between $V^{max\_critical}$ and $V^{min\_critical}$). The only difference is in PV internal control for reactive power. In the proposed internal control structure for PVs, the information state of each PV is a function of its bus voltage as well. In addition, the sensitivity of PV bus voltage to its reactive power and the reactive power of neighboring PVs are used to tune the transition weights which make this approach more efficient. Additionally, it is also shown how this control structure can effect and improve the utilization of other distribution network components such as AVR control loop.

The details of this approach are shown in Chapter 7. The IEEE 33 bus distribution system, as shown in Fig. 1-19, is used to assess the effectiveness of this approach.

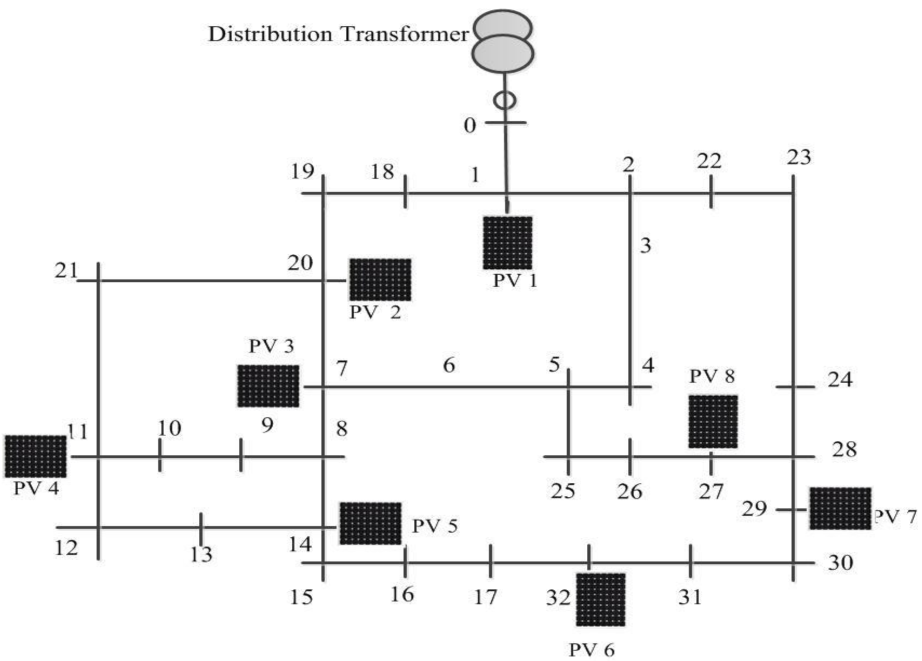
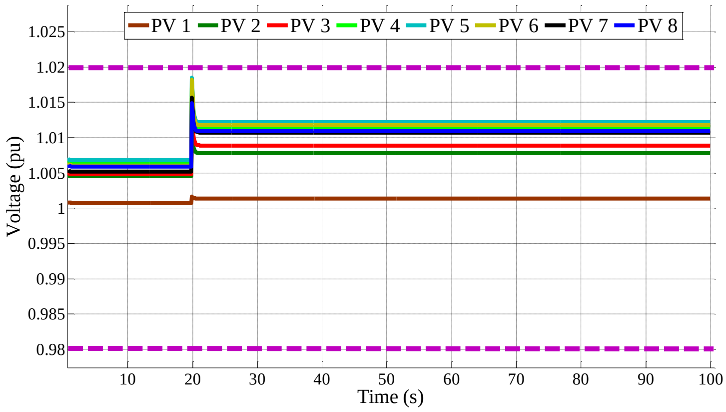


Fig. 1.19: IEEE 33 bus distribution system, case study.

The advantage of the proposed control is discussed compared with droop-based control for PV inverter. It is assumed that the load in all buses are 25% of their maximum value and PVs generation is increased from 400 kW to 700 kW at t=20s. The results for the case of droop-based control are shown in Fig. 1.20. It is assumed that PVs need to regulate their bus voltage in the range of 0.98-1.02 pu using droop-based control of reactive power. It can be seen that for both states (before and after generation rise), the PV bus voltages are kept in the desire range, by PV inverter contribution in reactive power as shown in Fig. 1.20 (b).



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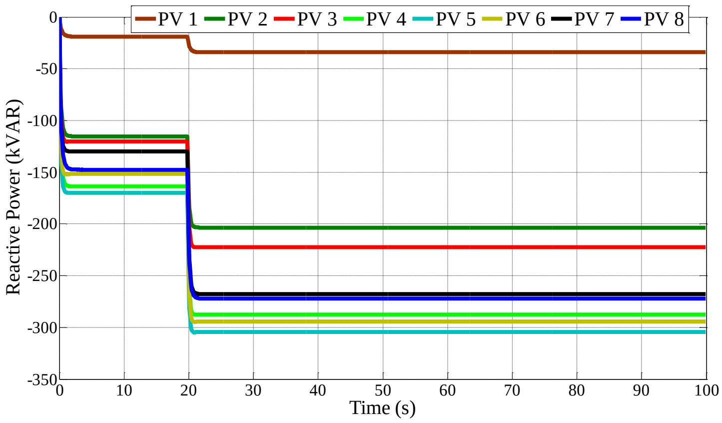
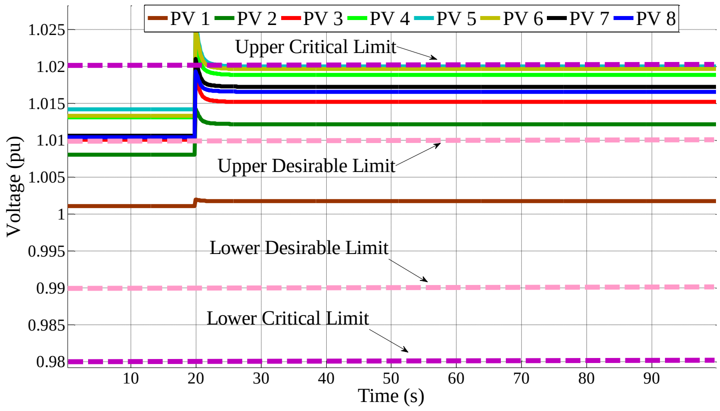


(b)

Fig. 1.20 Droop- based voltage control, (a) PV bus voltages, (b) PVs reactive power.

The same case is examined using the proposed control approach. The results are shown in Fig. 1.21. Before generation increase, all voltages are less than critical limit and compared with the case of droop-based control with total required reactive power of 1026 kVAR, this strategy does not need any reactive power contribution. However, after generation step change, the voltage at buses 4. 5, 6 and 7 passes the upper critical limit. Therefore, PVs at these buses initialize their coordination for voltage support. After 13 s, the voltage of all PV buses reduced to less than the upper critical limit.

For both noted control approach, PVs reactive power are listed in Table 1.6. As shown in this table, the proposed control structure results in much less reactive power contribution compared with the droop based control, which is attractive.



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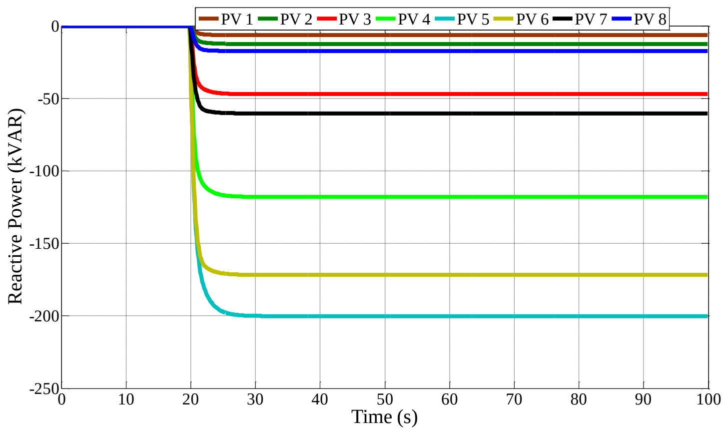


(b)

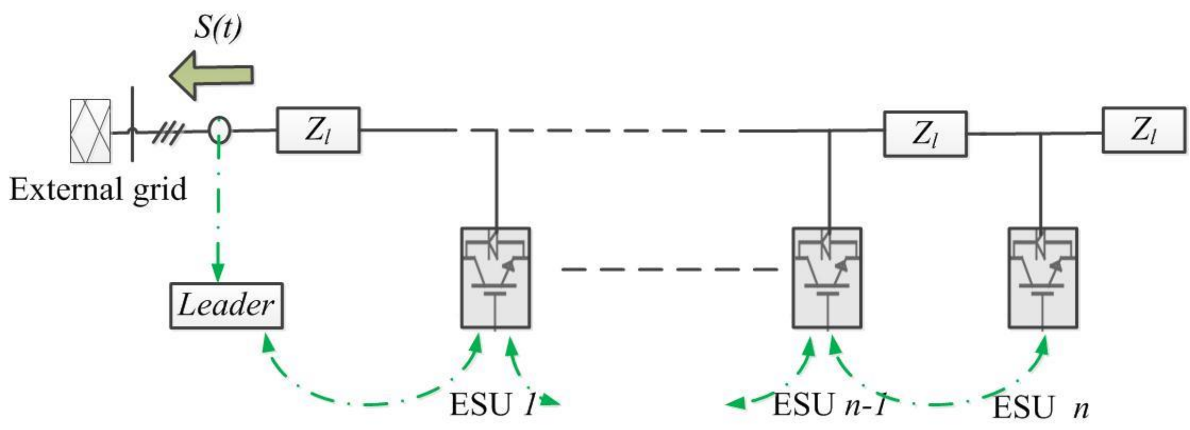
Fig. 1.21 Proposed approach, (a) bus voltages, (b) PVs reactive power.

Table 1.6 PVs reactive power (kVAR) after generation step change.

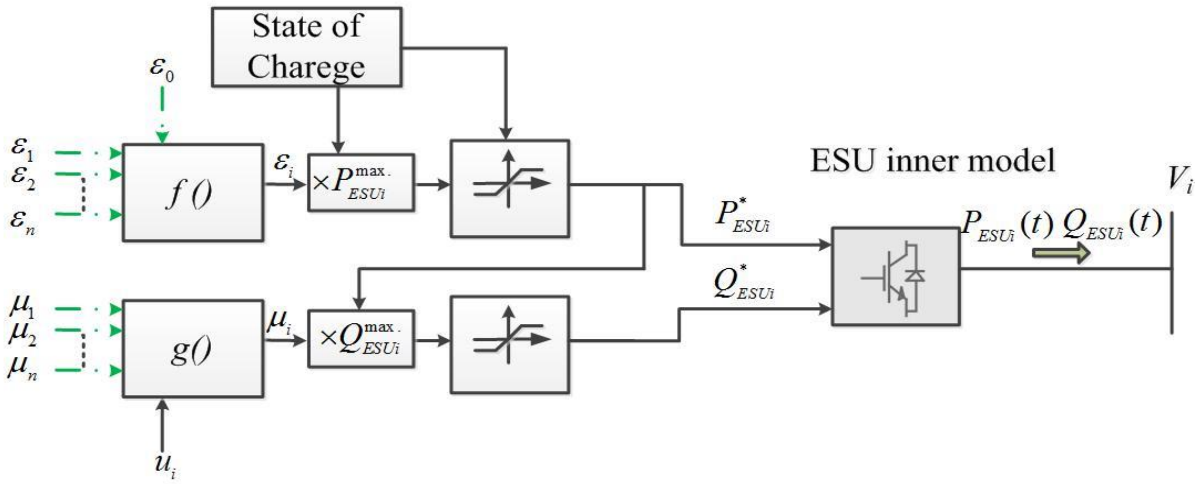
PV no.	Droop-based approach	Proposed approach
1	-34.21	-6.46
2	-203.53	-12.50
3	-222.25	-47.13
4	-287.56	-117.96
5	-304.35	-200.14
6	-294.24	-171.73
7	-267.90	-60.37
8	-272.33	-17.39
Total	-1886.4	-633.68

C. Smart Coordination of Energy Storage Units (ESUs) for Voltage and Loading Management in Distribution Networks

The proposed distributed control structure for coordination of ESUs is shown in Fig. 1-22, where the neighbouring ESUs are communicating to coordinate their operation. The proposed internal control structure for each ESU is shown in Fig. 1-22 (b). The reference value for ESU's active and reactive power depends on the information state of each ESU and its neighbours. The proposed control structure includes voltage and network loading management. Details of the proposed approach are presented in Chapter 8. The main focus of ESU coordination was to share the required active power among ESUs with respect to their State of Charge (SOC) which is an important parameter for ESU. In addition, the constraints for ESU reactive power such as operating in acceptable range of power factor are also considered.



(a)



(b)

Fig. 1.22 Proposed approach, (a) distributed control structure, (b) Internal control structure for each ESU.

A typical radial distribution network is selected to show the effectiveness of the proposed approach. The network parameters and load details can be found in [44]. There are 5 PVs connected in this network with rating listed in Table 1-7. The network structure with three ESUs and its communication topology is shown in Fig. 1-23. It is assumed for the period of study, all ESUs can continuously support the power shown in Table 1-8. It is assumed that ESU inverter rating is increased by just 11.8% to have the ability to supply nearly 50% reactive power while supplying full rated active power. The limits for voltage and network loading are listed in Table 1-9 and 1-10.

It is assumed that all loads are in 15% of their maximum. In addition, the PVs generation change from 75% to 95% at t=100 s. the result for this case is shown in Fig. 1-24.

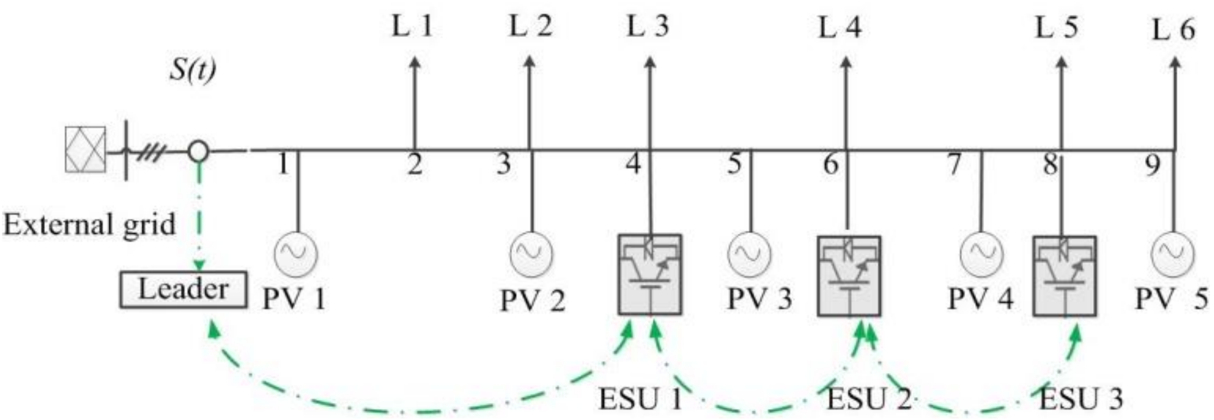


Fig. 1.23 Case study.

Table 1.7 PVs rating.

PV	PV1	PV2	PV3	PV4	PV5
Active power (kW)	550	600	500	450	650

Table 1.8 Available active power for ESUs.

ESU	ESU1	ESU2	ESU3
Active power (kW)	150	200	250

Table 1.9 Voltage limits in the proposed approach.

Parameter	Voltage (pu)
$V^{max\_permisIable}$	1.06
$V^{max\_critical}$	1.03
$V^{max\_desirable}$	1.02

Table 1.10 Network loading limits in the proposed approach.

Parameter	Power (kVA)
$S^{max\_permissible}$	2200
$S^{max\_critical}$	1800
$S^{max\_desirable}$	1500

It can be seen between t= 0s and t= 100s, all voltages and network loading are in the desirable range. Therefore, no ESUs coordination is needed. However, at t=100s, as the PV generation increases, the upper critical limit for voltage of ESUs 2 and 3 and network loading is violated. Therefore, the proposed control approach for both voltage and thermal constraints management is initiated. For network loading management, it can be seen that, at the equilibrium point, its value is less than upper critical limit. In addition, the ESU contribution is as follow which is equal sharing among ESUs with respect to their SOC.

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{-74.75}{150} = -0.49$$

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{-99.67}{200} = -0.49$$

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{-124.59}{250} = -0.49$$

In addition, after the generation step change, the ESU voltages follow the pattern based on equation (1-8). Accordingly, reactive power sharing among ESUs needs to follow as in (1-9) to have effective voltage support.

$$V_3 > V_2 > V_1 \tag{1-8}$$

$$\left|\frac{Q_{ESU3}}{Q_{ESU3}^{\max.}}\right| > \left|\frac{Q_{ESU2}}{Q_{ESU2}^{\max.}}\right| > \left|\frac{Q_{ESU1}}{Q_{ESU1}^{\max.}}\right| \tag{1-9}$$

The reactive power sharing at the equilibrium point of coordination is as follows. It can be seen that the proposed approach follow equation (1-9) to have efficient voltage reduction.

$$\left|\frac{Q_{ESU1}}{Q_{ESU1}^{\max.}}\right| = \left|\frac{Q_{ESU1}}{0.4843 \times P_{ESU1}}\right| = \left|\frac{-2.016}{0.4843*124.59}\right| = 0.033$$

$$\left|\frac{Q_{ESU2}}{Q_{ESU2}^{\max.}}\right| = \left|\frac{Q_{ESU2}}{0.4843 \times P_{ESU2}}\right| = \left|\frac{-5.28}{0.4843*124.59}\right| = 0.087$$

$$\left|\frac{Q_{ESU3}}{Q_{ESU3}^{\max.}}\right| = \left|\frac{Q_{ESU3}}{0.4843 \times P_{ESU3}}\right| = \left|\frac{-14.05}{0.4843*124.59}\right| = 0.232$$

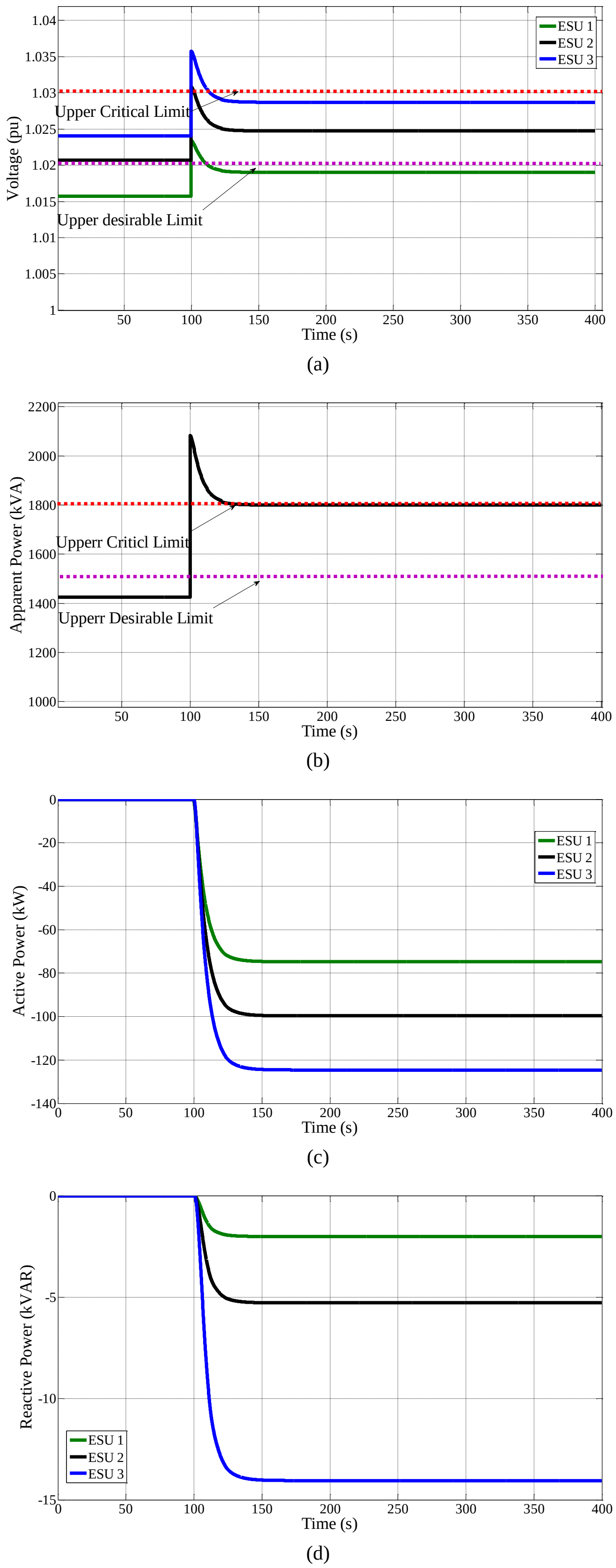


Fig. 1.24 Proposed control approach (a) ESUs bus voltage, (b) network loading, (c) ESUs active power, (d) ESUs reactive power.

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Statement of Contribution of Co-Authors

The authors listed below have certified that:

1- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

2- They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publications;

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In the case of this chapter:

Smart Robust Resources Control in LV network to Deal with Voltage Rise Issue.

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Contributor	Statement of contribution
Ghassem Mokhtari 21 May 2014	Proposed the control strategy. Developed the control strategy regarding the simulation and data analysis. Wrote the manuscript.
Ghavam Nourbakhsh	Aided data analysis and writing the paper
Arindam Ghosh	Aided data analysis and writing the paper
Gerard Ledwich	Aided data analysis and writing the paper

Supervisor Confirmation

I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

Prof. Arindam Ghosh

Name Signature Date: 2 Jan. 2014

Chapter 2

Smart Robust Resources Control in LV Network to Deal with Voltage Rise Issue

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Abstract— Often voltage rise along Low Voltage (LV) networks limits their capacity to accommodate more Renewable Energy (RE) sources. This paper proposes a robust and effective approach to coordinate customers' resources and control voltage rise in LV networks, where PVs are considered as the RE sources. The proposed coordination algorithm includes both localized and distributed control strategies. The localized strategy determines the value of PV inverter active and reactive power, while the distributed strategy coordinates customers' Energy Storage Units (ESUs). To verify the effectiveness of proposed approach, a typical residential LV network is used and simulated in the PSCAD-EMTC platform.

2.1. Keywords

LV Network, Consensus algorithm, Voltage Rise, ESU.

2.2. Introduction

The demand for electric energy continues to rise worldwide. At the same time, global warming concerns have led to the introduction of carbon taxes in many countries to regulate the electricity consumption, while providing incentives for the installation of RE resources [1]. It is anticipated that future LV networks will see a widespread use of small scale RE generators such as PV and wind turbine. The high penetration of RE generators may cause power quality issues. The main power quality issues referred in literatures include voltage rise [2], voltage regulation [3-5], voltage unbalancing [6], line overloading [7], flicker and harmonics [8]. Voltage rise is normally the main limiting factor to prevent the increase RE generation in LV networks. At peak generation period, the generated power by RE generator exceed the customer load. This surplus power, injected to the grid, will cause reverse power flow and hence voltage rise.

Many researchers have proposed several solutions to deal with this challenge. These are summarized below.

1- Network upgrading, which needs new expensive investment by utilities [9-11].
2- Changing network static set points, such as reduction of secondary LV transformer tap. Based on the randomness of load and generation, the main limitation of this approach is that the static set points would have to change frequently, which is not practical [4, 10].

3- Utilization of customers' resources such as RE generators (its active and reactive power) and Energy Storage Unit (ESU) to deal with voltage rise. In other words, in period of high generation and low load, these resources can be effectively utilized to deal with the problem of voltage rise.

The third approach is the most promising for future smart grid. However, the main challenge is to find a coordination control strategy for these resources. There are three types of control strategies that can be adopted. The first strategy can be employed in a centralized fashion in which a central controller coordinates various resources in the LV network. This approach, even though most efficient, requires online information of the network resources and high computation speed. In addition, it requires fast and reliable communication links. The second approach is a localized control strategy that is based on local measurements only, such as the one proposed in [12]. This control strategy is robust since only local measurements are utilized. However, it cannot effectively utilize all available resources. The third strategy involves distributed control. This approach can be as efficient as a centralized approach while avoiding its complexity. However, the robustness of this approach still depends on communication links.

This paper proposes an effective and robust approach based on both localized and distributed control strategies to coordinate the resources in LV network in order to deal with voltage rise. The main contributions of the paper include (1) allowing every owner of renewable energy sources to utilize all available resources (e.g. ESU, inverter active and reactive power) for voltage rise control, (2) design of internal ESU control to adapt for consensus algorithm and coordination, and (3) design a method using combined localized and distributed algorithms to achieve a robust and efficient voltage reduction.

2.3. Proposed Approach

LV networks usually are designed to allow a maximum of 5–10% (depending on national standards) voltage drop from LV transformer secondary to the last customer [12]. Consider the single-phase radial LV network with PV connection for each customer, as shown in Fig. 2-1. Usually, the distribution transformer tap setting is designed in such a way that the voltage level in critical node is within the standard limits in normal operation condition. However, as more and more PVs get connected to the LV networks, significant reverse power flow ensues, especially as the PV penetration level increases. This reverse power flow may cause voltage rise along the network and violate the upper permissible voltage limit

($V^{max\_permissible}$) in some nodes. To avoid this problem, this paper proposes a new robust and efficient approach for customers to coordinate their resources to avoid any upper permissible voltage limit violation.

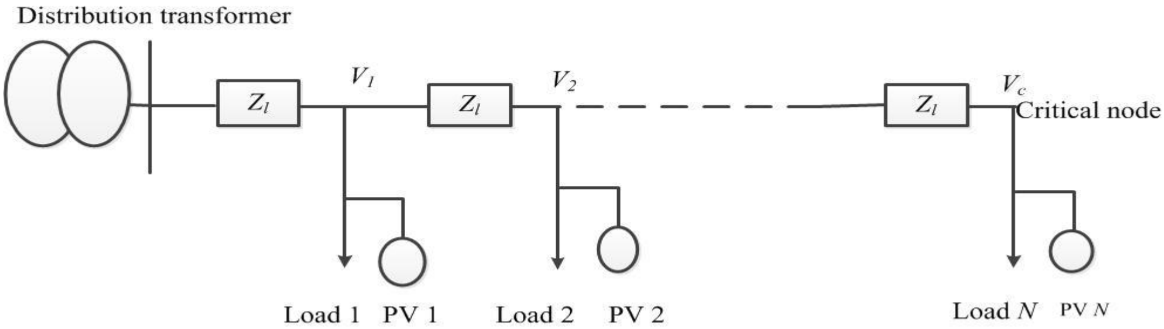


Fig. 2.1 Single-phase radial LV network.

The proposed RE system for a customer in an LV network is shown in Fig. 2.2. Depending on availability of ESU, structure (a) or (b) can be used. Each PV is connected through a DC-DC converter to a common DC link. The DC link also includes all available customer ESUs, which is charged or discharged through the DC link. In addition, the inverter injects the surplus active power in the DC link to the AC grid.

In the proposed RE system structure, there are three main resources which can be used by customer to deal with voltage rise. These resources include PV inverter active ($P_{inv.i}$) and reactive ($Q_{inv.i}$) power and ESU active power (P_{ESUi}). The proposed coordination approach uses these three resources to manage voltage rise. As shown in Fig. 2.2, the first and second resources are coordinated by a localized control strategy to have a robust voltage reduction. However, to make the voltage reduction more efficient, the charging of distributed ESUs along the network will be coordinated using a distributed control strategy based on a consensus algorithm. The details of these two control strategies are explained next.

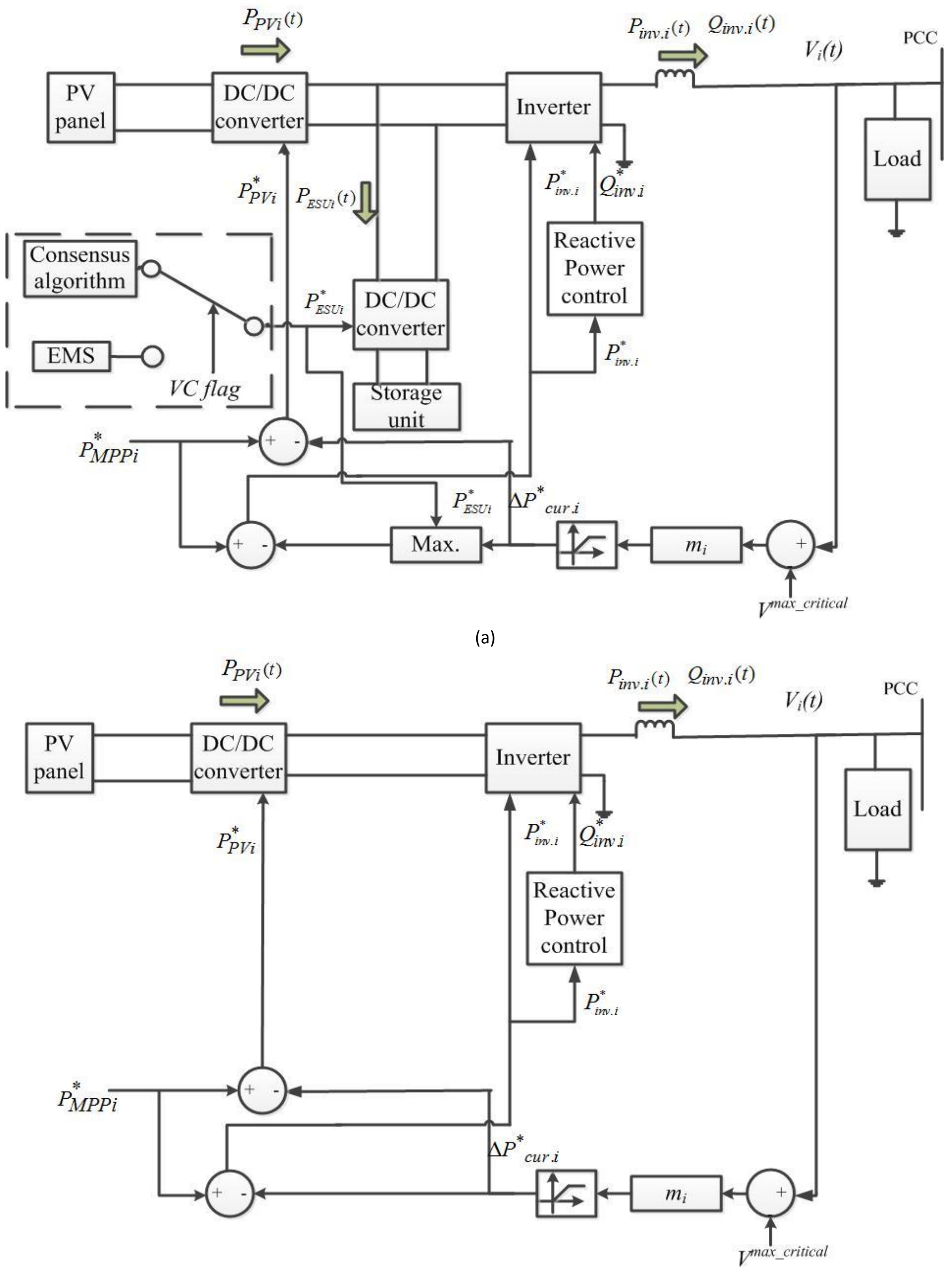


Fig. 2.2 Proposed RE system for a customer (a) with ESU, (b) without ESU.

2.3.1. Localized control strategy

As noted earlier, a localized control strategy will be used to coordinate the contribution of PV inverters for voltage support using their active and reactive power. Different localized techniques are proposed for voltage support based on reactive power control [13-21]. It is to be noted if a PV inverter VA rating is increased by just 11.8%, it will have the ability to supply 50% reactive power while supplying full rated power. Consequently, customers can use this capability for voltage reduction. The main strategies which use inverter reactive power for voltage reduction can be summarized as follows:

1- Fixed reactive power control: In this strategy, the inverter bus voltage is monitored. If the bus voltage goes above a predetermined limit, PV inverter starts to absorb a constant reactive power.

2- Reactive power control as a function of inverter bus voltage: This strategy is based on fixing the inverter bus voltage to a desired value by absorbing or injecting reactive power.

3- Reactive power control as a function of inverter active power: In this strategy, the inverter absorbs reactive power based on inverter active power.

Considering the simplicity and effectiveness of the third strategy [20], this technique is used in this paper for voltage support based on reactive power control. The reactive power control characteristic for each inverter is given in (2-1), where the superscript '*' denoted the reference values. As shown in this equation, whenever the inverter injected active power crosses the threshold value of $0.5 \times P_{PVi}^{max}$, P_{PVi}^{max} being the maximum rated power for PV, the inverter starts to absorb reactive power. It is to be noted that the reactive power can be set to zeros if grid code decrees the inverter to inject power at unity power factor.

$$Q^*_{inv.i} = \begin{cases} 0 & P^*_{inv.i} < 0.5 \times P^{\max.}_{PVi} \\ -0.4843 \times P^*_{inv.i} & P^*_{inv.i} > 0.5 \times P^{\max.}_{PVi} \end{cases} \tag{2-1}$$

As per (2-1), all customers who contribute in voltage rise by their active power injection will also contribute in voltage reduction by their reactive power absorption.

However, due to high *R/X* values in LV networks, reactive power alone cannot keep the voltages in the permissible range. As a result, the contribution of active power is also needed to have a robust voltage rise control. In order to determine the contribution of each inverter in voltage support using active power, an upper critical voltage limit ($V^{max\_critical}$) is defined, which is less than upper permissible voltage limit ($V^{max\_permissible}$). Each inverter, when its PCC bus voltage passes this critical limit, will curtail its active power using

$$\Delta P^*_{cur.i} = \begin{cases} m_i.(V_i(t) - V^{\max\_critical}) & V_i(t) > V^{\max\_critical} \\ 0 & V_i(t) \le V^{\max\_critical} \end{cases} \tag{2-2}$$

$$P^*_{inv.i} = P^*_{MPPi} - \Delta P^*_{cur.i} \tag{2-3}$$

where $V_i(t)$ is the i^{th} bus voltage, $\Delta P_{cur.i}$ is the required active power curtailment, P_{MPPi} is the maximum power available for PV at a given time and m_i is the droop gain that is determined as

$$m_i = \frac{P_{PVi}^{\max.}}{V^{\max\_permissable} - V^{\max\_critical}} \tag{2-4}$$

For customers with ESUs, (2-3) is modified to that given as

$$P^*_{inv.i} = P^*_{MPPi} - \max(\Delta P^*_{cur.i}, P^*_{ESUi}) \tag{2-5}$$

The value of ESU power will be coordinated by consensus algorithm which will be discussed later. To balance injected and drawn power from the DC link, the injected PV power through DC/DC converter is determined by

$$P^*_{PVi} = P^*_{MPPi} - \Delta P^*_{cur.i} \tag{2-6}$$

Based on (2-1)-(2-6), if voltage of any customer passes the upper critical voltage limit, its PV inverter contributes in voltage reduction using active power curtailment.

By applying the proposed localized control strategy, the voltage of all customers will be kept in the permissible range by controlling their inverter reactive power and curtailing the active power of those customers whose voltage pass the $V^{max\_critical}$ limit. However, the active power curtailment is not attractive. To reduce active power curtailment, a distributed control strategy, based on a consensus algorithm, discussed below, is proposed to coordinate the use of ESUs within the network for effective voltage reduction.

2.3.2. Distributed control strategy

Consensus algorithms have been applied in different application of distributed multivehicle control. In [22, 23], one such algorithm is used for rendezvous and axial alignment of multiple wheeled mobile robots. Reference [24] uses consensus algorithm for spacecraft formation flying. A cooperative control strategy based on consensus algorithm is used in [25] to coordinate unmanned air vehicles for fire monitoring.

In this paper, a consensus algorithm is proposed for distributed control strategy and to coordinate ESUs within the LV network for efficient voltage reduction while avoiding curtailment. Since single-phase PVs in a particular phase can cause voltage rise in that phase, the algorithm is applied in per phase basis.

Let us consider a phase that has n distributed ESUs. The proposed distributed control structure is shown in Fig. 2.3 in which the dashed lines show the information flow among

ESUs. In the proposed control structure, a higher control level named the leader is responsible to initiate consensus algorithm by turning on the voltage control flag (*VC flag*). The internal control structure for leader is shown in Fig. 2.4 (a), while the internal control structure for each ESU is shown in Fig. 2.4 (b). It can be seen that there are two states for control of each ESU. In state 1, the ESU is controlled by Energy Management System (EMS) of the customer. This is the state in which the network is in normal operation and all voltages are less than $V^{max\_critical}$. However, if there is voltage problem, *VC flag* becomes 1 and changes the control state of the customer to the distributed control strategy.

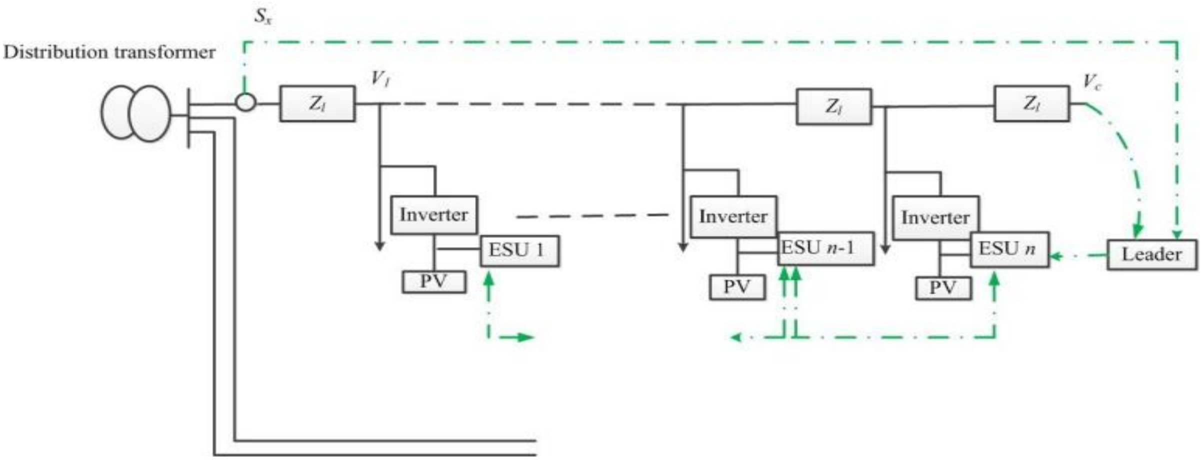
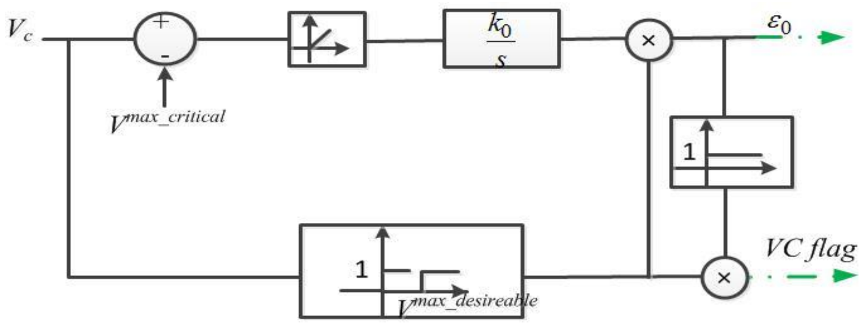
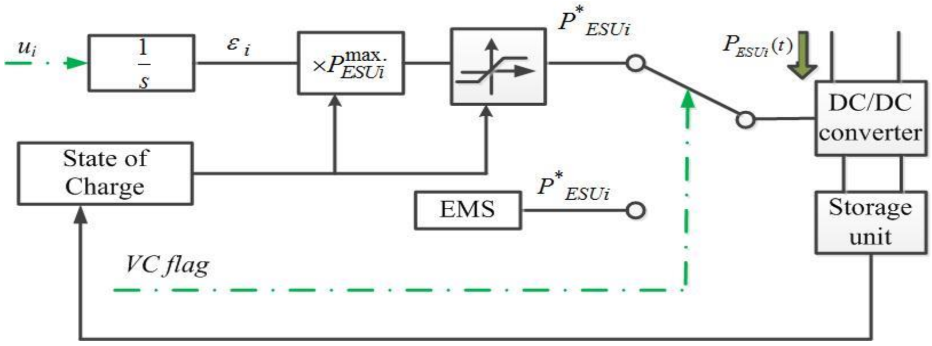


Fig. 2.3 The proposed communication structure.



(a)



(b)

Fig. 2.4 Proposed control structure, (a) for leader, (b) for each ESU.

The distributed control strategy for each ESU can be written in a general form as

$$u_i = f_i(s_{i0}.y_0, s_{i1}.y_1, ..., s_{in}.y_n) \tag{2-7}$$

where y_0 is the information state of the leader, y_j is the information state of j^{th} ESU and s_{ij} denotes the communication link between the i^{th} and j^{th} ESUs. If the j^{th} ESU sends information to i^{th} one s_{ij} =1; s_{ij} =0 otherwise. In addition, s_{i0}=1; if the i^{th} ESU can get information from the leader, otherwise s_{i0}=0. s_{ii}=1 for all ESUs. These time-varying coefficients can be written in a matrix form representing the entire communication system as

$$S(t) = \begin{bmatrix} s_{10}(t) & s_{11}(t) & ... & s_{1n}(t) \\ . \quad . & & & . \quad . \\ . \quad . & & & . \quad . \\ s_{n0}(t) & s_{n1}(t) & ... & s_{nn}(t) \end{bmatrix} \tag{2-8}$$

In the proposed control strategy, the first aim is to design a control u_i for each ESU in such a way that at the equilibrium points the following relationship is met.

$$\frac{w_1.P_{ESU1}}{P_{ESU1}^{max.}} = \frac{w_2.P_{ESU2}}{P_{ESU2}^{max.}} = ... = \frac{w_n.P_{ESUn}}{P_{ESUn}^{max.}} \tag{2-9}$$

where $P_{ESUi}^{max.}$ is the maximum available power for an ESU for a specific period of time, for example 30 minutes. In other words, for 30 minutes, this value is the maximum active power which ESU can continuously support. In this way, it can be said that the required active power will be shared with respect to ESU state of charge which is prominent parameter for ESU. w_i is the weighting factor for the i^{th} node. For example, if the ESU is far away from the critical node, a larger weight can be chosen to make less sharing for this ESU in voltage reduction. However, equal weighting is chosen here such that the required active power for voltage reduction is shared equally.

The second aim is to design a control for u_i such that the critical node voltage is reduced less than $V^{max\_critical}$ to avoid curtailment for customers.

$$V_c < V^{max\_critical} \tag{2-10}$$

To achieve these two objectives, the leader turns on *VC flag* whenever the voltage of critical node passes the $V^{max\_critical}$ limit. In addition, to initiate consensus algorithm, the information state for leader is updated by

$$\dot{\varepsilon}_0(t) = k_v.(V_c(t) - V^{max\_critical}) \tag{2-11}$$

In addition, for each ESU, the value of ε_i, shown in Fig. 2.4 (b), is considered as the information state that is communicated besides the value of *VC flag* among the neighbouring ESUs.

$$y_i(t) = \varepsilon_i(t) \tag{2-12}$$

Finally, the input control for each ESU can be determined as

$$u_i(t) = \dot{\varepsilon}_i(t) = -\sum_{j=0}^{n} a_{ij}(t).(\varepsilon_i(t) - \varepsilon_j(t)) \tag{2-13}$$

where $a_{ij}(t)$ is the (i,j) entry of adjacency matrix $A_{n+1}(t) \epsilon \mathcal{R}^{(n+1)\times(n+1)}$ and $a_{ij}(t)>0$ *if* $(j,i) \in E$, $a_{ij}(t)=0$ otherwise.

The interaction among ESUs can occur at discrete time steps. So, the information state of each ESU is updated using

$$\varepsilon_i[t] = \sum_{j=0}^{n} d_{ij}[t].\varepsilon_j[t - t_d] \tag{2-14}$$

where $d_{ij}[t]$ is the (i,j) entry of a row stochastic matrix which can be found in each discrete time data exchange by

$$d_{ij}[t] = \frac{c_{ji}.s_{ji}[t - t_d]}{\sum_{k=0}^{n} c_{ki}.s_{ki}[t - t_d]} \tag{2-15}$$

Here c_{ji} denotes the weights which are set to 1 in this paper to share the required active power equally among ESUs (first aim) and s_{ji} are the entries of communication matrix, given in equation (2-8).

Finally, the required contribution of each ESU can be determined by

$$P^*_{ESUi} = \varepsilon_i[t] \times P^{\max.}_{ESUi} \tag{2-16}$$

By applying the proposed control structure, both aims will be achieved and ESUs will contribute in voltage reduction to avoid or reduce the active power curtailment.

In a radial LV network, the last node is the critical node. Therefore, if the customers in this node do not experience any voltage limit violation, all other customers on the same phase will not face voltage problem. The proposed operation with the coordinated control strategy is illustrated in Fig. 2.5, based on the voltage of this node. The chronological course of events is described as follows:

- Between t=t_1 and t=t_2, the critical node voltage is within desirable voltage range. Consequently, the network is in normal operation condition. In this situation, all PV inverters are injecting maximum available active power and their reactive power is based on characteristics given in (2-1). Moreover, ESUs are controlled by customers EMS.

- At t=t_2, the upper critical voltage limit is violated in the critical node. Therefore, PV inverters, whose bus voltages pass this, start to curtail their active power based on (2-2) and (2-5). In addition, the leader initiates the communication among ESUs to find their contribution for voltage reduction.

- Depending on the communication speed, at $t_3+\Delta t$, the ESUs reduce the voltage of critical node below the upper critical limit, which results in preventing RE curtailment.

- At t=t_4, voltage of the critical node falls back in the desirable range which means the voltage of all nodes is in desirable range. As a result, *VC flag* becomes 0 and ESU control strategy is changed back to function based on customer's EMS commend.

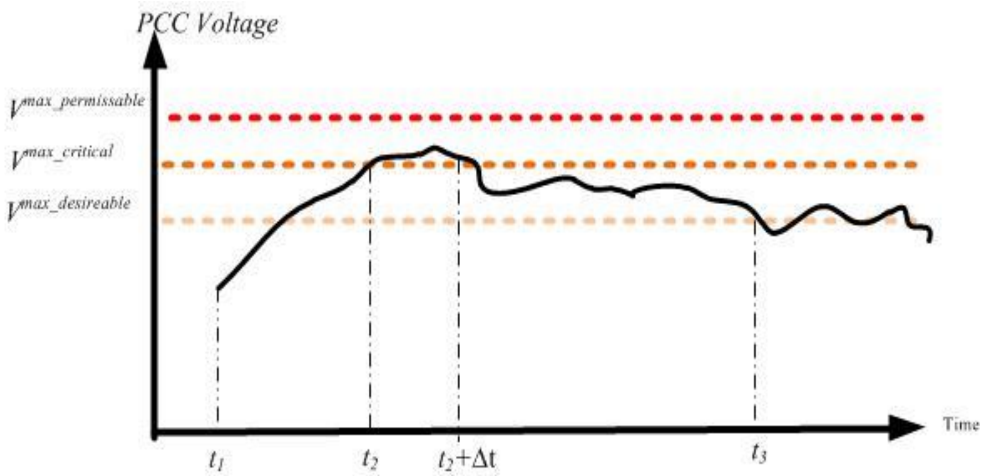


Fig. 2.5 Different operation modes of a radial LV network based on critical node voltage.

2.4. Case Studies

In this section, a typical residential LV network is used as a case study to show the effectiveness of proposed approach. The network parameters can be found in Reference [12]. There are 12 customers in this single-phase LV network (2 in each node). The maximum load for each customer is 6.25 kVA. Each customer has one PV connection with the rating of 8.4 kW. In addition, it is assumed that customers in nodes 2, 3 and 5 are supported respectively by ESU 1, ESU 2 and ESU 3 with ratings listed in Table 2-1. For simplicity, customers in each node are considered by a lumped model including PV, inverter and available ESU as shown in Fig. 2.6. The voltage parameters for proposed approach are listed in Table 2-2.

Table 2.1 ESU rating.

ESU	1	2	3
Rating (kW)	7.0	6.0	8.0

Table 2.2 Voltage parameters for the proposed approach.

Parameter	Voltage (pu)	Voltage (V)
$V^{max\_permissable}$	1.06	254.4
$V^{max\_critical}$	1.05	252.0
$V^{max\_desirable}$	1.04	249.6

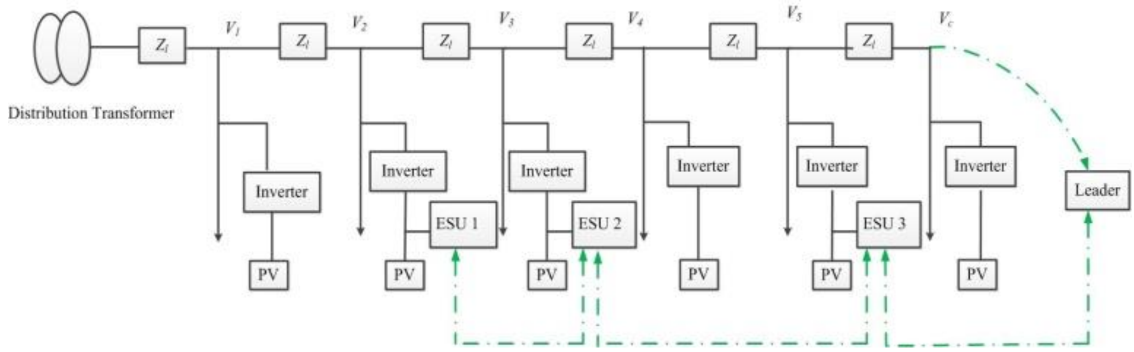


Fig. 2.6 Case study.

2.4.1. Case 1

To verify the effectiveness of proposed approach in different operation modes, the load and generation profiles shown in Fig. 2.7, are considered for each customer. To simulate the worst case scenario, it is assumed that all customers have the same load and generation profiles.

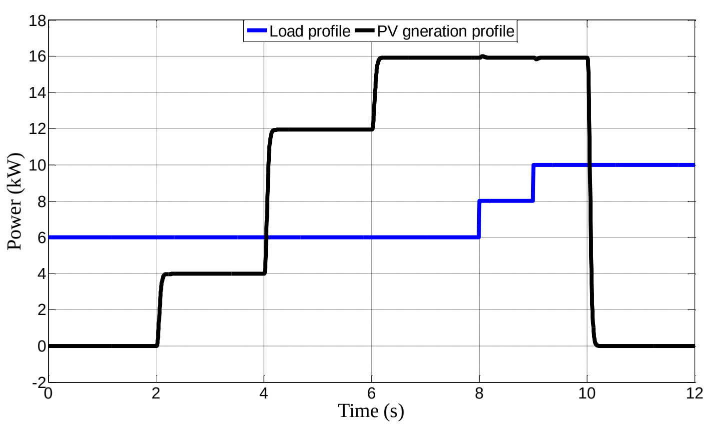


Fig. 2.7 Load and generation profiles in each node.

Without any voltage control, Fig. 2.8 shows the voltage of different nodes. It can be seen the voltage of nodes 4, 5 and 6 pass the upper permissible voltage limit between 6 s and 8 s, which is not acceptable.

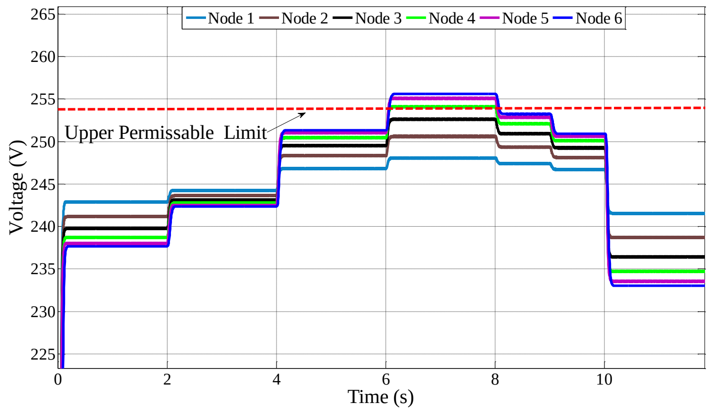


Fig. 2.8 Nodes voltage (no voltage control).

By applying the proposed operation approach, Fig. 2.9 shows the profile of nodes voltage, inverters active power, inverters reactive power and ESU active power at different time steps. It is assumed that ESU available power is equal to its rating for the period of study and its information state is updated at t_d=20 ms. The time sequence of operation is as follows:

5- Between 0 s and 2 s, there is no generation and all voltages are in desirable voltage range.

6- Between 2 s and 4 s, there is available power of 4 kW for each PV, and voltage of all nodes is still within the desirable range. As a result, the customers try to maximize their injection to the network.

7- Between 4 s and 6 s, the inverter's active power passes the limit $0.5\times P_{PVi}^{\max.}$ and inverters start to absorb reactive power as per (2-1).

8- At 6.05 s, critical node voltage passes the upper critical limit. Therefore, there is curtailment for customers in this node and node 5. However, the ESU coordination is initiated by leader as shown in Fig. 2.9 (d).

9- At 6.46 s, the critical node voltage reduced to less than 252 V and curtailments are avoided. It can be seen that at equilibrium point the sharing ratio of the ESUs is as follow:

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}}=\frac{3.85}{7}=0.55$$

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{3.30}{6} = 0.55$$

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{4.40}{8} = 0.55$$

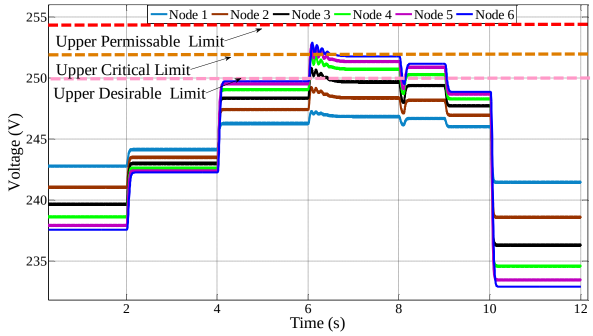
Consequently, both aims are achieved by the proposed control approach.

10- At 8.08 s, critical node voltage becomes less than upper desirable voltage limit, so the leader turns off *VC flag*. In this case, it is assumed the worst case scenario happens and all the ESUs stop charging. Consequently, the voltage of critical node rises again. However, this value is less than upper critical limit, which is acceptable.

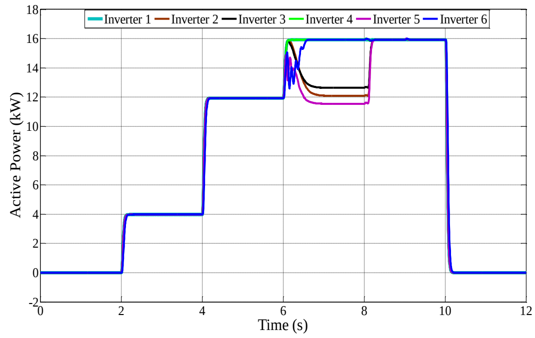
11- After 9 s, all voltages are in desirable range and inverters maximize their injection to the grid.

2.4.2. Case 2

As noted before, the interaction among ESUs will occur at discrete time step of t_d. In this case, the influence of t_d on voltage reduction is studied. It is assumed that the load in each node is 12 kW and the PV generation of each node changes from 12 kW to 16 kW at 2 s. The results for different value of t_d are shown in Fig. 2.10. The main feature in this figure is that by increasing the time step, the ESU coordination becomes slower. For example, for t_d=500 ms, ESUs attain their equilibrium point after nearly 24 s. In addition, it can be seen that when t_d increases from 20 ms to 50 ms and then to 100 ms, the critical node voltage reduces to be in the allowable range with less ESU contribution. However, when t_d is equal to either 200 ms or 500 ms, the required ESU contribution is more than the case with t_d=100 ms. As a result, t_d=100 ms is a suitable time step for updating ESU state information, since it is efficient and has a fast response.



(a)



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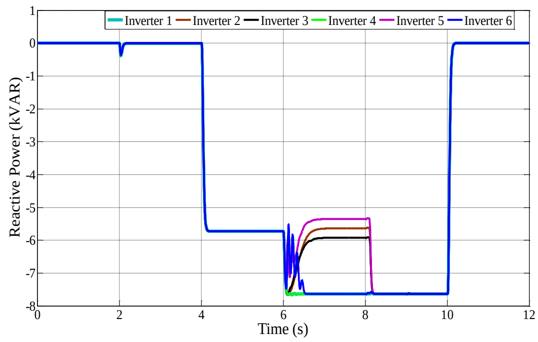

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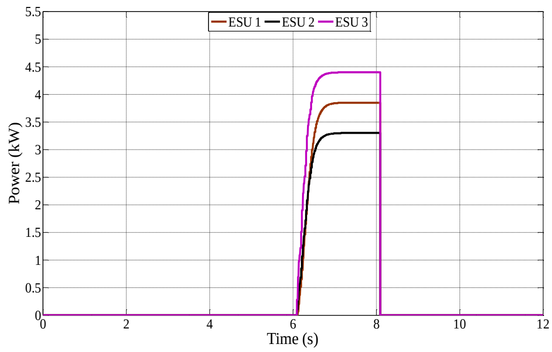


(a)

Fig. 2.9 Proposed voltage control approach, (a) nodes voltage, (b) Inverters active power, (c) Inverters reactive power, (d) ESUs active power.

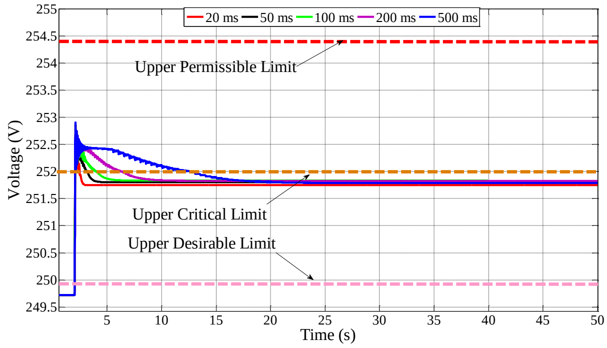
2.4.3. Case 3

In this case, the effect of communication drop on proposed approach is studied. The same case study as Case 2 is considered here. To illustrate the effect, it is assumed that there is only 2 kW available power for ESU 3. In addition, the communication link between ESU 2 and ESU 3 is time-varying due to communication malfunction as given by

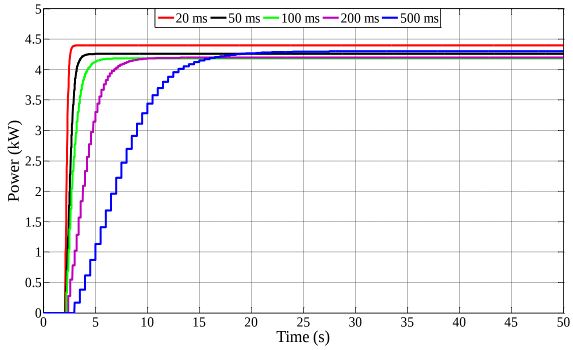
$$s_{23}(t) = s_{32}(t) = \begin{cases} 0 & t < 5 \\ 1 & t > 5 \end{cases} \tag{2-17}$$

The results for this case are shown in Fig. 2.11. As shown in this figure, at t=2.06, the voltage of nodes 5 and 6 pass the critical limit. Inverters in these nodes curtail their active power to keep the voltage in the allowable range. However, due to communication drop, only ESU3 can be coordinated for voltage reduction. This ESU contributes with its maximum power. However, the critical node voltage is still more than critical limit and there are nearly 2.6 kW active power curtailments in this node. At t=5 s, the communication link between ESU 2 and ESU 3 becomes available and ESUs 1 and 2 are coordinated for voltage reduction. Consequently, critical node voltage reduced to less than 252 V and curtailments are avoided.

The result of this case shows that the communication loss can cause some curtailment and ESUs may contribute at more than required. However, the control is still robust and the voltage rise problem is tackled effectively.



(a)



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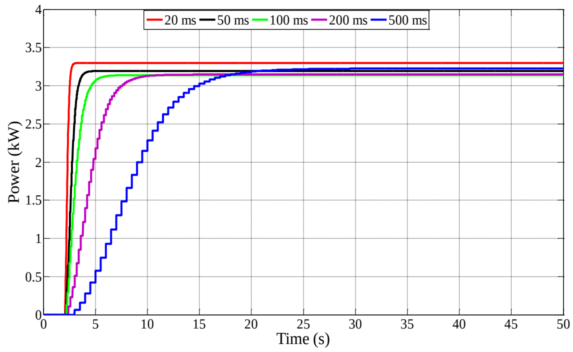

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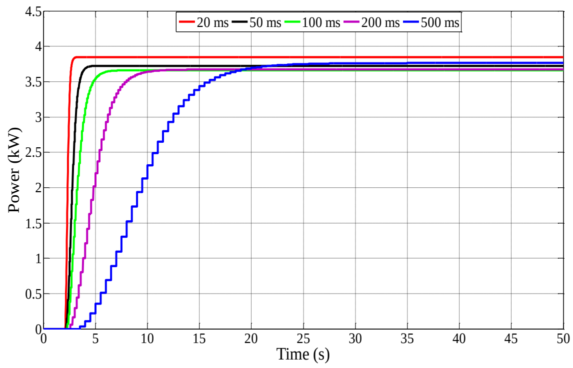
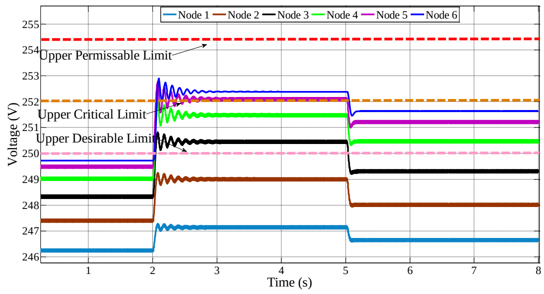
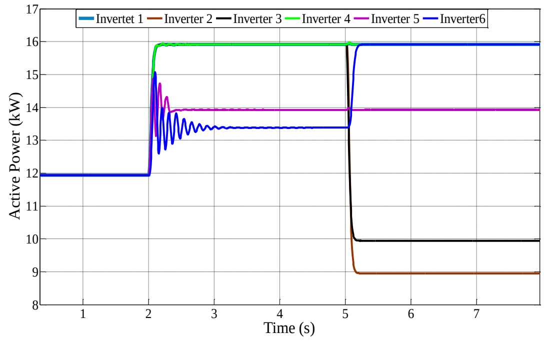


(d)

Fig. 2.10 Communication time step comparison, (a) critical node voltage, (b) ESU 1 active power, (c) ESU 2 active power, (d) ESU 3 active power.



(a)



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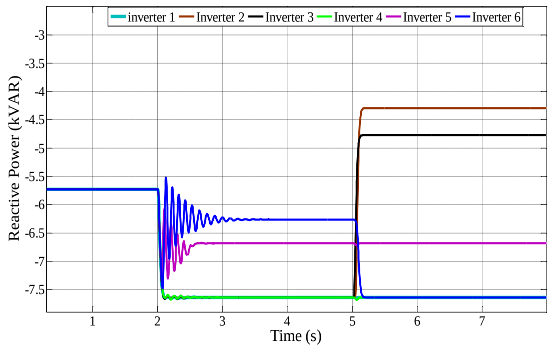

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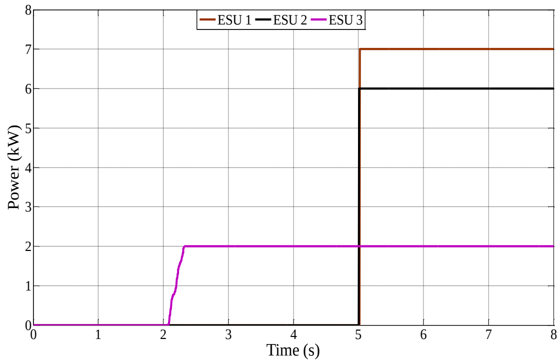

(d)

Fig. 2.11 Communication drop effect, (a) nodes voltage, (b) Inverters active power, (c) Inverters reactive power, (d) ESUs active power.

2.5. Conclusion

This paper proposes a new robust and efficient approach for operation of LV network to deal with voltage rise in the presence of rooftop PVs. Mixed distributed and localized algorithms have been used in this approach to manage resources and avoid upper permissible voltage limit violation. A typical residential LV network is simulated to show the effectiveness of the proposed approach to reduce the voltage rise. In addition, the effect of communication link failure is studied and the results show that this can only reduce efficacy of voltage reduction while keeping the robustness of voltage rise control.

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Statement of Contribution of Co-Authors

The authors listed below have certified that:

6- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

7- They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publications;

8- There are no other authors of the publication according to these criteria;

9- Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit;

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In the case of this chapter:

Load Leveling in LV Network Using Coordinated Energy Storage Units

Presented in: Australian Universities Power Engineering Conference, 29 September – 3 October 2013.

Contributor	Statement of contribution
Ghassem Mokhtari 21 May 2014	Proposed the control strategy. Develop the control strategy regarding the simulation and data analysis. Wrote the manuscript.
Ghavam Nourbakhsh	Aided data analysis and writing the paper
Arindam Ghosh	Aided data analysis and writing the paper

Supervisor Confirmation

I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

Prof. Arindam Ghosh
Name | Signature | Date: 2 Jan. 2014

Chapter 3

Load Leveling in LV Network Using Coordinated Energy Storage Units

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Presented in: Australian Universities Power Engineering Conference, 29 September – 3 October 2013.

Abstract—This paper proposes a new distributed coordination approach to make load leveling, using Energy Storage Units (ESUs) in LV network. The proposed distributed control strategy is based on consensus algorithm which shares the required active power equally among the ESUs with respect to their rating. To show the effectiveness of the proposed approach, a typical radial LV network is simulated as a case study.

3.1. Index Terms

Load Leveling, ESUs, consensus algorithm, LV network.

3.2. Introduction

Future Low Voltage (LV) networks will include widespread use of Renewable Energy (RE) sources Like PV, wind turbine and fuel cell. Networks with high penetration of RE sources can encounter two main power quality challenges. When PVs are used as RE sources in LV network, we may still experience voltage drop along the network in peak load period [1]. This is because the peak load normally happens in the evening when there are small or no PV output power. On the other hand, at noon when peak generation occurs, PV generated power would significantly exceed the load. The injected surplus power to grid can cause reverse power and hence may result in voltage rise in the network [2].

Different approaches have been suggested by researchers to deal with the noted issues such as network upgrading [3-5], changing network static set points [4, 6], that they all have their own drawbacks [7].

It is clear that the unbalancing between the generated power and load, in both periods, causes the issues. As a result, the introduction of ESU as a buffer is a promising solution which can store surplus power in high generation period and use it in peak load period (load leveling).

One of the main challenges for utilization of distributed ESUs for load leveling is their coordination. Distributed coordination strategy has promising application for future smart grid. This strategy has been applied in different applications. In reference [8], distributed algorithm has been used to coordinate resources in distribution network, providing ancillary services. Reference [9] uses a distributed algorithm based on multi-agent technology to coordinate customers in LV network, to deal with different power quality issues. In [10], distributed algorithm is used to control the reactive power in distribution network to avoid overvoltage and under voltage situations.

In this paper, a distributed control strategy based on consensus algorithm is proposed to coordinate distributed ESUs in an LV network, for load leveling purposes.

3.3. Proposed Approach

If ESUs are used with localized control, it would be difficult to guarantee an acceptable operating condition under varying factors outside local zone [11]. On the other hand, the centralized control strategy is neither practical nor reliable, since it requires global network information [11]. Therefore, a more practical approach can be through a distributed control strategy. In this paper, a distributed control technique based on consensus algorithm [12] is used to coordinate multiple ESUs for load leveling in LV networks. This approach coordinates ESUs to charge during the high generation period, which can resolve the voltage rise issue in network. While during the peak load period, ESUs will be coordinated to discharge and reduce the network peak demand avoiding unacceptable voltage drop along the network. The details of the proposed approach are given as follows. Since LV network include single-phase loads, RE sources and ESUs, therefore the algorithm applied is as per phase basis.

Let us consider phase X that has n distributed ESUs. The proposed distributed control structure for this network is shown in Fig. 3.1, in which the dashed arrows show the information flow. In this structure, a higher control level is named as the leader, which is responsible to initiate consensus algorithm whenever the ESUs coordination is needed. The internal control structure of leader is shown in Fig. 3.2 (a). $S(t)$ is the drawn power from or injected power to the higher voltage level network, and is considered as the controllable variable for load leveling. For both peak generation and peak load periods, two threshold limits have been defined to determine the operation mode of a network. In peak load period, the value of $S(t)$ is positive and if $S(t)$ is less than $S^{load\_desirable}$, network is in normal operation mode and ESUs coordination is not needed. However, if the $S(t)$ violates $S^{load\_critical}$, ESUs coordination is initiated by leader and the coordination will continue until the value of $S(t)$ becomes less than $S^{load\_desirable}$. The same procedure is applied for peak generation period in which $S(t)$ is negative and $S^{gen\_critical}$ and $S^{gen\_desirable}$ determine the operation of the network . In addition, the ESU internal control structure of Fig. 3.2 (b) is proposed for the proposed consensus application. The superscript * shows the reference value.

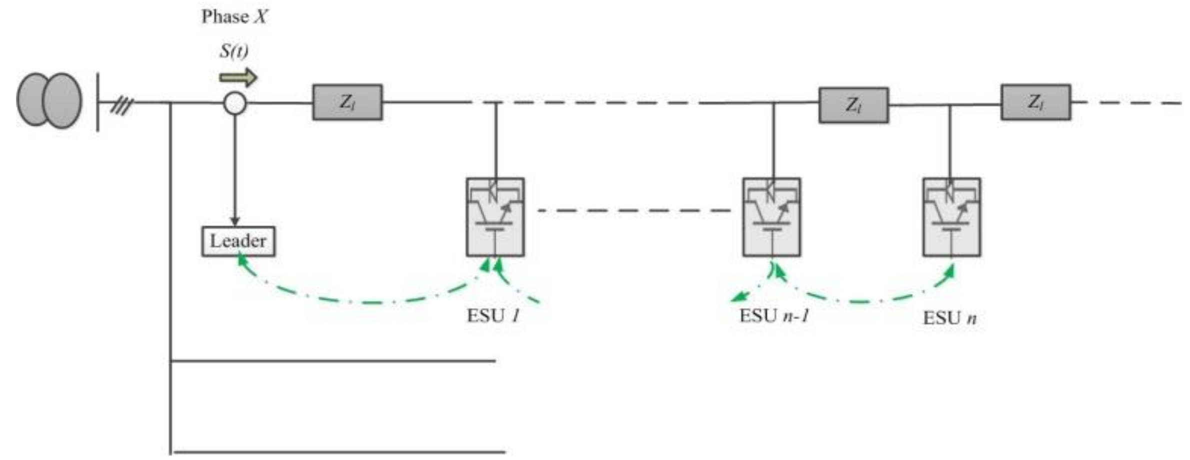
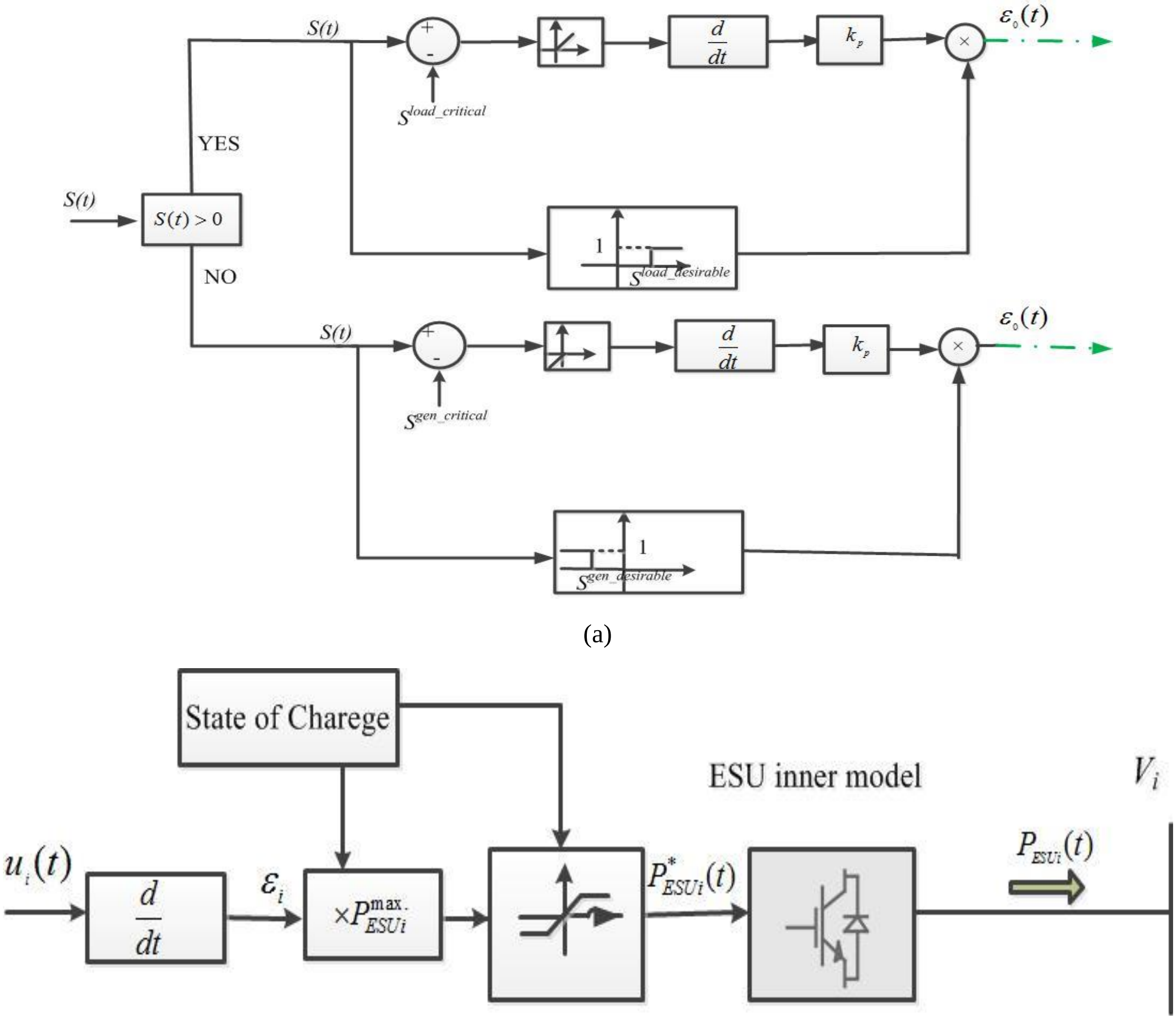


Fig. 3.1 Proposed distributed control structure.



(a)

(b)

Fig. 3.2 Proposed control structure, (a) for leader, (b) for each ESU.

The distributed control strategy for each ESU can be written in a general form as:

$$u_i(t) = f_i(c_{i0}(t).\varepsilon_0(t), c_{i1}(t).\varepsilon_1(t), \ldots, c_{in}(t).\varepsilon_n(t)) \tag{3-1}$$

where $c_{ij}(t)$ denotes the communication link between *i*th and *j*th ESUs, c_{ij} =1; if *j*th ESU send information to *i*th one, otherwise c_{ij} =0. In addition, c_{i0}=1; if the *i*th ESU can get information from the leader, otherwise c_{i0}=0. c_{ii}=1 for all ESUs.

This time-varying coefficients can be represented as a matrix presenting the whole communication topology as in equation (3-2).

$$C(t) = \begin{bmatrix} c_{10}(t) & c_{11}(t) & ... & c_{1n}(t) \\ . \ . & & & . \ . \\ . \ . & & & . \ . \\ c_{n0}(t) & c_{n1}(t) & ... & c_{nn}(t) \end{bmatrix} \tag{3-2}$$

Two general objectives need to be achieved to coordinate ESUs when required. The first is to design a control for u_i of each ESU to reduce the network apparent power to less than its critical limits. In other words, in peak load period, ESUs need to be coordinated to bring the value of *S(t)* to less than $S^{load\_critical}$, as shown in equation (3-3). Similarly, in peak generation period equation (3-4) needs to be met.

$$S(t) < S^{load\_critical} \tag{3-3}$$

$$S(t) > S^{gen\_critical} \tag{3-4}$$

The second objective is to design a control for u_i to share the required active power according to the same ratio among ESUs, as shown in equation (3-5).

$$\frac{P_{ESU1}}{P_{ESU1}^{max.}} = \frac{P_{ESU2}}{P_{ESU2}^{max.}} = ... = \frac{P_{ESUn}}{P_{ESUn}^{max.}} \tag{3-5}$$

To achieve the noted control objectives, the following steps need to be taken.

As shown in Fig. 3.2 (a), in peak load period, it is proposed that if the value of *S(t)* passes its critical limit, the leader initiates the consensus algorithm by (3-6).

$$\dot{\varepsilon}_0(t) = k_p.(S(t) - S^{load\_critical}) \tag{3-6}$$

However, in high generation period, if the value of *S(t)* violates its critical limit the leader initiates the consensus algorithm by (3-7).

$$\dot{\varepsilon}_0(t) = k_p.(S(t) - S^{gen\_critical}) \tag{3-7}$$

Based on consensus algorithm, the input control for each ESU is also determined as:

$$u_i(t) = \dot{\varepsilon}_i(t) = -\sum_{j=0}^{n} a_{ij}(t).(\varepsilon_i(t) - \varepsilon_j(t)) \tag{3-8}$$

where $a_{ij}(t)$ is the (i,j) entry of adjacency matrix$A_{n+1}(t)\epsilon R^{(n+1)\times(n+1)}$; $a_{ij}(t)>0$ *if* $c_{ij}(t)=1$ and $a_{ij}(t)=0$ otherwise.

In real case, the interaction among ESUs occurs at discrete time step t_d. Therefore, the information state of each ESU is updated using equation (3-9).

$$\varepsilon_i(t)=\sum_{j=0}^{n} d_{ij}(t).\varepsilon_j(t-t_d) \tag{3-9}$$

$d_{ij}(t)$ is the (i,j) entry of a row stochastic matrix which can be found in each discrete time data exchange by;

$$d_{ij}(t)=\frac{c_{ji}(t-t_d)}{\sum_{j=0}^{n} c_{ji}(t-t_d)} \tag{3-10}$$

Finally, the required contribution of each ESU at each time step is updated by:

$$P^{*}_{ESUi}(t)=\varepsilon_i(t)\times P_{ESUi}^{\max.} \tag{3-11}$$

3.4. Case Studies

A typical LV network is selected as the case study to illustrate the effectiveness of the proposed approach. The details of this network are provided in Table 3.1. This single-phase network includes 6 nodes with 2 customers in each node. The details of customer maximum load and generation can be found in reference [2]. For the sake of simplicity, customers in each node are modelled by a lumped model including their PV, load and available ESU, as shown in Fig. 3.3. There are 4 ESUs within the network with ratings listed in Table 3.2. The upper and lower permissible voltage limits for this network are listed in Table 3.3.

Table 3.1 Technical Parameters of the Studied LV Network.

Transformer	14.4/.240 kV, 75 kVA, x=0.04 pu, tap=1.00 single-phase
LV Feeder	Single-phase, 6 nodes, 240 V, length of 120 m long

Table 3.2 ESUs rating.

ESU	1	2	3	4
Rating (kW)	6.0	7.0	5.0	6.5

Table 3.3 Voltage limits in the proposed approach.

Parameter	Voltage (pu)	Voltage (V)
Upper Permissible voltage limit	1.06	254.4
Lower Permissible voltage limit	0.94	225.6

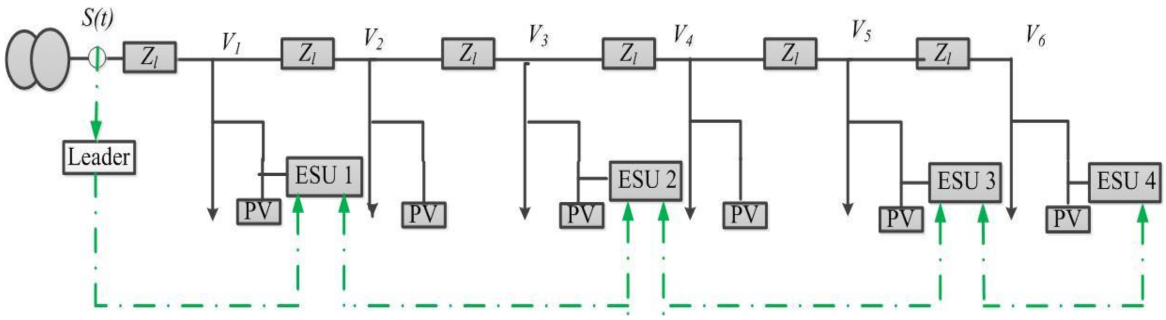


Fig. 3.3 Case study.

3.4.1. Case 1

A 24-seconds simulation representing a one-day operation has been performed using MATLAB software. It is assumed that all nodes have the same load and generation profiles, as shown in Fig. 3.4. In the first case, it is assumed that there is no coordination among ESUs. The profile of nodes voltage and network apparent power is shown in Fig. 3.5. It can be seen that nodes 5 and 6 voltage violate their upper permissible limit between t =12s to t=14s; in addition, node 6 voltage violates the lower permissible limit during t=21s to t=22s.

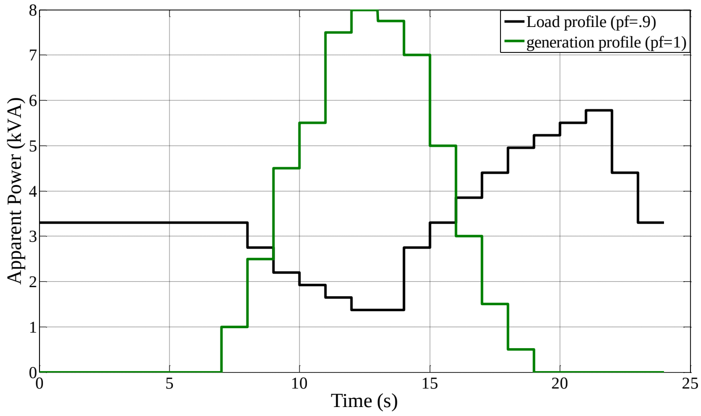
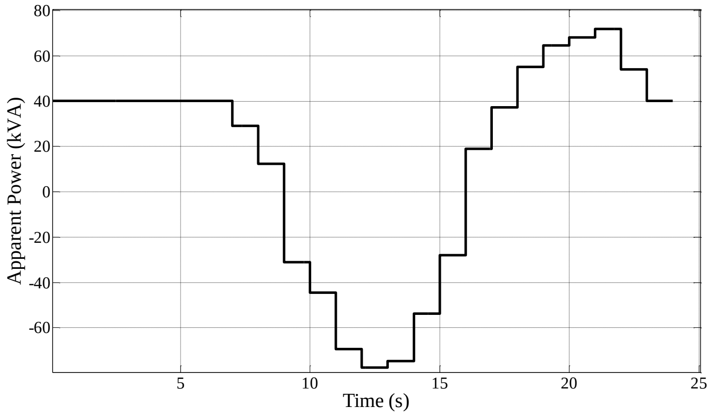
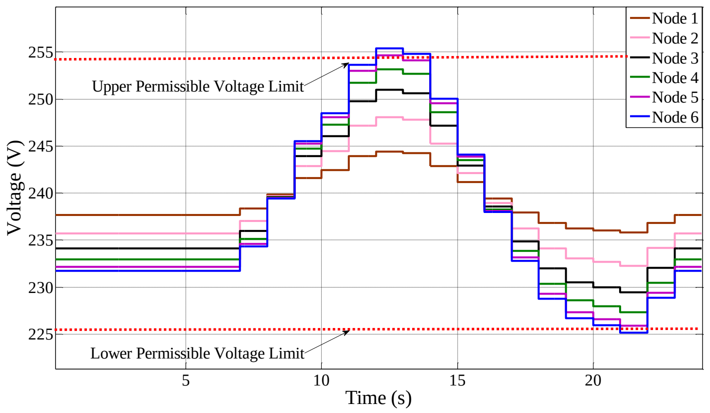


Fig. 3.4 Load and generation profile for customers.



(a)



(b)

Fig. 3.5 No ESUs coordination (a) voltage profile of critical buses, (b) Network apparent power.

3.4.2. Case 2

In the second case, the results for the same system are given using the proposed control strategy in this paper. Equivalent matrix for the proposed communication topology is represented in equation (3-12). The threshold limits for network apparent power are listed in Table 3.4, and it is assumed that ESUs and leader update their information state at each t_d=20 ms.

$$C(t)=\begin{bmatrix}1&1&1&0&0\\0&1&1&1&0\\0&0&1&1&1\\0&0&0&1&1\end{bmatrix} \tag{3-12}$$

Table 3.4 Network loading limits in the proposed approach.

Parameter	Power (kVA)
$S^{load\_critical}$	60
$S^{load\_desirable}$	50
$S^{gen\_desirable}$	-50
$S^{gen\_critical}$	-60

The results for this case, including the nodes voltage, network apparent power and ESUs power are shown in Fig. 3.6. The sequence of important events in simulation is as follows:

1- Between t=0s and t=9s, network load is more than generation and *S(t)* is positive. However, its value is within allowable range.

2- At t =9s, the power flow reverses and the distribution network starts to inject its surplus power to the MV network.

3- At t=11s, as the injection increases, *S(t)* passes its critical limit. Therefore, the ESUs coordination is initiated by leader as shown in Fig. 3.6 (c).

4- At t=11.19s, charging of ESUs causes PV injection to the MV network to reduce less than 60 kVA. As shown in Table 3.5, ESUs contribute with the same ratio in peak generation reduction.

5- At t=12s and t=13s, again *S(t)* violates its critical limit due to increase in injection, and therefore ESUs contribute again in peak generation reduction. Their contribution is shown in Table 3.5.

6- At t=14s, the value of *S(t)* goes to its desirable range and ESUs stop charging. As a result, the value of *S(t)* rises while still it is less than critical limit, which is acceptable. In addition, as shown in Fig. 3.6 (c), it can be seen that the charging of ESUs can also resolve the voltage rise issue for nodes 5 and 6.

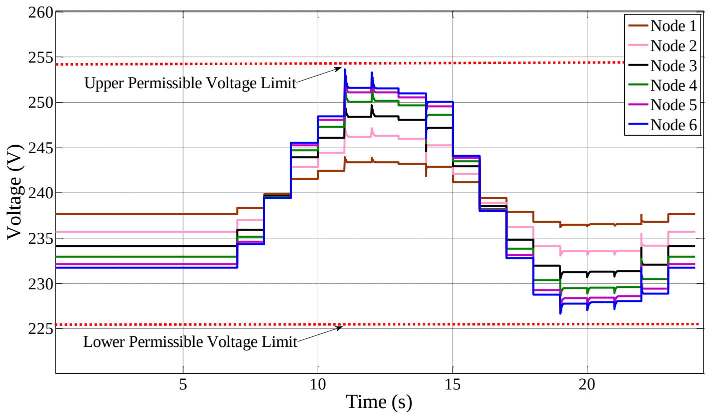
7- At t=19s, the network peak load passes the critical limit. Consequently, the consensus algorithm is initiated again to coordinate ESUs for peak load management.

8- At 19.15s, the network load is reduced to less than 60 kVA. It can be seen that ESUs again share equally in peak load management, as shown in Table 3.5.

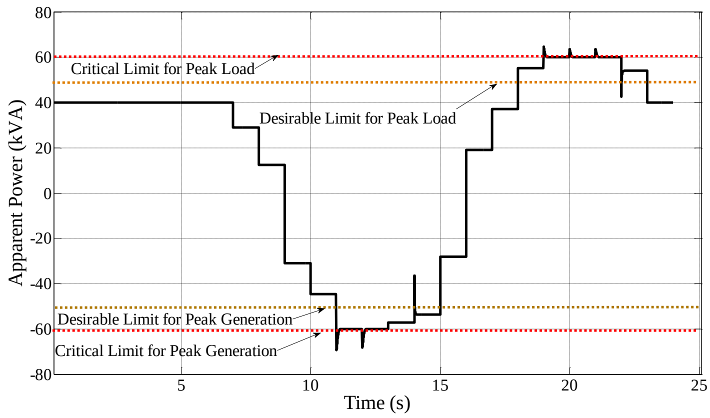
9- The ESUs coordination continue until t= 22s when the network goes to the normal condition and ESUs stop discharging their power.

3.5. Conclusion

In this paper, a new control strategy was proposed for distributed ESUs in LV network to provide load leveling. This distributed control strategy is based on Consensus algorithm. A new internal control strategy was proposed for each ESU to use the state information of its neighbouring ESUs and coordinate its operation. The proposed approach was applied to a typical LV network and the results were compared to traditional operation. It was shown that the proposed approach is promising in sharing the required active power among ESUs to improve and resolve voltage issues in LV network.



(a)



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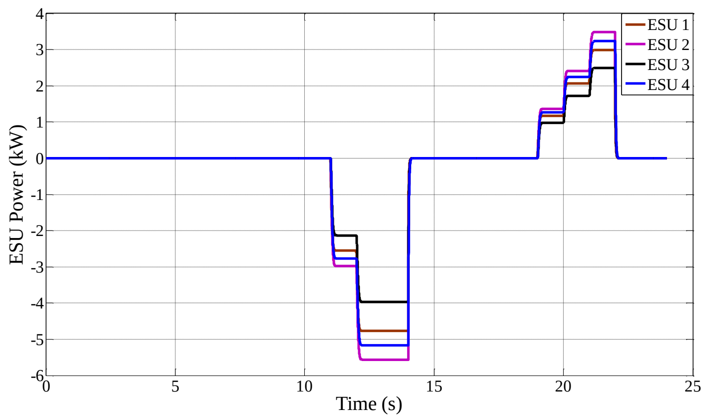

(c)

Fig. 3.6 Proposed control approach (a) Nodes voltage, (b) Network apparent power, (c) ESUs power.

Table 3.5 ESUs contribution at equilibrium point.

ESU	1	2	3	4	$\frac{P_{ESU1}}{P_{ESU1}^{max.}}$
11s-12s	-2.55	-2.98	-2.13	-2.76	-.42
12s-14s	-4.76	-5.56	-3.97	-5.16	-.79
19s-20s	1.16	1.36	0.97	1.26	0.19
20s-21s	2.06	2.41	1.72	2.41	0.34
21s-22s	2.98	3.48	2.48	3.23	0.49

3.6. References

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12- They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publications;

13- There are no other authors of the publication according to these criteria;

14- Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit;

15- They agree to the use of the publication in the student's thesis and its publication on the Australasian Digital Thesis database consistent with any limitations set by publisher requirements.

In the case of this chapter:

Improving the Penetration Level of PVs Using DC link for Residential Buildings

Published in Energy and Buildings journal, vol. 72, pp. 80-86, 2014.

Contributor	Statement of contribution
Ghassem Mokhtari 21 May 2014	Proposed the control strategy. Develop the control strategy regarding the simulation and data analysis. Wrote the manuscript.
Ghavam Nourbakhsh	Aided data analysis and writing the paper
Firuz Zare	Aided data analysis and writing the paper
Arindam Ghosh	Aided data analysis and writing the paper

Supervisor Confirmation

I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

Prof. Arindam Ghosh
Name Signature Date: 2 Jan. 2014

Chapter 4

Improving the Penetration Level of PVs Using DC link for Residential Buildings

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Abstract — This paper proposes the use of a common DC link in residential buildings to allow customers to inject their surplus power that otherwise would be limited due to AC power quality violation. The surplus power can easily be transferred to other phases and feeders through common DC link in order to maintain the balance between generated power and load. PSCAD-EMTDC platform is used to simulate and study the proposed approach. This paper suggests that this structure can be a pathway to the future DC power systems.

4.1. Keywords

Residential Building, Common DC link, PV, Voltage Rise.

4.2. Introduction

PV sources are the most popular small scale generation units around the world. These units enormously benefit customers and utilities, but their high penetration may introduce power quality issues in the electricity network [13-16]. The main concern is voltage rise during high generation mode of PVs [17, 18]. Therefore, the conventional operation of electricity grids needs to be updated with new strategies to deal with these concerns.

The best solution to resolve the PV penetration issues can be through balancing between power generation and load demand, especially in periods of high generation and low demand [19]. To balance generated PV power and load, researchers propose the following strategies for the operation of network.

1- Curtailing PV active power to resolve induced power quality issues [2, 20, 21]. The main issue of this strategy is the loss of renewable energy which results in loss of revenue for customers.
2- Using reactive power control for PVs [22-24] which is not promising due to high resistivity of LV networks.
3- Using Batteries in presence of PVs to charge during high generation and discharge during peak load time [25-29]. However, this approach is not economical option due to the high capital cost and low life cycle of batteries [30].
4- Shifting controllable loads to the high generation period to increase generation-load matching [16,31]. This strategy needs comprehensive communication to have effective control.

To avoid noted drawbacks, a new strategy based on a common DC link is proposed for residential building. It is suggested that a DC link can be used in residential buildings to accommodate the surplus injection and avoid voltage rise issue. The PVs surplus power can be used by customers in the same phase or in the other phases or feeders to increase generation-load balancing.

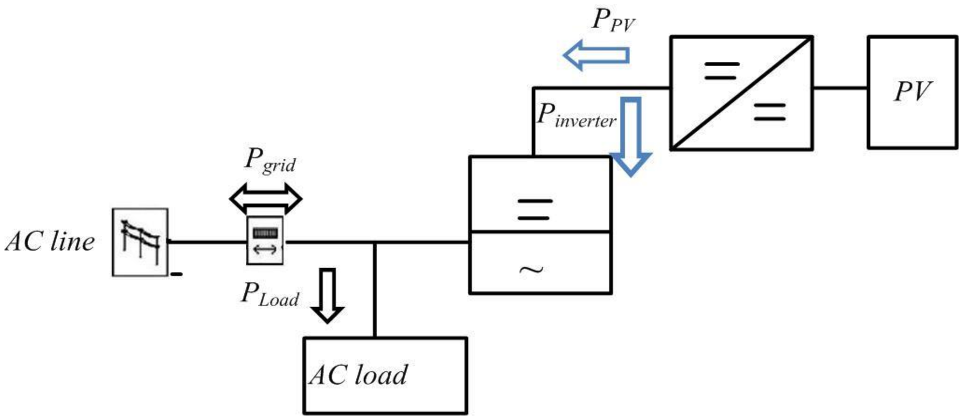
This paper is organized as follows. In section 4.3, the proposed approach is introduced and described. Section 4.4 describes the modeling and control of different components in the proposed approach. Finally, three case studies are analysed to show the effectiveness of this approach.

4.3. Proposed Approach

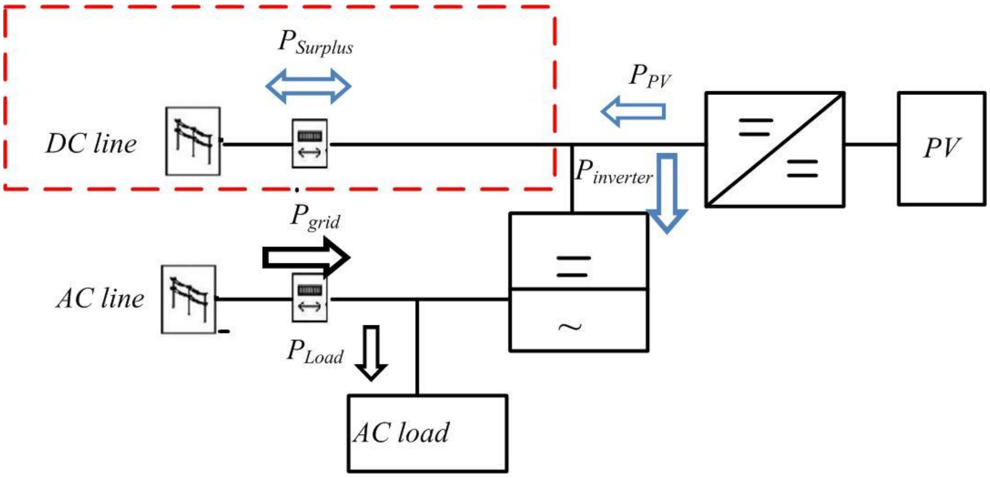
The maximum desirable penetration level of PVs can be achieved using a common DC link for residential buildings. This method can resolve the issue of the generation-load matching.

Fig. 4.1(a) presents the current energy system for a residential building with PV. The PV power supports the building load and the customer can exchange power with the electricity grid to balance the generation and load in the building. In this structure, the customer's surplus power will be injected to the electricity grid which may cause power quality issues, as noted earlier. This paper proposes the utilization of an auxiliary DC link as an alternative approach to resolve the AC power quality issues, while providing additional advantages such as higher level of redundancy and a pathway to the future DC network, as shown in Fig. 1(b). This system can efficiently provide supply to the AC loads, while the PVs surplus power can be injected into the common DC link. As a result, the issues associated with local surplus power injection to the low voltage AC lines will be resolved, while great deal of flexibility and redundancy are achieved.

In the proposed structure, the electricity exchange among local buildings can take place through the DC line while improving the local supply-demand matching and reduce the losses. For instance, customers with extra generation can inject their surplus power to the DC link while customers with higher load demand can import power from DC link, supplying to their load through an inverter. This strategy can also assist in load balancing among the phases and the power in phases with high generation can be circulated to the other phases which may need power.



(a)



(b)

Fig. 4.1 (a) A typical energy system for a residential building, (b) The proposed energy system for a residential building .

Fig. 4.2 shows one feeder in a LV network in which the proposed structure is used (other feeder will have the same structure). In this system, residential buildings are connected to both AC and DC lines to support their loads. The surplus power of building will be injected to the DC line. In addition, the overall surplus power can be transferred to the Medium Voltage (MV) network using a three-phase converter, given in Fig. 4.2.

It is anticipated that the DC appliances will be popular in the future distribution networks [28]. Reference [29] proved that if the local generation is provided for the DC loads, the efficiency of DC system is more than AC system. Therefore, the structure shown in this paper can be an efficient structure to achieve LV DC network. When the DC components and systems are completely installed, the existing AC lines can be kept in the network to add redundancy to the DC system.

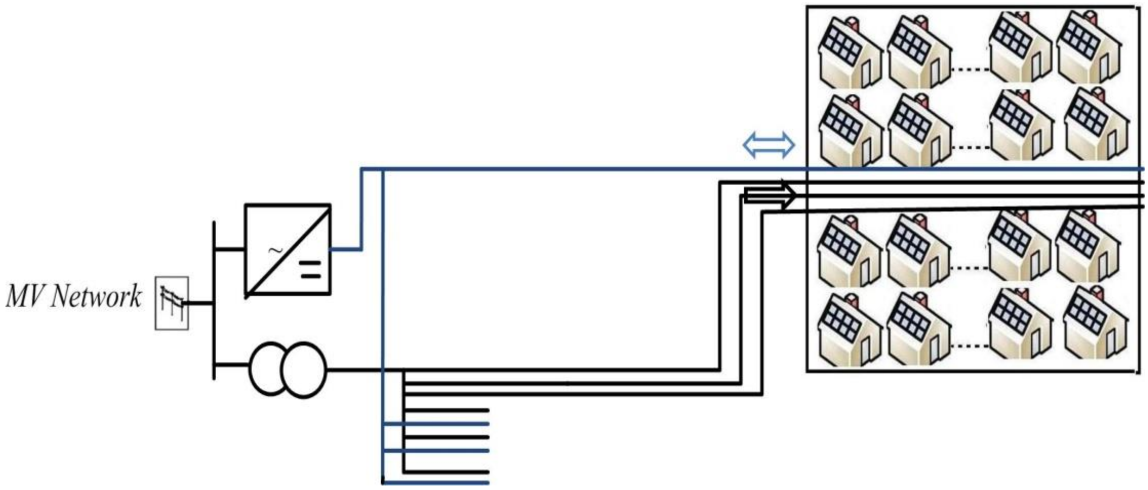


Fig. 4.2 Proposed structure for LV network.

4.4. System Modeling and Control

In this section, modeling and control of different components for the proposed approach have been shown.

4.4.1. Modeling of PV panel

Considering Fig. 4.3 as the equivalent circuit of a PV cell, the voltage output of the PV can be shown as in equations (4-1) [30]:

$$V_{PV} = n_p V_c = n_p \frac{AkT_{ref}}{q} \ln\left(\frac{I_{ph} + I_{sat} - \frac{I_{pv}}{n_s}}{I_{sat}}\right) - R_s \frac{I_{pv}}{n_s} \quad (4\text{-}1)$$

where;

V_{pv} PV panel voltage

I_{pv} PV panel current

n_p number of parallel cells

n_s number of series cells

V_c cell output voltage

I_c cell output current

A ideality factor

k Boltzman constant

T_{ref} reference operation temperature

I_{ph} photocurrent

I_{sat} reverse saturation current of diode

R_s series resistance of cell

q electron charge

The Maximum Power Point Tracking (MPPT) algorithm of reference [50] is used to determine the desired voltage of PV panel considering the solar irradiance and ambient temperature.

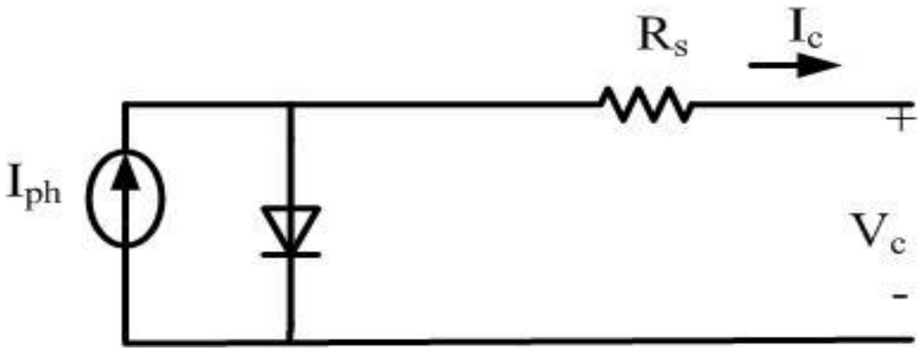


Fig. 4.3 PV cell equivalent circuit.

PVs for each customer are connected to the common DC link through a DC-DC boost converter. The control of boost converter is shown in the next part, with reference to the noted PV model.

4.4.2. Control of the Converters

Three types of converters can be anticipated in the proposed LV network structure, i) DC-DC boost converter of customer, ii) single phase inverter of customer and iii) three-phase inverter named grid converter in this paper. The DC-DC boost converter of each customer, together with a MPPT, is designed to inject the PV output power to the common DC link. A single phase inverter should support the customer AC load via DC link. Finally, a three-phase grid converter is used to inject the surplus power of the DC link to the MV network, by regulating the voltage of common DC link. It is shown that a robust localized control, based on local measurements, can be used for each converter as discussed in the following sections.

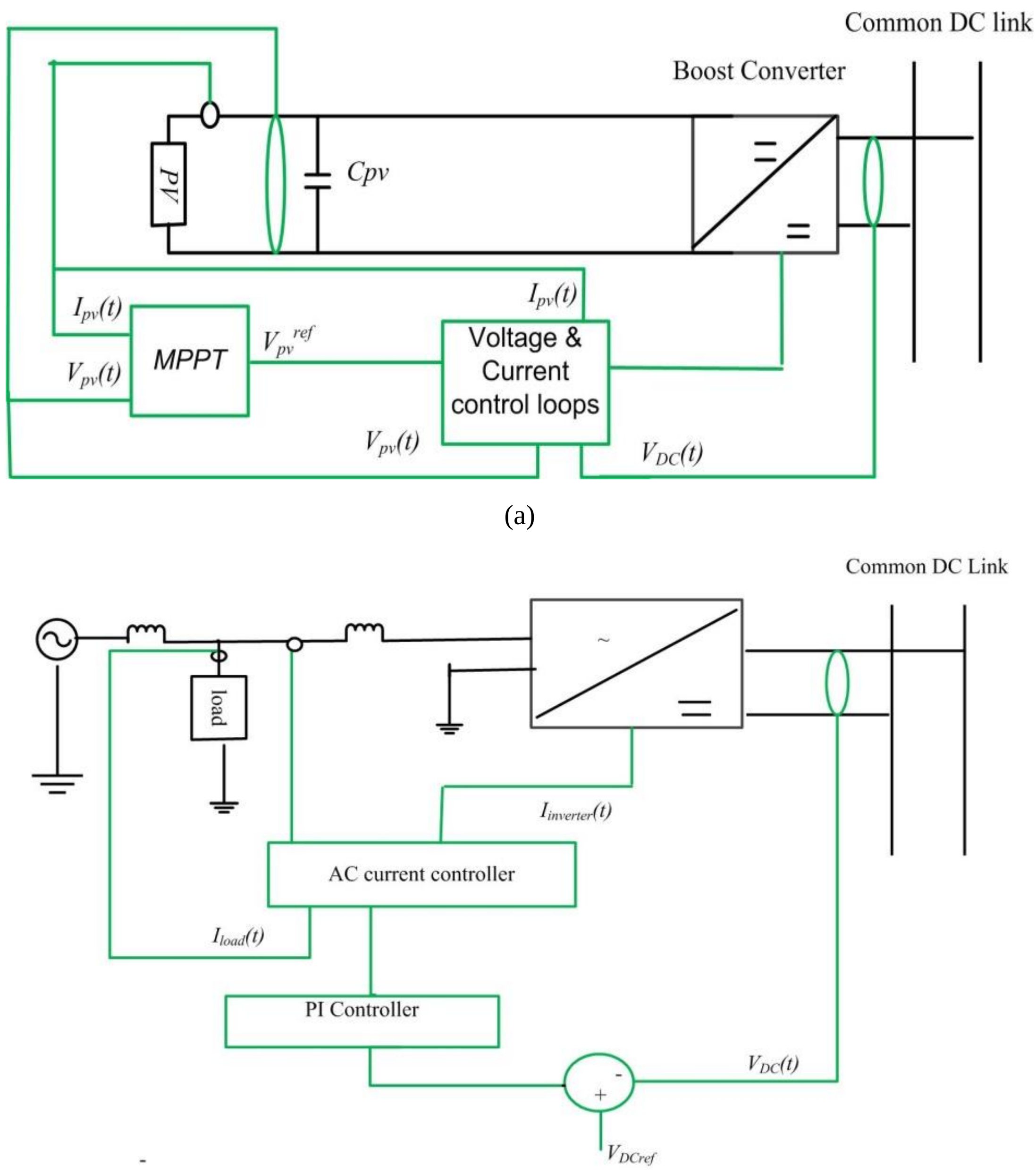
The most challenging issue in the current LV networks is the PVs tripping when the over-voltage limit is violated [31]. However, in the proposed structure, the extra power will be flown in DC link. Therefore, only the voltage protection levels of DC link need to be considered for the proposed operation strategy. The control structure of one PV unit for a customer, including DC-DC converter and a single phase inverter is shown in Figures 4.4 (a) and (b).

As shown in Fig. 4.4(a), v_{pv}^{ref} is determined based on MPPT. The DC-DC converter draws the current I_{pv}^{ref} to provide v_{pv}^{ref} at PV panel terminal. In addition, a feedback from DC link voltage ($V_{DC}(t)$) is used to control the injection to the DC link.

In Fig. 4.4(b), the inverter only supports the load and avoids injection to the AC network. In addition, a lower protection level is used to control the drawn power by inverter when the DC link voltage drops.

As noted before, the grid converter aims to inject the surplus power of DC link to the MV network. This goal can be achieved by controlling the voltage of the DC link. A dq-control approach, as given in [32], has been used for this converter. With reference to Fig. 4.5, the d-axis current controls the DC bus voltage. When there is a surplus power in DC link, the rising of DC link voltage causes higher I_d^{ref} and force I_d to increase. As a result, the surplus power of the common DC link will be transferred to the MV network. In addition, the grid converter can be used for voltage support in MV network using reactive power contribution. Consequently, the value of required reactive power determines the I_q^{ref}.

It is worth noting that the grid converter regulates only the DC link voltage whenever there is surplus power (injection is greater than demanded power) in DC line. However, when there is deficit power, grid converter does not regulate the voltage and the DC link voltage starts to decrease until its lower protection level reached. Consequently, single phase inverters modify their drawn power from DC link to keep the DC link voltage in permissible range.



(b)

Fig. 4.4 Localized control for PV unit, (a) Control of DC-DC converter, (b) Control of inverter.

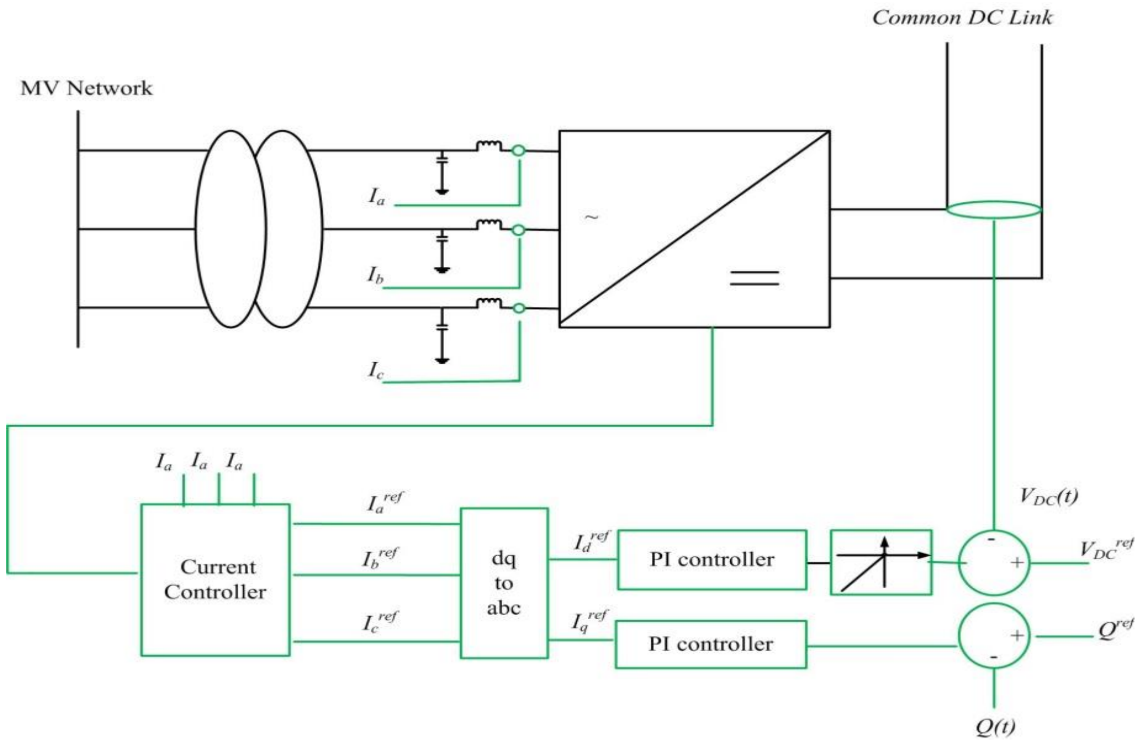


Fig. 4.5 Configuration and control of grid converter.

4.5. Simulation Results

In this section, the operations of a LV network with PVs including a common DC link is simulated to verify the proposed approach. Three cases have been simulated. The parameters for DC link voltage are listed in Table 4.1.

Table 4.1 DC link Voltage parameters.

Parameter	value
DC link voltage	400 V
Upper permissible limit	480
Lower permissible limit	360

4.5.1. Case1

In this case, the operation of one customer, supported by both AC and DC lines, is studied, as shown in Fig. 4.6. The DC link is modelled by a 4700 μF capacitor bank. The simulation of this model aims to show that the intermittency of load and generation cannot affect the performance of this approach and each customer can control its operation in localized mode. As grid converter is not considered here, if there is surplus power in DC link, the voltage rises and DC-DC converter is responsible for upper permissible limit. In addition, in case of deficit power in DC link, inverter is responsible for lower permissible limit.

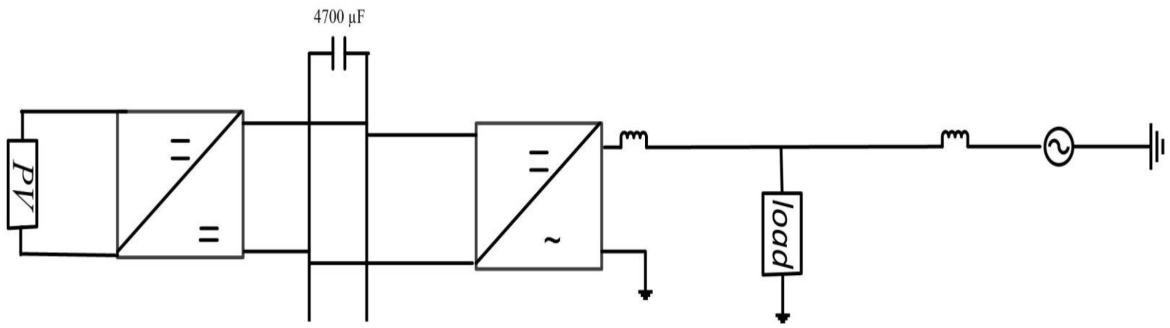
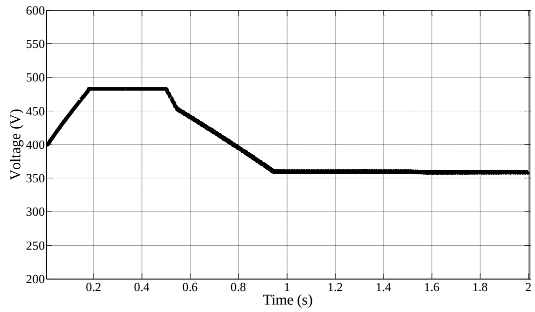


Fig. 4.6 Case 1.

In this case, it is assumed that the PV generates 1kW and the load for this building changes from 1.4 kW to 2.4 kW at t=1.5 s. Moreover, the customer’s inverter start to operate at t=0.5 s. The results are presented in Fig. 4.7. The main features of the results can be summarized as follows.

(1) At t=0 s, PV start to inject power to the DC link through DC-DC converter. The DC link voltage starts to increase.
(2) At t=0.18 s, upper permissible limit for DC link is violated. Therefore, DC-DC converter decreases its current to keep the voltage at this level.
(3) At t=0.5 s, inverter starts to operate. As a result, the entire load will be supported by DC link. Moreover, the DC link voltage starts to decrease which allows the DC-DC converter to inject power.
(4) At t=0.95 s, the lower permissible limit is violated for DC link voltage. As a result, inverter modifies its drawn power to stabilize the voltage.
(5) At t=1.5 s, as the customer load increase to 2.4 kW, power drawn from AC grid increases to 1.45 kW.



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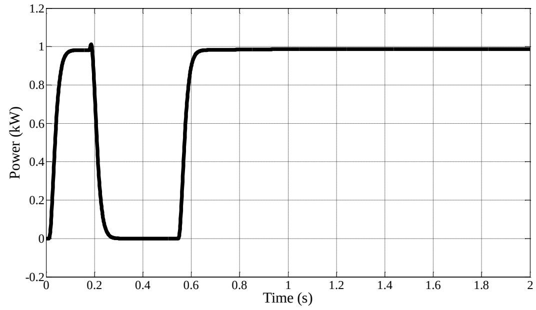

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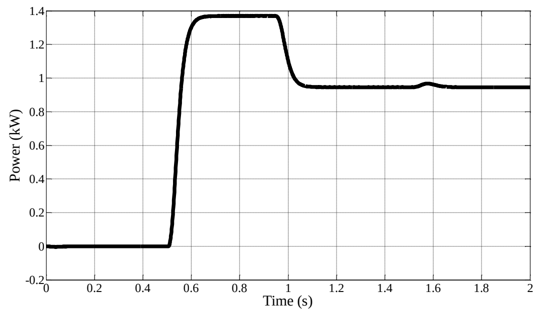

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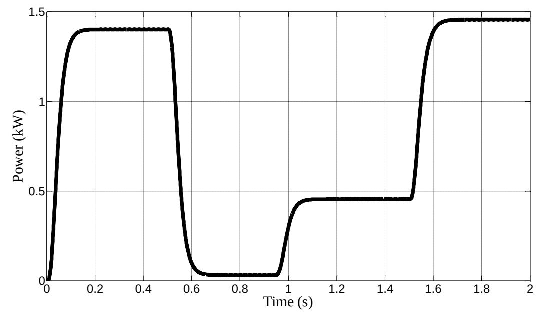

(d)

Fig. 4.7 (a) DC link voltage, (b) DC-DC converter power, (c) Inverter power, (d) Power injected to the AC grid

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This case was designed for the worst case scenario of violation of protection levels. However, the auxiliaries in the network such as grid converter can avoid such cases which include energy losses.

4.5.2. Case2

The LV network presented in Fig. 4.8 is considered as the second case study. The network parameters can be found in Reference [8]. In this system, transformer tap is set to have a voltage level of 245 V in the secondary of transformer. Customers in each node are considered by a lumped model, given in Fig. 4.8.

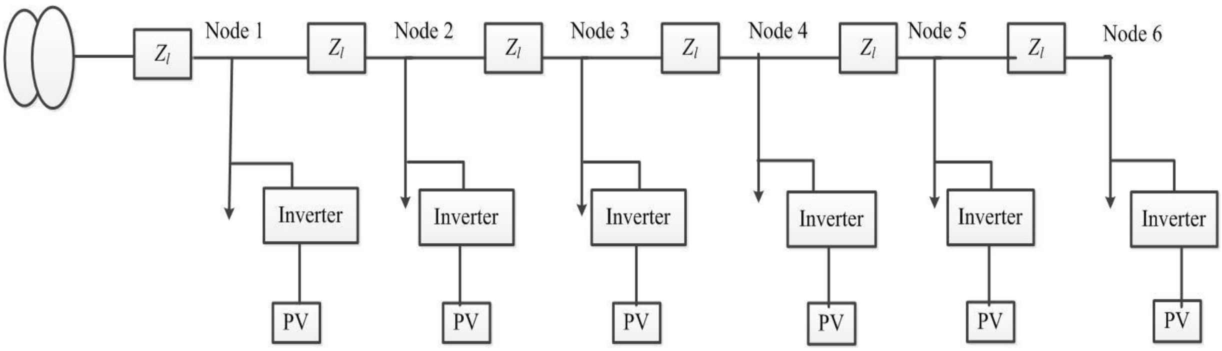


Fig. 4.8 Network structure.

As the voltage rise is the main limiting factor to increase the penetration level of PVs [4], different strategies including proposed approach are studied to avoid overvoltage and to verify the effectiveness of the proposed approach. It is assumed that the upper permissible voltage limit in this network is 254.4 V (1.06 pu). It is also assumed that each node has a generation of 8 kW which is available after t=1 s. In addition, the nominal load in each node in the period of study is as shown in Table 4.2, which are resistive and voltage dependent. Four types of scenario have been considered for this case. The PV unit parameters for each node are listed in Table 4.3.

Table 4.2 The nominal load value in each node at 240 V.

	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
0-2 s	8 kW	9 kW	6 kW	7 kW	6 kW	9 kW
2-4 s	6 kW	5 kW	4 kW	1.5 kW	3 kW	2 kW

Table 4.3 PV unit parameters for each customer.

Parameter	Value
DC/DC converter efficiency	100%
Inverter efficiency	97%
DC link capacitor	2000 uF
Inverter inductor	1 mH

In the first scenario, it is assumed that overvoltage would not pose any problem and PVs can generate power without voltage control. Fig. 4.9 shows all node profile voltages. It can be seen that the voltage for nodes 3, 4, 5 and 6 pass the upper permissible voltage limit between t=2 s and t=4 s. Although this situation does not have real application, it is only included for comparison purposes.

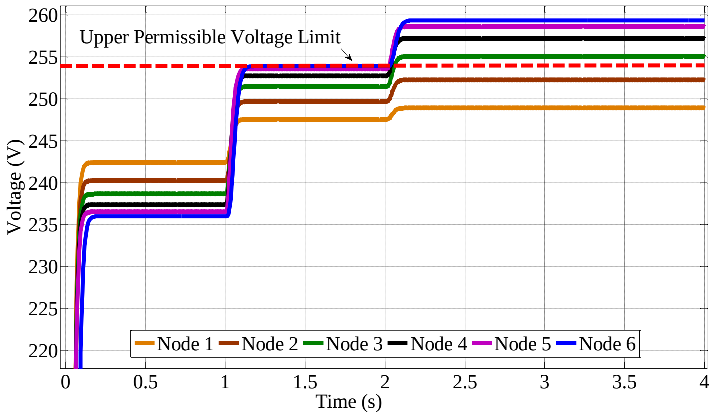


Fig. 4.9 Nodes voltage (no voltage control).

For the second scenario, it is assumed that overvoltage protection is applied for each inverter and whenever the inverter bus voltage violates the upper permissible voltage limit, the PV inverter will trip and reclose after 5 s if the inverter bus voltage is in permissible range [33]. The results for this case are shown in Fig. 4.10. It can be seen that as the voltages in nodes 5 and 6 passed the upper permissible limit, the inverters in these nodes trip and disconnect from the network.

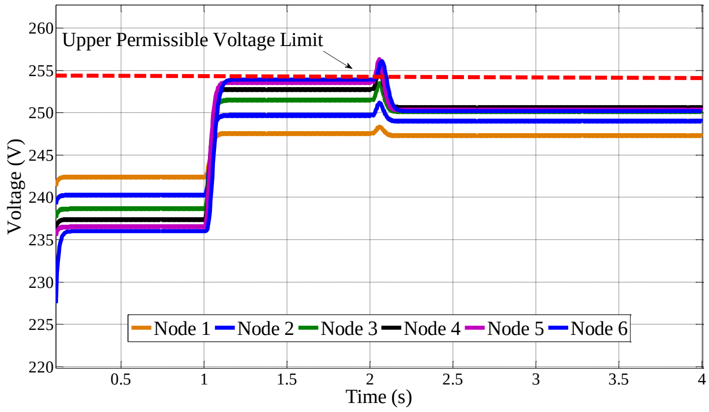


Fig. 4.10 Nodes voltage (Overvoltage protection strategy).

In the third scenario, Active Power Curtailment (APC) strategy as shown in [8] is used to avoid overvoltage. The parameters of this approach are given in Table 4.4. Fig. 4.11 shows the results for this case. It can be seen that at t=1 s, voltage at nodes 5 and 6 pass the critical limit ($V^{cri.}$) which result in power curtailment in these nodes. In addition, at t= 2s voltage at nodes 4, 5 and 6 pass the limit and inverters in these nodes curtail their power again. It can be seen that using this approach the voltage of all nodes will be kept in permissible range while losing renewable energy.

Table 4.4 APC parameters.

Parameter	Value
$V^{cri.}$	252 V (1.05 pu)
m_i	6.66 V/kW

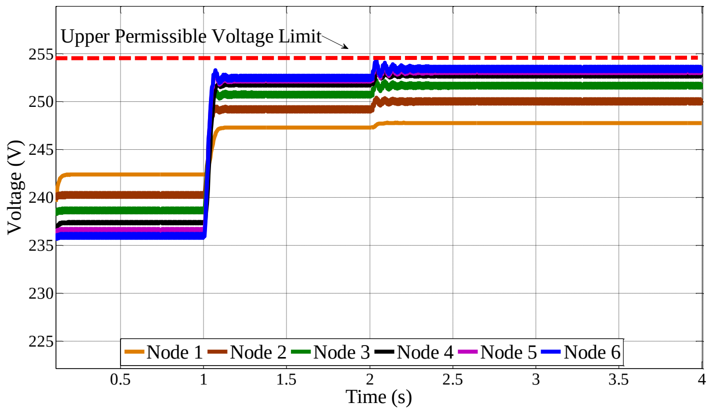


Fig. 4.11 Nodes voltage (APC strategy) .

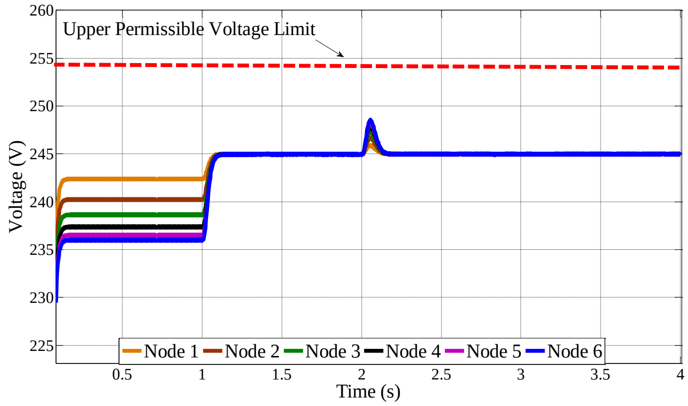
Finally, the proposed operation approach in this paper is used. The DC line resistor value is the same as the AC line resistor (skin effect is not considered). Fig. 4.12 shows the profile of AC and DC node voltages and the injected power to the AC grid. The operation based on proposed approach can be summarized as follows:

(1) Between t =0 s and 1 s, DC/DC converters and inverters for different customers are not operating. Therefore, customers load are supported by AC grid.

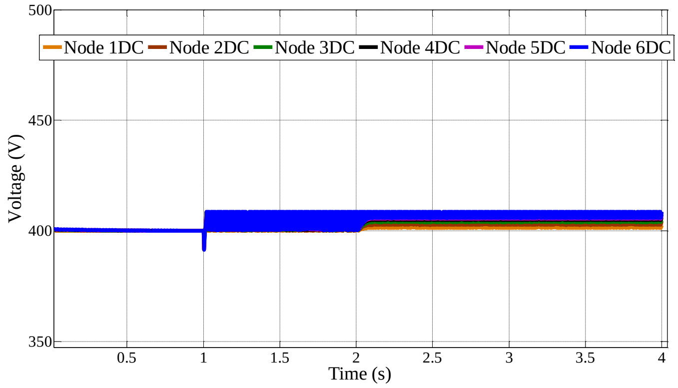
(2) At t =1s, DC/DC converters and inverters start to operate. It can be seen that the AC grid power in each node reduces to zero and loads are supported from the DC link through the inverters. In addition, all customers experience the same AC voltage profile and DC bus voltage for all customers are in desirable range.

(3) At t=2s, the network load decreases causing the injection to the DC link increase. However, the voltages of all DC nodes are in the desirable range.

As it can be seen, for this approach, overvoltages and renewable energy losses can be avoided which is promising for future smart grid.



(a)



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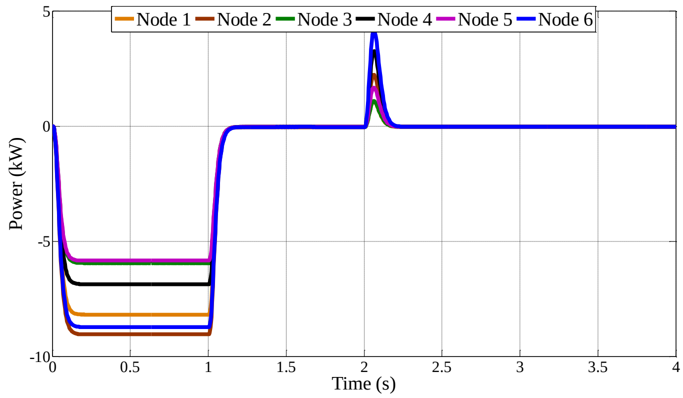

(c)

Fig. 4.12 Proposed control approach (a) AC node voltages, (b) DC node voltages, (c) injected power to the AC grid.

4.5.3. Case3

In this section, the benefits of the proposed approach are discussed based on a set of energy utilization indices. The main focus of this part is to show how the proposed approach can improve the energy utilization in LV network, both for consumption and export to the grid.

For better understanding and comparison purposes, the following indices related to energy utilizations are defined:

$$\eta_l = \frac{\sum_{k=1}^{6} load_k}{\sum_{k=1}^{6} load_k^{nominal}} \tag{4.2}$$

$$\eta_g = \frac{\sum_{k=1}^{6} gen_k}{\sum_{k=1}^{6} gen_k^{nominal}} \tag{4.3}$$

where η_l is the load consumption index, $load_k$ is the value of energy consumed at *k*th node in the period of study, $load_k^{nominal}$ is the value of consumed energy in nominal voltage (240 V) at *k*th node in the period of study, η_g is the generation utilization index, gen_k is the generated energy at *k*th node in the period of study and $gen_k^{nominal}$ is the available energy at *k*th node in the period of study..

In the first scenario (no voltage control) noted earlier, the generation utilization index for the network is equal to 0.97 as all customers can inject all their available power to the grid through their inverter. However, as noted before, this is a hypothetical situation. In addition, as the loads experience higher voltages, the total load consumption index will equal to 1.0624.

In the second strategy (overvoltage protection), the inverters in bus 5 and 6 will be unavailable during t=2 s and t=4 s which reduce the generation utilization index to 0.7677. In addition, as the voltage is reduced compared with the previous scenario, the load consumption index will amount to 1.0499, in this case.

Using the third strategy (APC), we obtain a generation utilization index of 0.8087. This is due to the fact that; there is energy curtailment for inverters in nodes 5 and 6. It is also noted that; the load consumption index is equal to 1.0512, in this case.

Finally, application of the proposed approach will increase the generation utilization index to 1 which is the maximum possible outcome, and it is higher than the other strategies. In addition, as the load nodes in this strategy experience the minimum voltage, the load consumption index for the proposed method gives 1.0180, which is the minimum as compared with the other strategies.

The results of this section shows that the proposed approach can increase the local energy utilization in LV network, which can translate into a significant economical benefits on a large scale measure.

Moreover, Table 4.5 shows the total energy injected to the upper voltage level network in the period of study. It can be seen that, as the proposed approach has the maximum generation utilization and minimum load consumption indices, its energy injected to the upper voltage level network is the maximum value, which shows another attractive aspect of this approach as well.

Table 4.5 Energy injected to MV network.

Strategy	value
No control	0.0489 kWh
protection	0.0336 kWh
Curtailment	0.0367 kWh
Proposed approach	0.522

4.6. Conclusion

This paper proposed a new structure with corresponding control design strategies for increased utilization of residential building PVs in LV networks. This approach proved to overcome the power quality issues associated with augmented PV penetrations. However, the proposed techniques can add significant advantages, such as; taking into account different operational situations in the future for LV networks, where combined AC and/or DC links can be employed effectively, and provide high level of redundancy and reliability. It is worth noting that at this stage a fully DC operated system, where links and loads can be DC are still far from reality, as surrounding technologies are yet to be designed and accommodated. Nonetheless, the backbone of our proposed structure can support any of the perceived options for the future network technology and is not dependent on battery storages.

4.7. Reference

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Statement of Contribution of Co-Authors

The authors listed below have certified that:

1- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

2- They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publications;

3- There are no other authors of the publication according to these criteria;

4- Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit;

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Overvoltage Prevention in LV Smart Grid Using Customer Resources Coordination

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Ghassem Mokhtari	Proposed the control strategy. Develop the control strategy regarding the simulation and data analysis. Wrote the manuscript.
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Ghavam Nourbakhsh	Aided data analysis and writing the paper
Firuz Zare	Aided data analysis and writing the paper
Arindam Ghosh	Aided data analysis and writing the paper

Supervisor Confirmation

I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

Prof. Arindam Ghosh
Name　　　　Signature　　　　Date: 2 Jan. 2014

Chapter 5

Overvoltage Prevention in LV Smart Grid Using Customer Resources Coordination

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Abstract— Voltage rise is one of the main factors which limits the capacity of Low Voltage (LV) network to accommodate more Renewable Energy (RE) sources. This paper proposes a robust and effective approach to coordinate customers' resources and manage voltage rise in residential LV networks. PV is considered as the customer RE source. The suggested coordination approach in this paper includes both localized control strategy, based on local measurement, and distributed control strategy based on consensus algorithm. This approach can completely avoid maximum permissible voltage limit violation. A typical residential LV network is used as the case study where the simulated results are shown to verify the effectiveness of the proposed approach.

5.1. Index Terms

Consensus algorithm, DER, LV Network, Smart Meter, Voltage Rise.

5.2. Introduction

In future, the layout of RE sources in the electricity network will be a mixture of both concentrated and distributed. The choice will depend on many factors such as geographic location, load diversity, network configuration, population density etc. Loads in LV network are normally residential and commercial which constitute a greater portion of most electricity systems [1]. For example, in the US, domestic loads consume nearly 40 percent of national electricity generation [2]. In France, buildings consumes nearly 45% of primary energy [1]. Generally, it is desirable to have electric energy generation close to the loads. This approach can help in avoiding long distance transmission of electric energy that can be associated with cost and energy losses [3], improving the security of supply and reducing the electricity bill for customers [4]. Consequently, it makes sense to encourage customers in residential/commercial buildings to install RE sources. This way, the customers can generate electricity for their own consumption and export the surplus power to the grid. As a result, it is anticipated that future LV networks with residential and commercial buildings will see a widespread use of small scale RE sources like PV and wind turbine. The high penetration of RE sources may cause power quality issues such as voltage rise [5-11], voltage unbalancing [12], line overloading [5, 13-18], flicker and harmonics [19]. Voltage rise is normally the main limiting factor in increasing RE generation in LV networks [1]. This problem is likely to happen during the periods when load is low and RE generation is high, causing reverse power flow and therefore voltage rise [20]. Overvoltage is not permitted as it may cause damaging effect on customer electric devices and sensitive electronic equipment [21]. Therefore, loss of RE supply may become inevitable if the voltage violates stationary limits.

Reasearchers proposes the following strategies to deal with the voltage rise issue.

1- Network upgrading, such as increasing conductor size. This approach needs new expensive investment by utilities for upgrading the networks [22-24].

2- Changing network static set points. Based on the randomness of RE generator output power, the main limitation of this approach is that the static set points would have to change frequently which is not practical [23, 25].

3- Utilization of Distributed Energy Resources (DERs) in customer side such as RE generator and controllable devices for voltage support. It has been estimated that nearly 33% of customer's demand including, dishwasher, washing machine, cooling load, storage units and electric vehicle, can be considered as controllable loads [26]. Therefore, in period of high generation, e.g., mid day for residential area with solar PVs, these resources can be utilized to deal with voltage rise problem.

The third approach is the most promising. However, the main challenge is to determine a coordination strategy for these resources. There are three types of coordination strategies that can be implemented. The first strategy is a centralized control in which the central controller coordinates various resources in the LV network. This approach, even though most efficient, requires online information of the network resources, large memory space for data storing and high data sorting and calculation speed. In addition, it requires fast and reliable communication links. The second strategy is a localized control which is based on local measurements only, such as the one proposed in [20] and [27]. This control approach is robust in the sense that only local measurements are utilized. However, it cannot effectively utilize all the available resources. The third approach involves distributed control. This approach can have the effectiveness of centralized approach while avoiding its complexity. However, the robustness of this approach still depends on the communication links.

Many large-scale projects are currently being conducted around the world on smart meters to make the network more intelligent. Italy and Sweden have nearly 100% installations by the end of 2011 [28]. The primary role of smart meters are to generate customer consumption data for utilities [28]. In addition, the meter can give the customers the ability to use its data and control their load, local generation and battery storage through their Energy Management System (EMS) [29]. The smart meters also have the ability to communicate through communication infrastructure. In this paper, it is proposed that a new functionality can be added to the smart meters in which they can communicate with each other. This functionality can give the flexibility to customers in a local area to use their EMS and collaborate with each other for different operational goals including voltage support, which is the focus of this paper.

Based on the suggested functionality, this paper proposes a new coordination arrangement for LV network which can deal with voltage rise problems due to increased penetration of RE sources. PV is considered as the customer RE source. Two operating modes have been defined for a LV network, normal operating mode and voltage control mode. In the normal operating mode, customers continue to operate based on their own objectives. However, in the voltage control mode, two control strategies, localized and distributed, will be used to avoid permissible voltage limit violation. Localized control strategy responds fast and keeps the voltage in permissible range by determining the share of PV inverters active and reactive power for voltage reduction. However, to make the voltage reduction more efficient, a distributed control strategy based on consensus algorithm will be initiated as a supplementary control to find the contribution of customers in voltage control mode using controllable devices.

The rest of the paper is organized as follows: in Section 5.3, the problem of voltage rise is defined and the effective parameters for voltage support are introduced. Section 5.4 provides the details of the proposed approach. This method is applied to a typical LV network in section 5.5 and the results are analyzed. Finally, the paper concludes in Section 5.6.

5.3. Problem Definition

Standards allow a maximum of 5% voltage drop from LV transformer secondary to the last customer [20]. In order to achieve such voltage drop at the end of feeder, the LV transformer tap is normally set to have no-load voltage of 1.02-1.05 in the secondary side of the transformers. This strategy is adequate for a passive network where no RE sources are connected.

However, as more and more RE sources get connected to LV networks, significant reverse power flow ensues, especially as the RE penetration level increases. This reverse power flow may cause different power quality issues including voltage rise along the feeders. The voltage rise problem can mathematically be explained considering the system shown in Fig. 5.1 where V_t and $Z_t = R_t + jX_t$ are the equivalent circuit parameters in upstream network for the i^{th} customer Point of Common Coupling (PCC). The voltage magnitude difference between the source and the PCC bus voltages (ΔV) can be approximated by the following equations.

$$\Delta V = V_i - V_t = \frac{P_i.R_t + Q_i.X_t}{V_i} \tag{5-1}$$

$$P_i = P_{gi} - P_{cr.i} - P_{cdi} \tag{5-2}$$

$$Q_i = Q_{gi} - Q_{cr.i} - Q_{cdi} \tag{5-3}$$

where P_{gi} and Q_{gi} are the generated active and reactive power of RE generator, $P_{cr.i}$ and $Q_{cr.i}$ are the active and reactive power of critical load, P_{cdi} and Q_{cdi} are the active and reactive power of controllable devices.

The value of ΔV is positive when the customer is in generation mode, indicating voltage rise with reference to source voltage. As it can be seen from (5-1)-(5-3), six parameters (P_{gi}, P_{cdi}, $P_{cr.i}$, Q_{gi}, Q_{cdi} and $Q_{cr.i}$) in customer side would affect voltage rise.

Critical loads ($P_{cr.i}$ and $Q_{cr.i}$) need to be supplied on demand and cannot be used for voltage support. In addition, reactive power of controllable devices (Q_{cdi}) is usually function of their active power. As a result, only P_{gi}, Q_{gi} and P_{cdi} can effectively be used for voltage support in the LV network. Our suggested new coordination approach in this paper uses these resources to control voltage rise, where localized control strategy coordinates the value of P_{gi}, Q_{gi} for customers to have robust overvoltage prevention in the network. However, to make the voltage reduction more efficient (avoiding or reducing RE curtailments), a supplementary control approach based on consensus algorithm is proposed to coordinate the value of P_{cdi} for the customers.

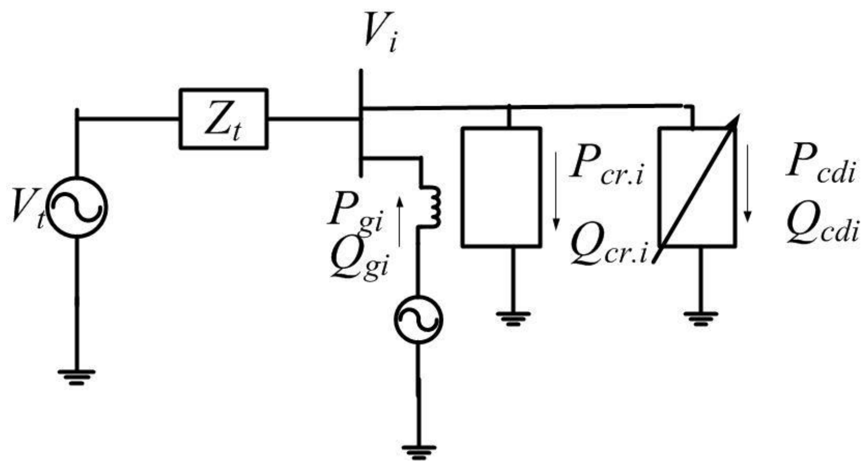


Fig. 5.1 Circuit equivalent.

5.4. Proposed Approach

The schematic layout of the proposed structure is shown in Fig. 5.2. The dashed arrows show the information flow. As shown in this figure, individual customers are controlled by their own EMS. There is a communication link between EMS and customer's resources. The

EMS receives the resources' information and sends back required command, taking into account customer's objective or any external command.

In addition, there are communication link between EMSs of adjacent customers through their smart meters. This functionality can give customers the ability to collaborate with each other for different operational goals such as voltage support. It is worth noting that voltage rise is a single-phase problem rather than three-phase problem, and hence, it is assumed that the control structure provided in this paper is applied in per phase basis.

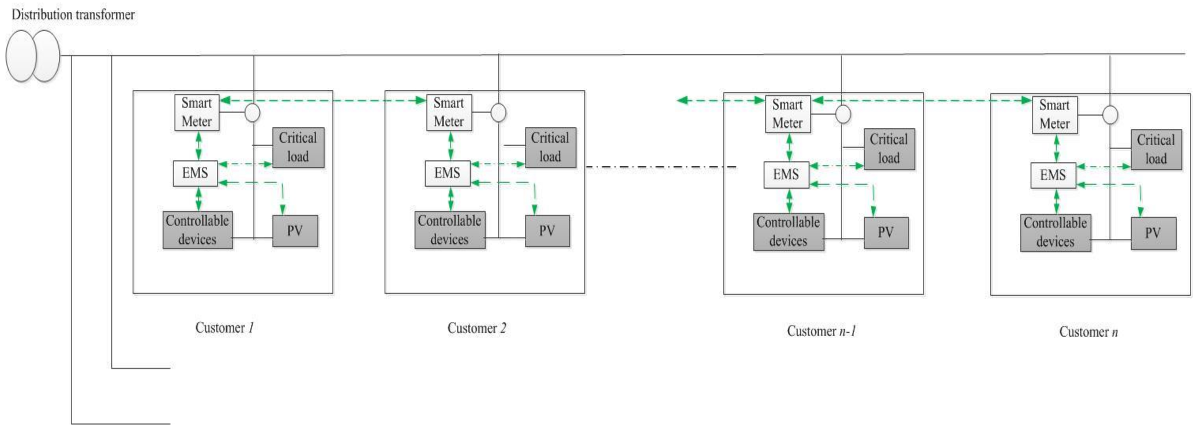


Fig. 5.2 Proposed structure for residential LV network.

Three voltage limits have been defined for operation of network. Based on these limits, the operating state of individual customers can be determined by their own PCC voltage (V_i) as shown in Table 5.1.

Table 5.1 Customer operation states.

State	Definition
Normal	$V_i \leq V^{max\_desirabele}$
Alert	$V^{max\_desirabele} \leq V_i \leq V^{max\_critical}$
Emergency	$V^{max\_critical} \leq V_i$

The network operating mode is defined based on the operating state of all customers. If all customers are in normal state, the LV network is in normal operating mode. In this operating mode, there is no need for voltage support and all customers are free to maximize their injection to the grid.

However, if there is any customer in emergency state, network goes to the voltage control mode. Consequently, two control strategies (localized and distributed) will be used to prevent permissible voltage limit violation. The details of these strategies are explained in following parts;

5.4.1. Localized Control Strategy

Localized control strategy will coordinate the value of P_{gi} and Q_{gi} for customers. Different localized techniques are used for voltage support [3, 30-37]. It is interesting to note if the PV inverter rating increases to $1.1\times P_{PV}^{\max.}$, it can give the ability of reactive power absorption around $0.5\times P_{PV}^{\max.}$, even in maximum active power injection (where $P_{PV}^{\max.}$ is PV rating). Consequently, this capability can be used for voltage reduction in LV network. The main strategies which use inverter reactive power for voltage reduction can be summarized as follows:

1- Fixed reactive power control,

2- Reactive power control as a function of inverter bus voltage,

3- Reactive power control as a function of inverter active power.

Considering the simplicity and effectiveness of the third strategy [36], it is proposed in this paper to be used by customers for voltage support using reactive power. The reactive power control characteristic, for each inverter, is given by equation (5-4). As shown in this equation, whenever the inverter active power passes the value of $0.5\times P_{PVi}^{\max.}$, the inverter start to absorb reactive power, where the superscript '*' denotes the reference value.

$$Q^{*}_{gi}=\begin{cases}0 & P^{*}_{gi}<0.5\times P_{PVi}^{\max.}\\ -0.4843\times P^{*}_{gi} & P^{*}_{gi}<0.5\times P_{PVi}^{\max.}\end{cases} \tag{5-4}$$

As a result, customers who contribute to voltage rise by their active power injection will also contribute to voltage reduction by their reactive power absorption. It is worth noting that the customer reactive power contribution does not depend on customer state or network operating mode and it only depends on the value of injected active power.

However, due to high value of R/X in LV networks, reactive power cannot be the only promising resource to be used and keep the voltage in permissible range. Therefore, the contribution of active power is also needed for a robust voltage rise control. To find the contribution of each customer in voltage rise control using active power, an active power curtailment is proposed for customers who are in emergency state, as given in the following equations.

$$\Delta P_{cur.i}=\begin{cases}m_i.(V_i - V^{\max\_critical}) & V_i>V^{\max\_critical}\\ 0 & V_i\le V^{\max\_critical}\end{cases} \tag{5-5}$$

$$P^*_{gi} = P_{MPPTi} - \Delta P_{cur.i} \tag{5-6}$$

where $\Delta P_{cur.i}$ is the required curtailment for the i^{th} customer and P_{MPPTi} is the maximum available PV power for the customer. In addition, a droop gain m_i is used for each inverter, which is given by

$$m_i = \frac{P_{PVi}^{max.}}{V^{max\_permissable} - V^{max\_critical}} \tag{5-7}$$

The localized control strategy for each customer is as shown in Fig. 5.3. Using this control strategy, all voltages will be kept in the permissible range by curtailing the active power of customers who are in emergency state.

To minimize active power curtailments, a distributed control strategy is proposed to coordinate the controllable devices within the network for effective voltage reduction. The details of this algorithm are explained in the following part.

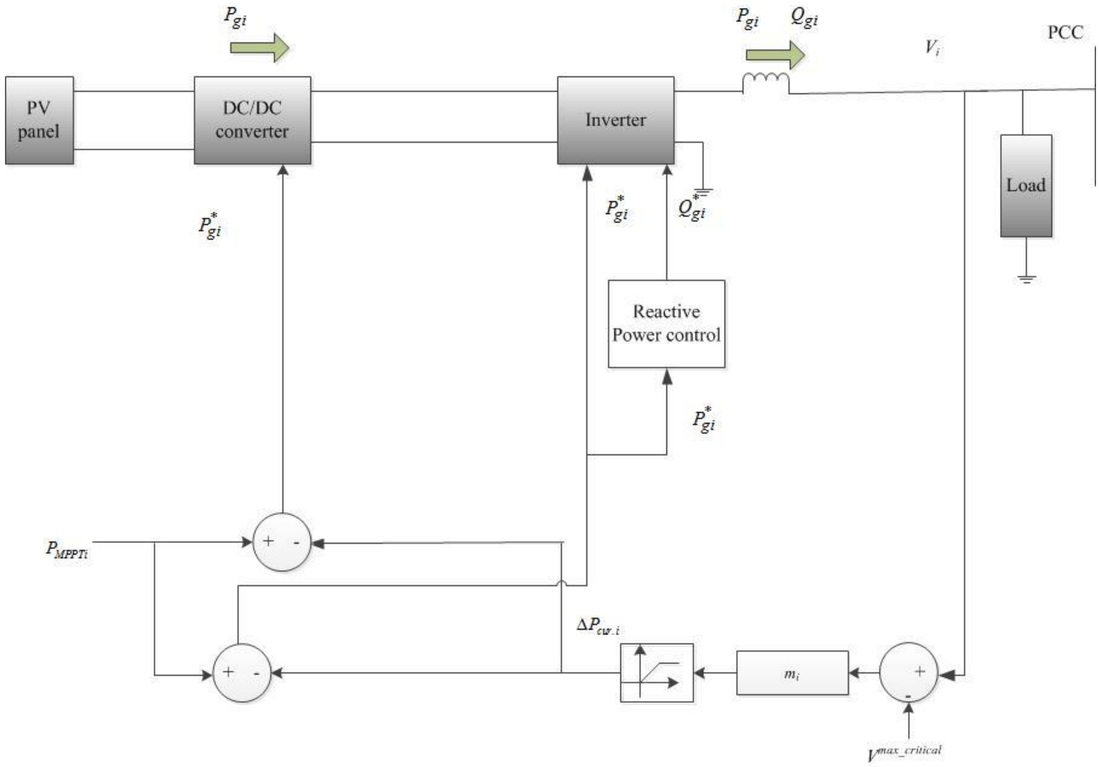


Fig. 5.3 Proposed Localized control for voltage support.

5.4.2. Distributed Control Strategy

Consensus algorithm has been applied in different application of distributed control. In [26, 38], this algorithm is used to coordinate multiple wheeled mobile robots. Reference [39] uses consensus algorithm for spacecraft formation. A cooperative strategy uses consensus algorithm [40] to coordinate unmanned air vehicles for fire monitoring. In this paper, this algorithm is proposed to coordinate customer controllable devices during voltage control mode in order to avoid RE curtailments.

In the proposed control structure, the first objective is to design a distributed control strategy for controllable devices to reduce the voltage of all nodes to less than $V^{max\_critical}$ limit to avoid RE curtailments. To achieve this, it is proposed that the voltage of critical node (V_c) can be considered as the controllable variable. If the voltage in this node does not violate $V^{max\_critical}$, all other nodes on the same phase will not face this problem. Therefore, the first aim can be given by following equation.

$$V_c < V^{\max\_critical} \tag{5-8}$$

The second objective is to design a distributed control strategy in such a way that the sharing of controllable power between customers fulfils the following criteria:

$$\frac{w_1.P_{cd1}}{P_{cd1}^{\max.}} = \frac{w_1.P_{cd2}}{P_{cd2}^{\max.}} = ... = \frac{w_n.P_{cdn}}{P_{cdn}^{\max.}} \tag{5-9}$$

where $P_{cdi}^{\max.}$ is the maximum capacity of controllable power for the i^{th} customer and w_i is its weighting factor for efficient voltage reduction. For example, if the customer is far away from critical node, a larger weight can be chosen to make less sharing for this customer in voltage reduction. However, in this paper, the same weight is considered for customers such that the required active power for voltage reduction is shared equally among customers.

To achieve these two aims, distributed control strategy based on consensus algorithm is designed as follows:

Let us consider Phase x with n customers. The proposed communication structure can be shown by a time-varying matrix as given in equation (5-10).

$$S(t) = \begin{bmatrix} s_{11}(t) & s_{12}(t) & ... & s_{1n}(t) \\ . & . & . & . \\ . & . & . & . \\ s_{n1}(t) & s_{n2}(t) & ... & s_{nn}(t) \end{bmatrix} \tag{5-10}$$

where s_{ij} denotes the communication link between the i^{th} and j^{th} customer; s_{ij} =1; If the j^{th} customer sends information to the i^{th} customer, and s_{ij} =0 otherwise. In addition. $s_{ii}=1$ for all customers.

Based on consensus algorithm, the information state of each customer can be updated by the following equation:

$$\dot{\varepsilon}_i = -\sum_{j=1}^{n} a_{ij}(t).(\varepsilon_i(t) - \varepsilon_j(t)) \tag{5-11}$$

where $\varepsilon_i(t)$ is the information state for *i*th customer, $a_{ij}(t)$ is the *(i,j)* entry of adjacency matrix $A_n(t) \in \mathbb{R}^{n \times n}$.

In a practical situation, the interaction among customers occurs at discrete time step (t_d). So, the information state of each customer is updated using equation (5-12).

$$\varepsilon_i[t] = \sum_{j=1}^{n} d_{ij}[t].\varepsilon_j[t - t_d] \tag{5-12}$$

where $d_{ij}[t]$ is the *(i,j)* entry of a row stochastic matrix which can be found in each discrete time data exchange by the following equation.

$$d_{ij}[t] = \frac{s_{ji}[t - t_d]}{\sum_{j=1}^{n} s_{ji}[t - t_d]} \tag{5-13}$$

In the proposed control strategy, smart meters sample the voltage at each time step *{T1, T2,….},* which has been chosen as 1 s in this paper. If the voltage of all customers is in the desirable range, the LV network is in the normal operating mode. However, if the critical voltage limit is violated for any customer, the proposed consensus algorithm needs to be utilized to coordinate controllable devices and reduce the voltage. As the customer in the critical node have the information of voltage in this node, it is proposed that EMS of this customer is responsible to turn on the VC flag and initiate the customer's coordination when required. In addition, this EMS approximates the required active power for voltage reduction by the following equation:

$$\rho = \left(\frac{\partial V_c}{\partial P_c}\right)^{-1}.(V_c - V^{\max\_desireable}) \tag{5-14}$$

where $\frac{\partial V_c}{\partial P_c}$ is the sensitivity of voltage in critical node to the changes in active power which do not change much with respect to changes in the operating point [41]. Therefore, its nominal values are used in this paper to design the controller. The value of ρ is calculated in such a way to reduce the voltage of critical node to less than $V^{\max\_critical}$ (objective 1).

In order to find the contribution of each customer in voltage reduction using controllable devices, two cases need to be initiated in parallel to allocate the required power from controllable devices of each customer. In the first case, the consensus algorithm will be initiated by the following equation:

$$\varepsilon_i[0] = \begin{cases} \rho & i = c \\ 0 & i \neq c \end{cases} \quad i = 1,...,n \tag{5-15}$$

In this case the maximum capacity of controllable power for each customer is not considered. To consider this constraint, the second case is initiated by following equation:

$$\varepsilon_i[0] = P_{cdi}^{\max.} \qquad i = 1,...,n \tag{5-16}$$

By applying the initialization process, the customers start to exchange data based on the proposed communication structure (equation (12) starts to iterate), and both cases converge to a feasible solution as $\hat{\varepsilon} = [\hat{\varepsilon}_1, \hat{\varepsilon}_2, ..., \hat{\varepsilon}_n]$ and $\bar{\varepsilon} = [\bar{\varepsilon}_1, \bar{\varepsilon}_2, ..., \bar{\varepsilon}_n]$, respectively.

Finally, the required controllable active power for each customer is determined by the following equation.

$$P_{cdi} = \frac{\hat{\varepsilon}_i}{\bar{\varepsilon}_i} . P_{cdi}^{\max} \qquad i = 1,...,n \tag{5-17}$$

Through this scheme, when the contribution of each customer is applied, normally customers in emergency state change their state to the alert and RE curtailments are avoided. The contribution of customers (P_{cdi}) will be kept until all customers go to the normal state. At this stage, EMS of customer in critical node turns off the VC flag which means that the LV network goes to the normal operating mode and customers can work based on their own objectives.

In a radial LV network, last node is the critical node. The proposed operation with the coordinated control is illustrated in Fig. 5.4, based on the voltage at this node. The chronological course of events is described as follows:

- At t=t_1, the voltage of this node is within desirable voltage range. In this situation, all PV inverters are injecting their maximum surplus active power and their reactive power is based on the characteristics shown in equation (5-4).

- The injections to the grid increase and at t=t_2, the maximum desirable voltage limit is violated for this node. However, the network is still in normal operating mode.

- At t=t_3, the maximum critical voltage limit is violated in this node. At this stage, customers who experience the emergency state start to curtail their injection based on equation (5-6), to keep the voltage in permissible range.

- At t=T_2, the EMS of customer in critical node sense the emergency state. As a result, this EMS turns on the VC flag and initiates the communication among customers to find the contribution of each customer in voltage control mode using controllable devices.

- After applying the contribution of customers, at $T_2+\Delta t$, the voltage of this node will be reduced to less than maximum critical limit, while avoiding RE curtailments within the network. The network continues with the voltage control operating mode until all customers go to the normal state.

- At t=T_3, all customers are in normal state and the corresponding EMS turns off the VC flag and network goes back to the normal operating mode.

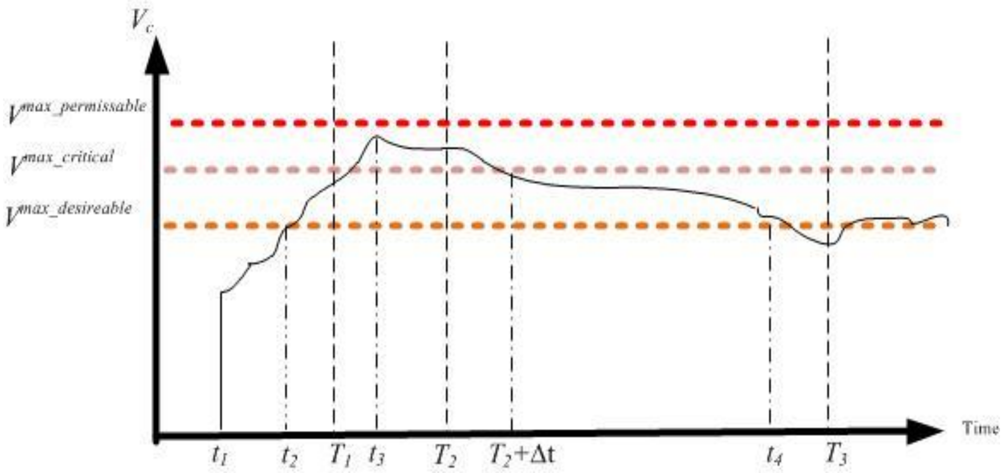


Fig. 5.4 Different operation modes of a radial LV network base on voltage in critical node.

5.5. Case Studies

A typical residential LV network is considered as a case study, to verify the effectiveness of the proposed approach. The network parameters can be found in Reference [20]. There are 12 customers in this single-phase LV network (2 in each node). The maximum load for each customer is 6.25 kVA. In addition, each customer is supported by one PV with rating of 8.4 kW. For the sake of simplicity, customers in each node are considered by a lumped model as shown in Fig. 5.5. It is assumed that the EMS of each customer can communicate with other EMSs through the proposed communication structure. The value of t_d for interaction is chosen 1 ms, and it is assumed that smart meters sample the voltage at each 1 s time interval. The voltage parameters of proposed approach are shown in Table 5.2. In addition, the available controllable power in each node is listed in Table 5.3.

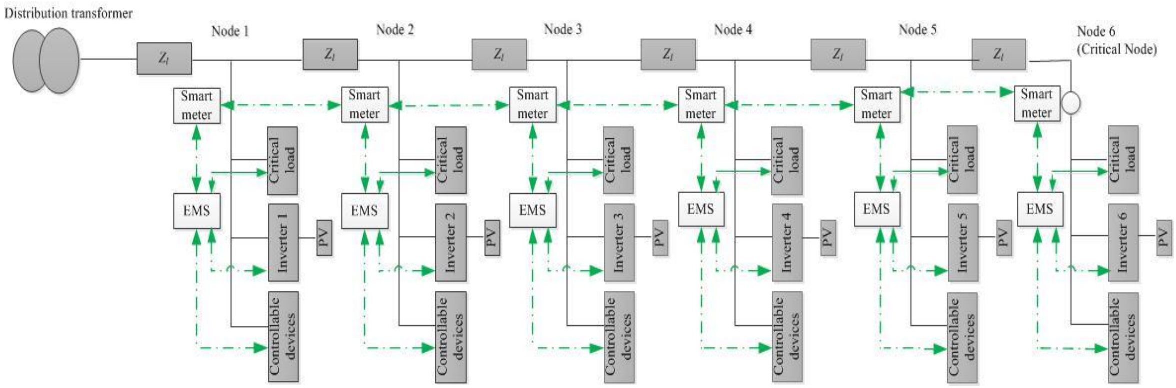


Fig. 5.5 Case study.

Table 5.2 Voltage parameters for the proposed approach.

Parameter	Voltage (pu)	Voltage (V)
$V^{max\_permisisable}$	1.06	254.4
$V^{max\_critical}$	1.05	252.0
$V^{max\_desirable}$	1.045	250.8

Table 5.3 Available controllable power in each node.

Node	1	2	3	4	5	6
Controllable power (kW)	3.0	3.5	4.0	3.0	1.5	1.0

5.5.1. Case 1

To verify the effectiveness of the proposed approach in different operating modes, the load and generation profiles shown in Fig. 5.6 are considered for each customer. To simulate the worst case scenario of voltage rise, it is assumed that all customers have the same load and generation profile as shown in this figure. Three types of scenario have been considered for this case. In the first scenario, it is assumed that overvoltage would not pose any problem and PVs can generate power without voltage control. For this situation, Fig. 5.7 shows all node profile voltages. It can be seen that the voltage for nodes 5 and 6 pass the maximum permissible voltage limit between t=5.5 s and t=10.5 s. Although this situation is not realistic, it is only included for comparison purpose. Assume the efficiency of PV inverters is equal to 0.95. The RE energy whole network which is injected by PV inverters between t=0s and t=12 s is equal to 0.21413 kWh for this scenario. If the energy yield defined to be as the value of PV inverters injected power to the value of available PVs power, the energy yield for this scenario is equal to 0.9394.

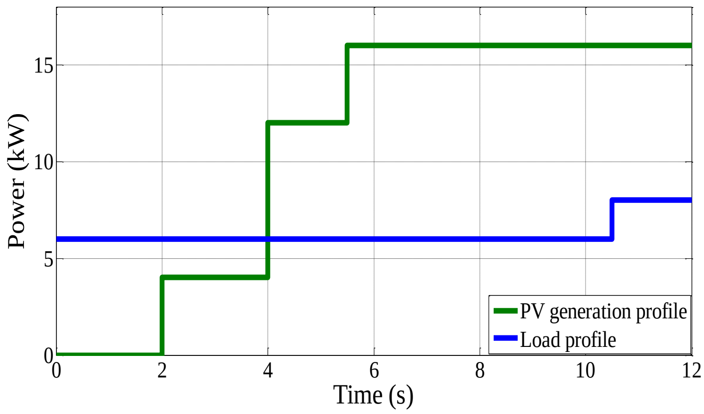


Fig. 5.6 Customer load and generation profiles.

For the second scenario, it is assumed that overvoltage protection is applied for each inverter and whenever the inverter bus voltage violates the maximum permissible limit, the PV inverter will trip and reclose after 5 s, that is if the PCC voltage is in permissible range [42]. With this strategy, the inverters in bus 5 and 6 will be unavailable between t=5.5 s and t=10.5 s which reduces the energy yield to 0.7481.

In the third scenario, the proposed operation approach is used. Fig. 5.9 shows the profile of nodes voltage, inverters active and reactive power in different time steps. The time sequence of operation for this case is as follows:

4- Between t=0 s and t=2 s, there is no generation and all voltages are in desirable voltage range. As a result, network is in normal operating mode.

5- Between t=2 s and t=4 s, there is of 4 kW available for each PV, and voltage of all nodes are still within the desirable range. As a result, the customers try to maximize their injection to the network.

6- At t=4 s, the inverters active power pass the $0.5\times P_{PVi}^{max.}$ limit and inverters start to absorb reactive power with the noted characteristic. The network is still in normal operating mode.

7- At t=5.55 s, voltage in nodes 5 and 6 pass the maximum critical limit. Therefore, customers in these nodes start to curtail their injection.

8- At t= 6 s, the emergency state is sensed by EMS in critical node. As a result, this EMS turns on VC flag and initiate consensus algorithm to reduce its node voltage to less than 252 V.

9- After 44 ms, the contribution of each customer for voltage reduction, using controllable devices is determined. These values are listed in Table 5.4. It can be seen that all customers contribute with the same ratio, regarding their maximum available controllable power (objective 2 is achieved). By applying this contribution, critical node voltage become less than maximum critical limit at t=6.88 and RE curtailments are avoided (objective 1 is achieved).

10- At t=10.5 s, customers loads are increased which make the critical node voltage to become less than maximum desirable voltage limit.

11- At t=11s, EMS of the customer in critical node sense its voltage is in normal state which means that all voltages are in normal state. Therefore, it turns off the VC flag. In this case, it is assumed that the worst case scenario happens and all customers disconnect all their controllable devices which cause voltage rise again. However, results show that the voltages are still less than maximum critical limit which are acceptable.

Application of the proposed method in this paper can provide an energy yield of 0.9357. This approximately increases the energy yield by 20% compared to the case with overvoltage protection, thereby saving a large amount energy on a large scale.

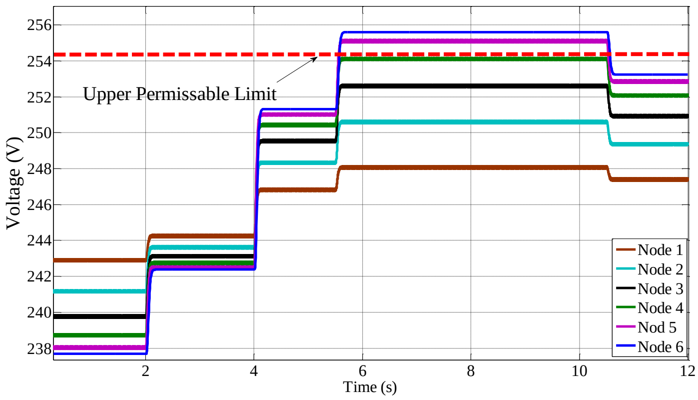
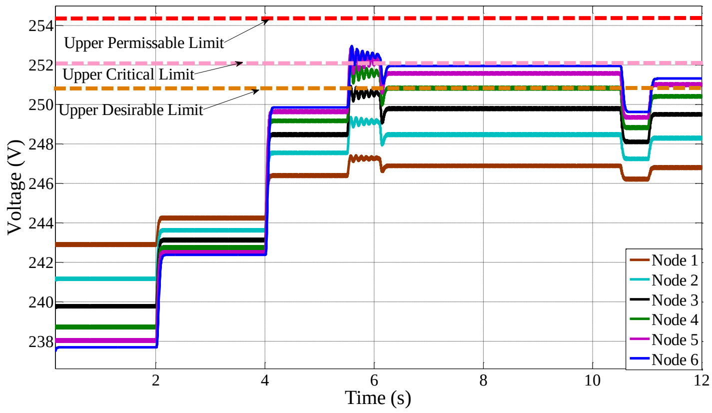
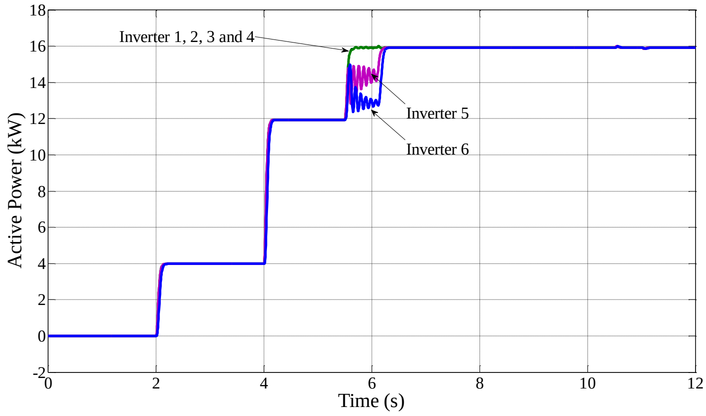


Fig. 5.7 Nodes voltage (conventional operation).



(a)



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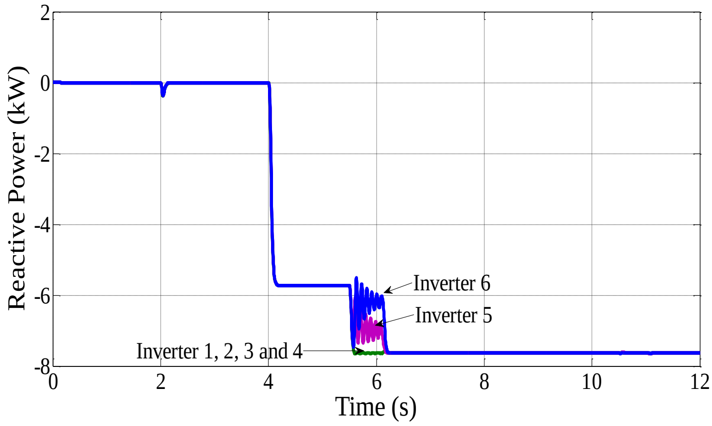


(c)

Fig. 5.8 Proposed voltage control approach, (a) nodes voltage, (b) Inverters active power, (c) Inverters reactive power.

Table 5.4 Contribution of controllable devices in each node.

Node	1	2	3	4	5	6
Controllable power (kW)	2.07	2.41	2.76	2.07	1.04	0.69
Ratio ($\frac{P_{cdi}}{P_{cdi}^{\max.}}$)	0.69	0.69	0.69	0.69	0.69	0.69

5.5.2. Case 2

In this case, the effect of communication drop on the proposed approach is studied. The same case study is considered, and it is assumed that the communication link between customers 4 and 5 is time-varying due to communication malfunction as shown in Fig. 5.9. As shown in Fig. 5.10, at t=5.56 voltages at nodes 5 and 6 pass the critical limit and customers in these nodes start to curtail their active power. At t=6 s, consensus algorithm is initiated to find the contribution of each customer for voltage reduction. However, due to the communication drop, only customers in node 5 and 6 can be coordinated for voltage reduction. As shown in Table 5.5, they contribute with their maximum available power while the voltage at node 6 is still more than maximum critical limit and there are nearly 1.3 kW active power curtailments for customers in this node.

At t=7 s, again emergency state is sensed by EMS at critical node and consensus algorithm is initiated. However, there is no available controllable power to be coordinated. At t=7.5 s, the communication link between customers in node 4 and 5 becomes available. Consequently, at t=8 s consensus algorithm coordinates the controllable devices of customers in other nodes. Their contribution is shown in Table 5.5. by applying these contributions, voltage at node 6 becomes less than 252 V and curtailment is avoided. The energy yield for this case is equal to 0.9331.

The result of this case shows that the communication issues can only affect the efficiency of voltage reduction and robustness of the proposed control approach does not depend solely on communication availability.

5.6. Conclusion

This paper proposes a new joint coordination approach for the operation of LV network to deal with voltage rise issue. Mixed distributed and localized control strategies have been used to avoid overvoltages in LV network. With this method, two operating modes (normal and voltage control) have been introduced for LV network which were established to assist the application of method proposed in this paper. This approach was applied to a typical residential LV network and the results show the effectiveness of the proposed approach to resolve the voltage rise issue in LV network. It is worth noting that the same strategy can be applied for other operational goals such as undervoltage prevention and peak load shaving which will be considered in future research work.

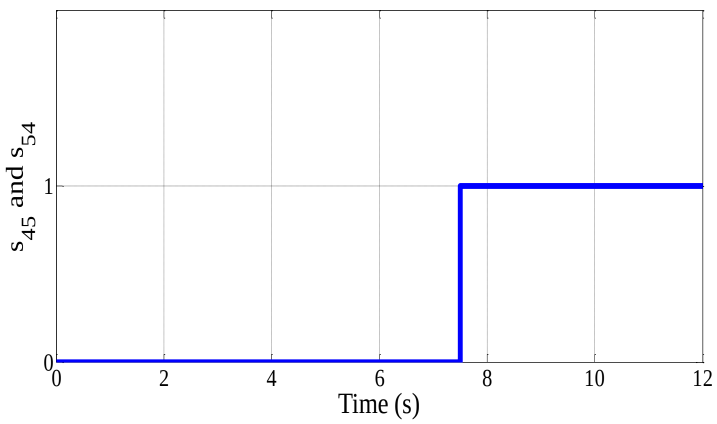
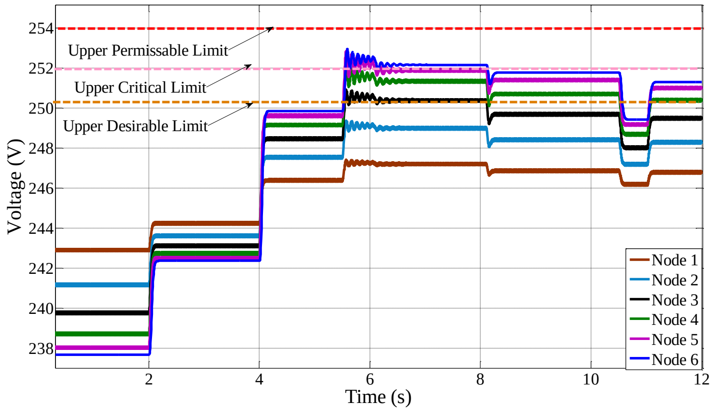


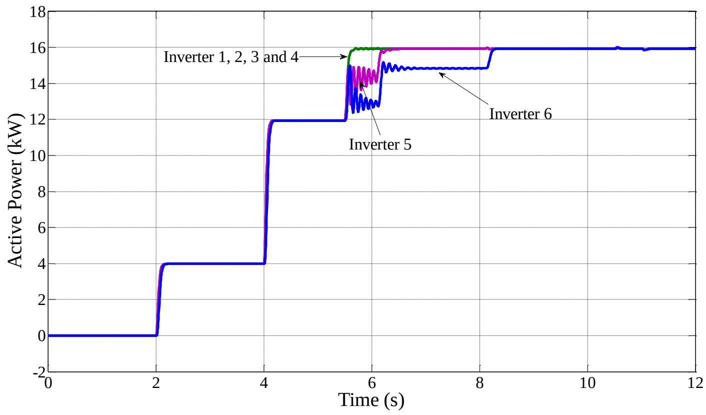
Fig. 5.9 Communication link between customers 4 and 5.

Table 5.5 Contribution of controllable devices in each node.

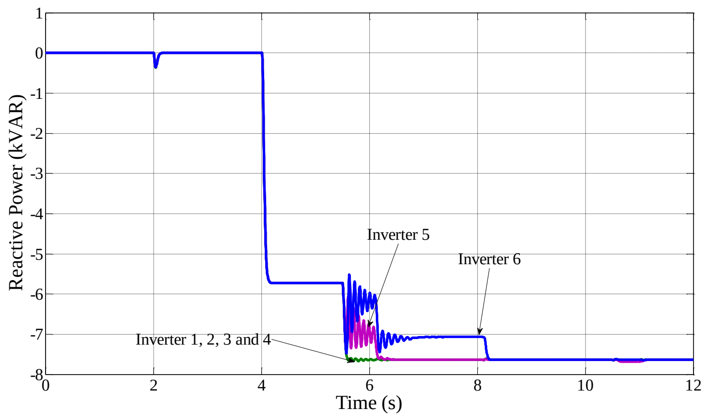
Node	1	2	3	4	5	6
Controllable power (kW)	2.00	2.33	2.66	2.00	1.50	1.00



(a)



(b)



(c)

Fig. 5.10 The effect of communication drop on the proposed voltage control approach, (a) nodes voltage, (b) Inverters active power, (c) Inverters reactive power.

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Statement of Contribution of Co-Authors

The authors listed below have certified that:

They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publications;

There are no other authors of the publication according to these criteria;

Potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit;

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In the case of this chapter:

Overvoltage and Overloading Prevention Using Coordinated PV Inverters in Distribution Network

To be submitted to IECON 2014.

Contributor	Statement of contribution
Ghassem Mokhtari 21 May 2014	Proposed the control strategy. Develop the control strategy regarding the simulation and data analysis. Wrote the manuscript.
Ghavam Nourbakhsh	Aided data analysis and simulation
Gerard Ledwich	Aided data analysis and writing the paper
Arindam Ghosh	Aided data analysis and writing the paper

Supervisor Confirmation

I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

Prof. Arindam Ghosh
Name Signature Date: 2 Jan. 2014

Chapter 6

Overvoltage and Overloading Prevention Using Coordinated PV Inverters in Distribution Network

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To be submitted to IECON 2014.

Abstract- Overvoltage and overloading due to high utilization of PVs are the main power quality concerns for future distribution power systems. This paper proposes a distributed control coordination strategy to manage multiple PVs within a network to overcome these issues. PVs reactive power is used to deal with overvoltages, and PVs active power curtailment are regulated to avoid overloading. The proposed control structure is used to share the required contribution fairly among PVs, in proportion to their ratings. This approach is examined on a practical distribution network with multiple PVs.

6.1. Keywords

Consensus algorithm, overloading, PV, overvoltage.

.

6.2. Introduction

Power quality challenges caused by high utilization of PV sources are the main concerns for utilities around the world [1]. The main concerns include overvoltages and overloading [2-9] in the period of high generation. These problems constitute the major cause of renewable energy capacity limitation in future distribution systems planning.

As listed in literature, using resources in distribution network such as PVs active and reactive power [10], controllable loads [11, 12], DSTATCOMs [13] and energy storage units [14] has promising features to avoid such issues.

This paper proposes an effective approach for regulating PV active and reactive power, according to the network voltage and loading requirements. Consensus algorithm is used as the coordination strategy to avoid overvoltages and overloading in distribution network. PVs active power curtailment are regulated to keep the injected power in acceptable range while the contribution of PVs reactive power are coordinated to reduce overvoltage in the network. The main contributions of this work include: 1- designing of a new internal control structure for PVs to adapt for coordination, and 2- Applying the consensus control strategy to share the contribution fairly among PVs in distribution network.

6.3. Proposed Approach

Consensus algorithm is a promising distributed control approach to manage a network with multiple devices. References [15, 16] manage multiple robots using this control algorithm. In reference [17], this algorithm harmonise unmanned devices for fire monitoring. This algorithm has also been applied to power system as well. Reference [10] uses this algorithm as a supplementary control to coordinates batteries within low voltage network and avoid voltage rise issue. In reference [14], this algorithm is used to coordinate storage units for loading management in distribution network. The main feature of this algorithm is its sharing ability among multiple devices.

This algorithm was applied in this paper using the following scheme. Every PV is supported by a control agent who determines the reference value for active and reactive power. There also exists a communication system among the control agents of neighbouring PVs. Additionally, a higher control agent, named the leader, is used to initiate the coordination of PVs. The structure for leader control agent is shown in Fig. 6.1. For the purpose of managing the voltage at all buses, critical bus voltage (*Vc*) is assigned as the controlling variable and the aim is to keep this bus voltage less than a critical limit ($V^{critical}$).

The injected apparent power to the upper voltage level network is termed *S*, where a part of the control strategy is to keep this value less than $S^{critical}$, for overloading prevention.

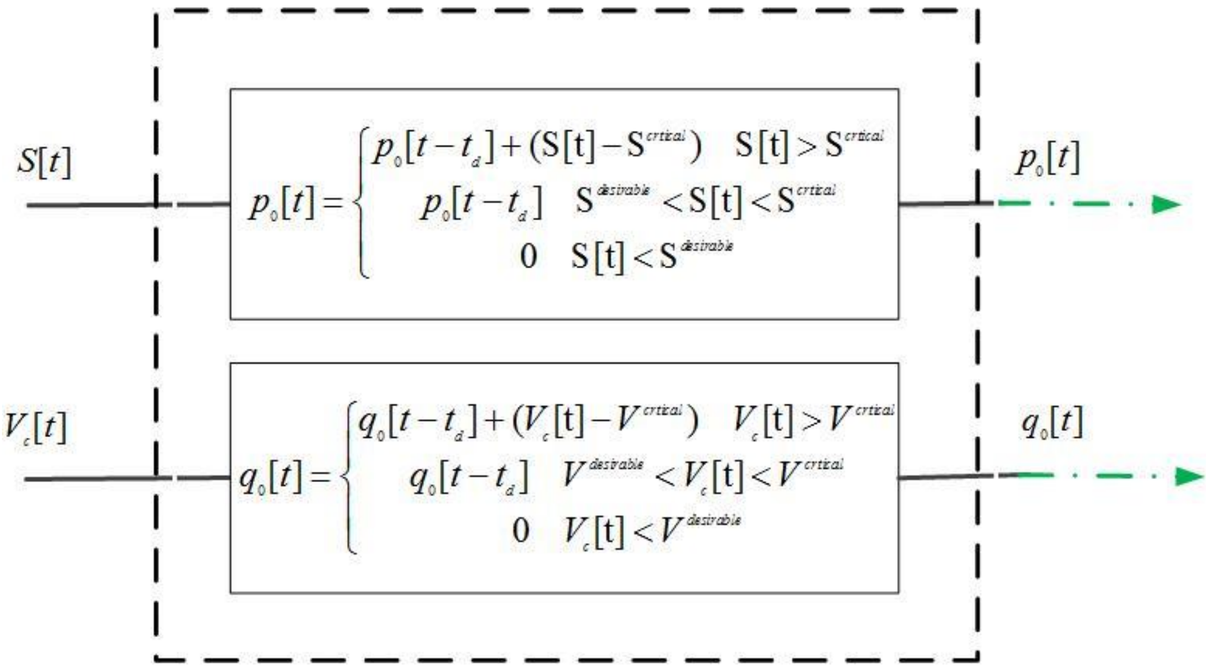


Fig. 6.1 Proposed control structure for leader.

The structure of PV control agent is shown in Fig. 6.2. Every PV control agent has parameters named information state based on consensus algorithm. The information state for active power is shown by p_i and for reactive power is shown by q_i .

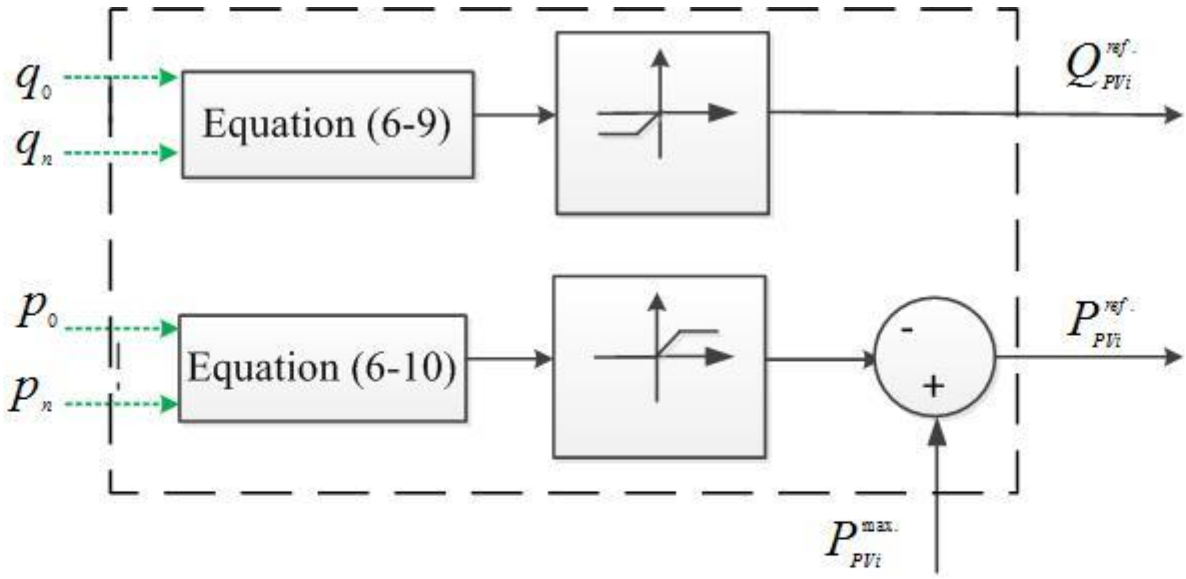


Fig. 6.2 Proposed control structure for control agent of each PV.

In our proposed approach, reactive power absorption using PV inverters are utilized to avoid overvoltages. The control design goal is to reduce the critical bus voltage less than $V^{critical}$, when this limit is violated. In other words, when critical bus voltage violates $V^{critical}$, the PVs coordination needs to be initiated, and when the critical bus voltage is less than $V^{desireable}$, the coordination needs to be stopped. Additionally, a relationship describing the sharing of reactive power among inverters, similar to equation (6.1) in this paper, needs to be achieved.

$$\frac{Q_{PV1}}{Q_{PV1}^{max.}} = \frac{Q_{PV2}}{Q_{PV2}^{max.}} = ... = \frac{Q_{PVn}}{Q_{PVn}^{max.}} \tag{6.1}$$

where Q_{PVi} is the reactive power of ith PV and $Q_{PVi}^{max.}$ is the maximum available reactive power of the same PV.

In order to achieve these goals, the information state for reactive power of leader is determined equation (6.2), when the critical bus voltage passes $V^{critical}$ limit.

$$q_0[t] = q_0[t - t_d] + k_q.(V^{critical} - V_c[t]) \tag{6.2}$$

In addition, based on consensus algorithm [16], the information state of reactive power for each PV is determined as:

$$q_i[t] = \sum_{k=0}^{n} c_{ik}[t - t_d].q_k[t - t_d] \tag{6.3}$$

where $c_{ik}[t]$ is a coefficient which depends on communication structure as shown in (6.4) [14]:

$$c_{ik}[t] = \frac{l_{ik}[t-t_d]}{\sum_{j=0}^{n} l_{ij}[t-t_d]} \tag{6.4}$$

where l_{ij} equals to 1 if there is communication link between *i*th and *j*th control agents, and zero otherwise.

Correspondingly, to manage the loading of the network, a set of similar goals need to be achieved for the associated controllable variables. Consequently, equations (6.5) and (6.6) need to be achieved for the purpose of this control design.

$$S(t) < S^{critical} \tag{6.5}$$

$$\frac{P_{PV1}}{P_{PV1}^{\max.}} = \frac{P_{PV2}}{P_{PV2}^{\max.}} = ... = \frac{P_{PVn}}{P_{PVn}^{\max.}} \tag{6.6}$$

where P_{PVi} is the active power of *i*th PV and $P_{PVi}^{\max.}$ is the maximum available active power for the same PV.

In order to meet the noted goals, the information state of active power for control agents need to be updated in the same time step as in equations (6.7) and (6.8), respectively.

$$p_0[t] = p_0[t-t_d] + k_p.(S[t] - S^{critical}) \tag{6.7}$$

$$p_i[t] = \sum_{k=0}^{n} c_{ik}[t-t_d].p_k[t-t_d] \tag{6.8}$$

The reference values for active and reactive power of PVs are updated as functions of information state, shown in equations (6.9) and (6.10).

$$Q_{PVi}^{ref.}[t] = q_i[t] \times Q_{PVi}^{\max.} \tag{6.9}$$

$$P_{PVi}^{ref.}[t] = P_{PVi}^{\max.} \times (1 - p_i[t]) \tag{6.10}$$

It is worth nothing that to avoid curtailments for PVs (equation (6.10)), storage units can be added beside PV units and the reference value for storage active power ($P_{Bi}^{ref.}$) can be determined as equation (6.11).

$$P_{Bi}^{ref.}[t] = p_i[t].P_{PVi}^{\max.} \tag{6.11}$$

6.4. Case Studies

A network with multiple PVs is used to examine this approach [18]. The network and communication structure is shown in Fig. 6.3. The value of load in each node and PV rating are listed in Table 6.1 and 6.2, respectively. In this application, the generation profile shown in Fig. 6.4 is considered for each PV. The threshold limits for voltage and network loading are listed in Table 6.3 and 6.4, respectively.

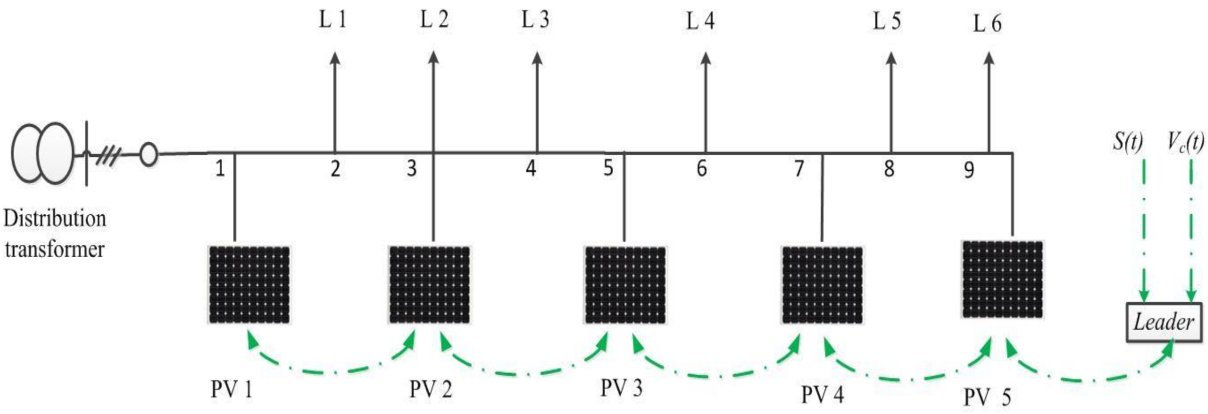


Fig. 6.3 Distribution network schematic diagram.

Table 6.1 Load information.

Load	L1	L2	L3	L4	L5	L6
Active power (kW)	34.6	36.5	47.4	39.5	41.3	27.3
Reactive power (kVAR)	9.2	5.8	9.7	6.3	12.2	7.8

Table 6.2 PVs rating.

PV	PV1	PV2	PV3	PV4	PV5
Active power (kW)	550	600	500	450	650
Reactive power (kVAR)	275	300	250	225	325

Table 6.3 Voltage limits in the proposed approach.

Parameter	Voltage (kV)	Voltage (pu)
$V^{permisIable}$	10.6	1.06
$V^{critical}$	10.5	1.05
$V^{desirable}$	10.4	1.04

Table 6.4 Network loading limits in the proposed approach.

Parameter	Power (kVA)	Power (pu)
$S^{permissible}$	2000	2
$S^{critical}$	2000	2
$S^{desirable}$	1500	1.5

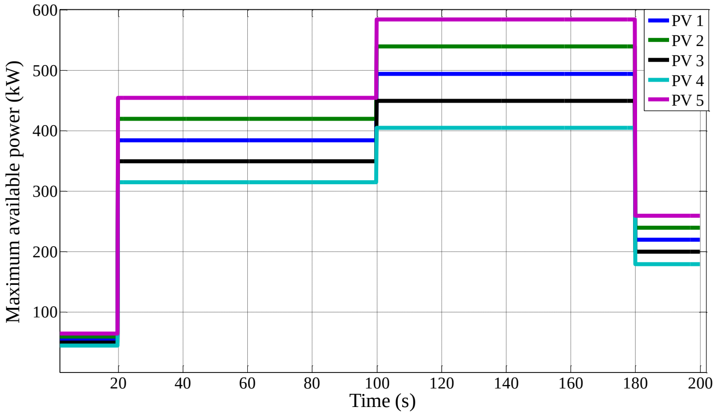
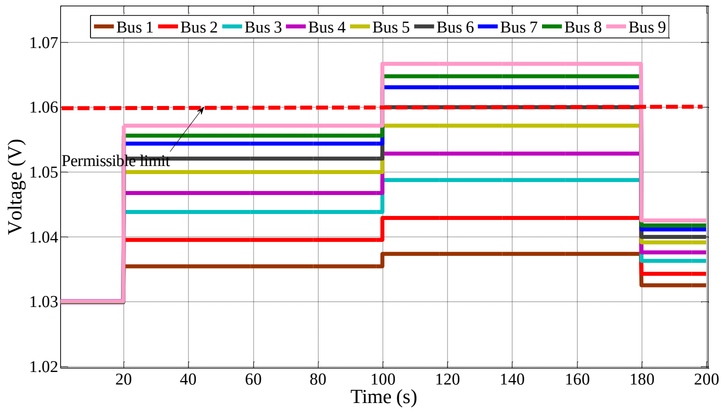
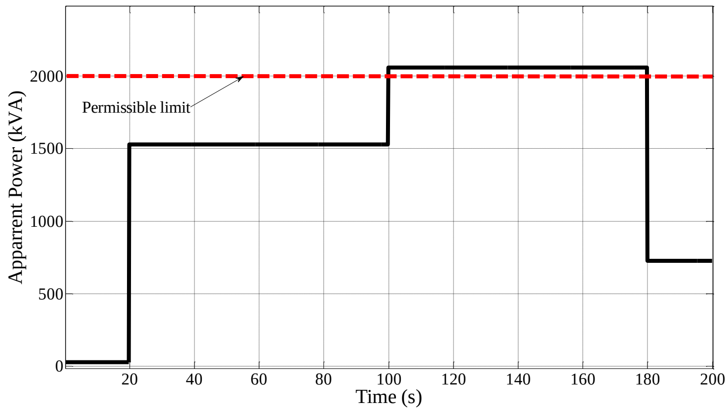


Fig. 6.4 PVs Generation profile.

Fig. 6.5 shows the bus voltages and injection to the higher grid when no control is applied. It can be seen that there is overvoltage in buses 6, 7, 8 and 9 between t=100 s and t=180 s. Furthermore, the injection to the higher grid, as seen in Fig. 6.5, is more than its permissible limit (2000 kVA) in the same period.



(a)



(b)

Fig. 6.5 Traditional operation, (a) Bus voltages, (b) network loading.

Using the proposed control approach, the results in Fig. 6.6 show the bus voltages (a), network loading (b), PVs active power (c), and PVs reactive power (d), in different time steps. As shown in this figure, between 0 s and 20 s, all voltages and loading are in desirable range and PVs are injecting their maximum active power with no required coordination. However, at t=20 s, the PVs injection rise and the critical bus voltage passes $V^{critical}$. Consequently, leader control agent initializes the coordination of PV inverters reactive power to reduce the voltage. At t=68 s, the critical bus voltage become less than $V^{critical}$ while fair sharing of PVs reactive power is achieved, as listed in Table 6.5. Then, at t= 100 s, the critical limit for both voltage and network loading is violated and coordination for managing both issues are initiated. Same as, and in addition to the last case, leader control agent also initializes the coordination of PV active and reactive power. The required contribution is listed in Table 6.5 and 6.6. Finally, at t=180 s, all the voltages and network loading go to the desirable range and PVs start to maximize their injection without any coordination.

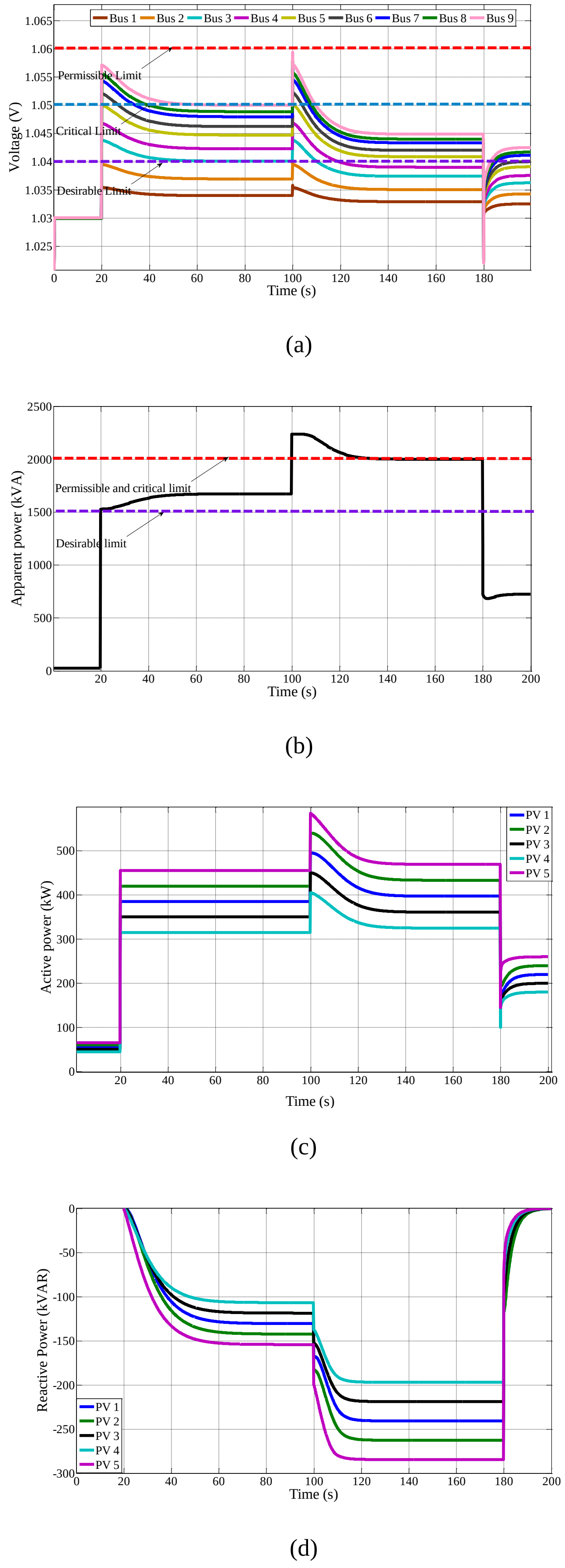


Fig. 6.6 Proposed control approach, (a) bus voltages, (b) network loading, (c) PVs active power, (d) PVs reactive power.

Table 6.5.PVs reactive power in different time interval.

	Q_{PV1}	Q_{PV2}	Q_{PV3}	Q_{PV4}	Q_{PV5}	$\frac{Q_{PVi}}{Q_{PVi}^{\max.}}$
0-20s	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0*
20-100s	*130.45*	*142.32*	*118.61*	*-106.74*	*154.17*	*0.47*
100-180s	*240.67*	*262.55*	*218.79*	*196.91*	*284.43*	*0.87*
180-200s	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0*

Table 6.6.PVs active power in different time interval.

	P_{PV1}	P_{PV2}	P_{PV3}	P_{PV4}	P_{PV5}	$\frac{P_{PV1}}{P_{PV1}^{\max.}}$
0-20s	*55.00*	*60.00*	*50.00*	*45.00*	*65.00*	*1.00*
20-100s	*385.00*	*420.00*	*350.00*	*315.00*	*455.00*	*1.00*
100-180s	*397.23*	*433.34*	*361.12*	*325.00*	*469.46*	*0.80*
180-200s	*220.00*	*240.00*	*200.00*	*180.00*	*260.00*	*1.00*

6.5. Conclusion

This paper proposed a distributed control coordination technique to manage the voltage rise and overloading in presence of high PV penetration in distribution systems. In this method, the resources including PVs active and reactive power were used to overcome these issues. PVs active power curtailment was coordinated to avoid overloading while PVs reactive power was utilized to deal with overvoltages. This approach was examined by applying the method to a distribution network with multiple PVs, and the results given in this paper confirm that the methodology is suitable for the intended outcome. Therefore, this method successfully proved to be effective in resolving overvoltage and loading issues arising from increased PV penetration in distribution systems.

6.6. References

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Statement of Contribution of Co-Authors

The authors listed below have certified that:

1- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

2- They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publications;

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In the case of this chapter:

A New PV Reactive Power Control to Improve Voltage Profile of Distribution Network

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Contributor	Statement of contribution
Ghassem Mokhtari	Proposed the control strategy. Develop the control strategy regarding the simulation and data analysis. Wrote the manuscript.
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Ghavam Nourbakhsh	Aided data analysis and writing the paper
Gerard Ledwich	Aided data analysis and writing the paper
Arindam Ghosh	Aided data analysis and writing the paper

Supervisor Confirmation

I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

Prof. Arindam Ghosh
Name Signature Date: 2 Jan. 2014

Chapter 7

A New PV Reactive Power Control to Improve Voltage Profile of Distribution Network

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Abstract- This paper proposes a new approach to manage the reactive power generated by PV inverters efficiently to avoid under and over voltage violations in distribution network. In this approach, control agents use the local information for robust voltage control, and through distributed communication they also use neighbouring information to coordinate all PVs reactive power for voltage support. The proposed method is applied to IEEE 33 bus system with various operating situations, and the results are shown to prove the effectiveness of this approach.

7.1. Keywords

Distribution Network, Voltage Support, PV, AVR control loop.

7.2. Introduction

There is special interest among researchers to study the adverse impacts of high penetration of PVs on future electricity grid [1]. The main problem recognized by researchers is voltage violation. This issue normally is experienced in situations as described in the following. In periods of peak load, while PVs output power are low, voltage drop can occur along the network [2]. Additionally, in periods of high generation, reverse power may result in voltage rise in the network [3-9]. These issues are the main concerns for the planners of future electricity networks [10].

The suggested strategies to avoid these issues include; network reinforcement [11-13], PVs power curtailment [14], utilization of controllable devices such as batteries [15-22] which include investment cost or loss of energy.

Currently, a lot of research works on this topic are being conducted which are centred around PV reactive power for voltage support. In this regard, three control structures are applied in literature. The first structure is supervisory control in which usually optimization algorithms are used to have efficient voltage support. Reference [23] uses a linear programming formulation to find the optimal power factor of PV generator to prevent voltage limits violation. Other algorithm such as Artificial Neural Network (ANN) [24], Fuzzy logic [25], State Machine concept [26] and multifrontal algorithm [27] are also utilized to coordinate various components for voltage support in distribution network in an optimal way. The supervisory control is efficient while it requires fast algorithms and reliable communication links [28]. The localized control structure use local information to control the network. For example, in [29], it is proposed that PV inverter power factor can be changed in local mode based on PV bus voltage. In [30], droop-based voltage control is proposed to regulate PV inverter reactive power. In this control structure, while the voltage control is designed to be robust, but it is not efficient [31]. In addition, the interaction among the local controllers may lead to stability issue [30]. The third approach as distributed control structure uses neighbouring resources information for effective network voltage support.

This paper uses a voltage control strategy based on both localized and distributed control structures where PVs inverter reactive power are effectively managed for voltage support in distribution network. This approach was previously applied to storage unit for voltage support in [31]. However, the main novelties of this paper include: 1. The application of this control structure for PV reactive power for voltage support, demonstrating its effectiveness compared with other approaches. 2. Advantage of this method in improving the utilization of other voltage support devices, such as AVR control loop and On-Load Tab Changer (OLTC).

7.3. Problem Definition

The acceptable voltage tolerance for distribution network is within ± 5-10% [32]. Distribution networks are planned to have the voltage within these standard limits. However, during peak generation period the upper permissible voltage limit ($V^{upper\_permissible}$) can be violated in critical buses [32]. Additionally, lower permissible voltage limit ($V^{lower\_permissible}$) can also be violated in peak load period [10].

As PV units are interfaced to the grid with inverters, they can contribute in voltage support using their reactive power. The internal control structure of a PV, with various coordination strategies, is shown in Fig. 7.1. As shown in this figure, Maximum Power Point Tracking (MPPT) algorithm determines the reference value for PV active power. The supervisory, localized and the proposed control can be achieved through this control structure for reactive power. In supervisory control structure, the reference value for PV reactive power is sent by central controller (u_i). As noted before, this reference value is usually computed to optimize the network operation such as minimizing the network loss.

In localized control structure, the reference value for PV reactive power is a function of local information such as PV bus voltage. One of the popular localized voltage approach is droop-based voltage control [30]. Based on this control approach, PVs regulate their bus voltage within a voltage range (between $V^{lower\_critcal}$ and $V^{upper\_critical}$). In other words, the voltage reference value at *i*th PV is a function of its reactive power, as in equation (7.1).

$$V_i^* = 1^{pu} - m_i.Q_i \tag{7.1}$$

where m_i is a droop factor which is determined by equation (7.2).

$$m_i = \frac{V^{upper\_critical} - V^{lower\_critical}}{Q_{si}^{max.}} \tag{7.2}$$

u_i in this case can be found by equation (7.3).

$$\dot{u}_i = k_{qi}.(V_i^* - V_i) \tag{7.3}$$

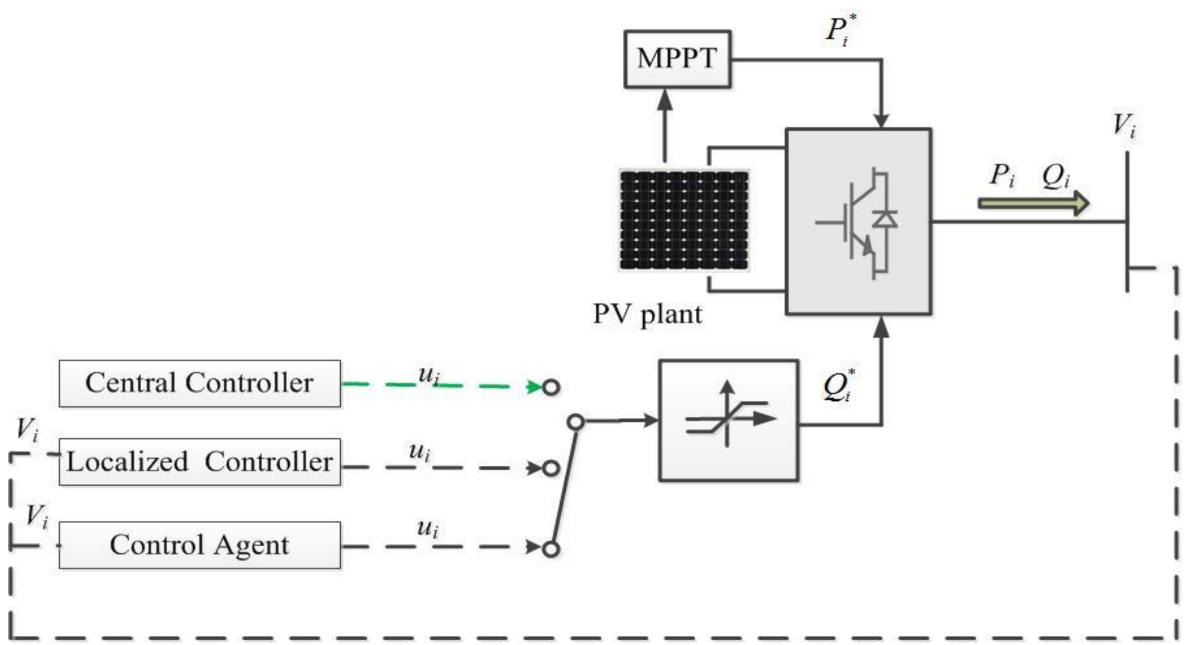


Fig. 7.1 Internal control diagram for PV system.

As noted before, both supervisory and localized control structures have their own drawbacks. To avoid these drawbacks, the approach in this paper is proposed to be applied. In this strategy, a control agent is introduced and used for each PV system, as shown in Fig. 7.1. This control agent provides the ability to apply the mixed localized- distributed control structure [31]. The details of this control structure are shown in the following section. Additionally, as most distribution networks are supported by OLTC transformers with Automatic Voltage Regulator (AVR), the proposed control structure is designed in such a way to have coordination with these components in distribution network. The model used for

OLTC transformer with AVR control loop is shown in Fig. 7.2 [24]. In this structure, the current and voltage at secondary side of OLTC transformer is used to approximate the voltage at critical bus (V^c), as given in equation (7.4). The aim here is to regulate the voltage at critical bus close to $V^{ref.}$, given in Fig. 7.2. For this purpose, the comparison of these two voltages is passed through a dead-band control. And finally, after applying a delay on control, the position of tap (up or down) is determined.

$$V^C = V_S + I_S * |Z_l| \tag{7.4}$$

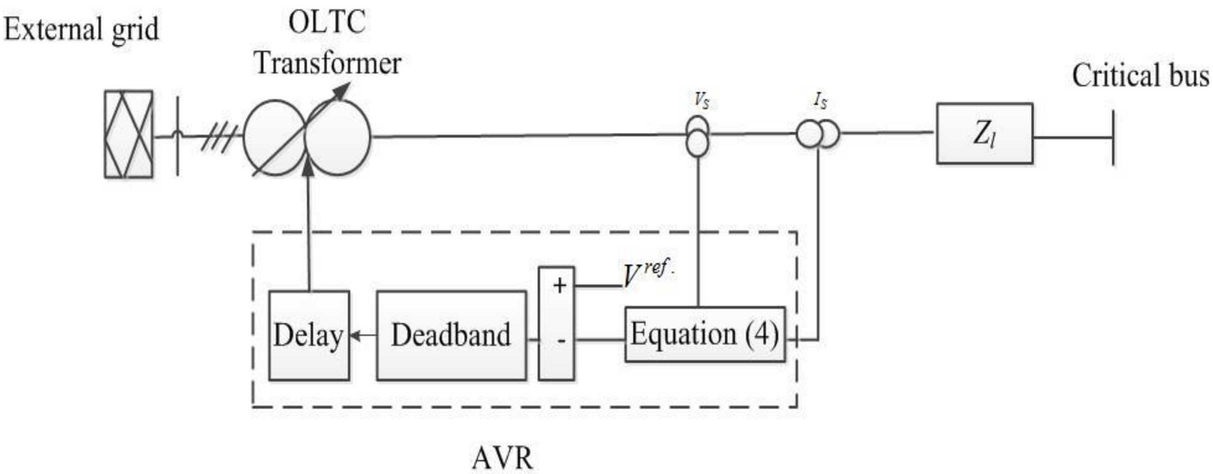


Fig. 7.2 OLTC transformer and AVR control loop [24].

7.4. Proposed Approach

In the proposed mixed control structure, all PVs use their local bus voltage information for robust voltage control. Furthermore, neighbouring PVs are communicating with each other to bring together all PVs for voltage support. The suggested control structure is shown in Fig. 7.3. It can be seen that there are two layers in the proposed structure, cyber and physical. In cyber layer, all PVs are supported by control agent that uses local and neighbouring information to control PVs reactive power. The whole cyber layer can be modelled by a time-varying matrix as *L(t)* given in equation (7.5).

$$L(t) = \begin{bmatrix} l_{11}(t) & l_{12}(t) & \dots & l_{1n}(t) \\ . \; . & & & . \; . \\ . \; . & & & . \; . \\ l_{n1}(t) & l_{n2}(t) & \dots & l_{nn}(t) \end{bmatrix} \tag{7.5}$$

Where;

$l_{ij}(t)$ =1 if *j*th control agent send information to *i*th PV at time *t*

$l_{ij}(t)$ =0 if *j*th control agent do not send information to *i*th PV at time *t*

and $l_{ii}(t)$=1for all control agents.

The same as droop-based control, the goal of this control structure is to keep the PV bus voltage within a range (between $V^{upper\_critical}$ and $V^{lower\_critical}$). Four limits are defined for voltage of PV buses. The voltages $V^{upper\_desirable}$ and $V^{upper\_critical}$ are provided as the network upper voltage operation indicators and $V^{lower\_desirable}$ and $V^{lower\_critical}$ as the lower voltage operation indicators. If all PV bus voltages are within $V^{lower\_critical}$ and $V^{upper\_critical}$, PVs coordination for reactive power is not required. However, if these limits are violated for any PV bus voltages, the suggested control method needs to bring the voltages less than these limits.

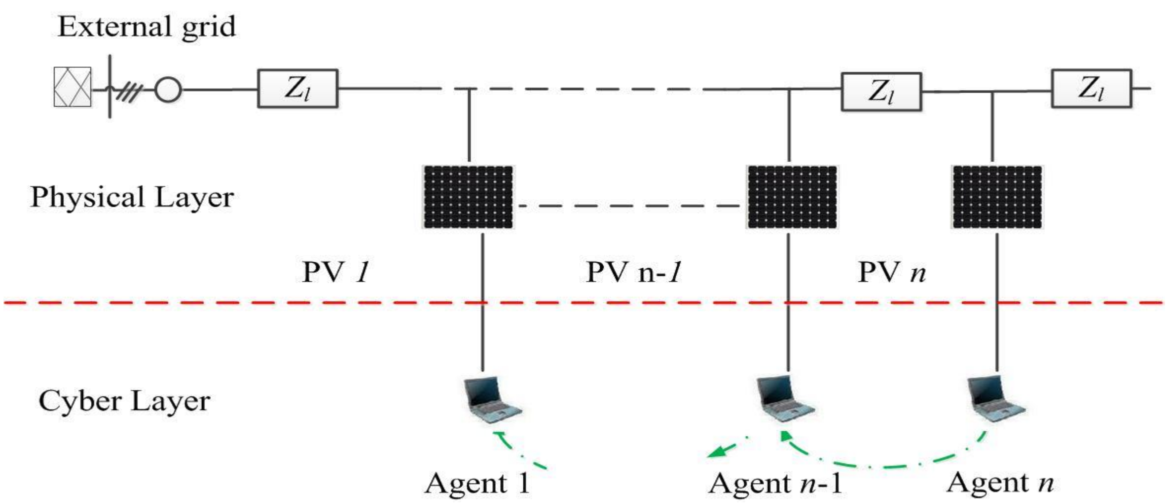


Fig. 7.3 Proposed network control structure.

In the proposed control structure, two control parameters are defined for each PV. The first one is y_i as the feedback control term for each PV, which is a function of local information, and q_i as the information control term which is communicated among neighbouring PVs. The control design for each PV (*u*) is a function of feedback control term and information control terms of neighbouring PVs, as in equation (7.6).

$$u_i(t) = f_i(l_{i1}(t).q_1(t),...,l_{ii}(t).y_i(t),...,l_{in}(t).q_n(t)) \quad (7.6)$$

The main goal of designing this control is to keep all PV bus voltages within critical limits, while achieving effective voltage support. Through this scheme, the PVs making higher effect on voltage will contribute more.

To achieve noted effective voltage support, the following control structure is proposed.

Firstly, the structure of each control agent given in Fig. 7.4 need to be used. All control agents are supported by 4 modules: Sensing, Communication, Computational and Actuating modules. The sensing module provides the local information of voltage while communication module provides the information control terms of neighbouring PVs. The computational module includes three parts. The first part computes the feedback control term based on the local information of voltage in the discrete time of t_d, this computation can be given as equation (7.7).

$$y_i[t]=\begin{cases} y_i[t-t_d]+k_i.(V^{\text{upper}\_critical}-V[t]) & V[t]>V^{upper\_critical} \\ y_i[t-t_d] & V^{upper\_desirable}<V[t]<V^{upper\_critical} \\ 0 & V^{lower\_desirable}<V[t]<V^{upper\_desirable} \\ y_i[t-t_d] & V^{lower\_critical}<S[t]<V^{lower\_desirable} \\ y_i[t-t_d]+k_i.(V^{lower\_critical}-V[t]) & V[t]<V^{lower\_critical} \end{cases} \quad i=1,...,n \tag{7.7}$$

The second part of computation module updates the information control term for each PV as a function of feedback control and information control terms of neighbouring PVs. To achieve the effective voltage support, it is proposed that the information control be updated based on equation (7.8).

$$q_i[t]=c_{ii}[t].y_i[t]+\sum_{j=1:n} c_{ij}[t].q_j[t-t_d] \tag{7.8}$$

where;

$$c_{ij}[t]=\frac{s_{ij}.l_{ij}[t]}{\sum_{k=1}^{n} s_{ik}.l_{ik}[t]} \tag{7.9}$$

where s_{ij} is the approximate sensitivity of voltage at ith PV bus to the reactive power at jth PV bus. These values, which are used for effective voltage support, can be found using Jacobean matrix as shown in [31].

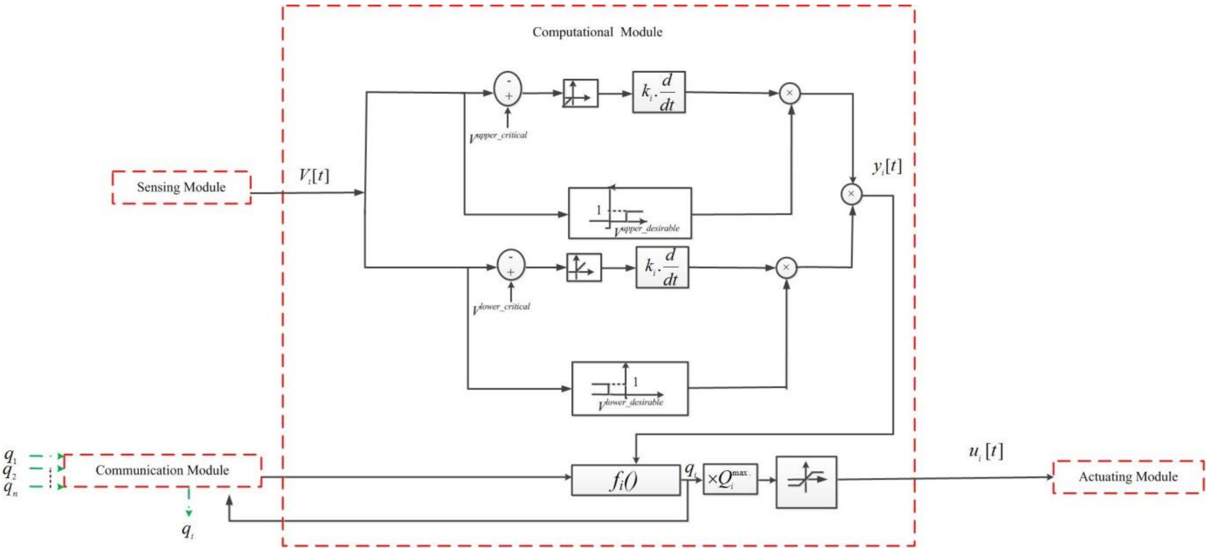


Fig. 7.4 Proposed control structure for each PV control agent.

Finally, in the third part of computational module, the required control for each PV is determined. In other word, the control term (*ui*) for each PV will be determined using equation (7.10), and will be sent to the actuating module.

$$u_i[t] = q_i[t] \times Q_i^{\max}. \tag{7.10}$$

The proposed control structure is summarized as a flowchart given in Fig. 7.5. This process can achieve the control goals for voltage support application.

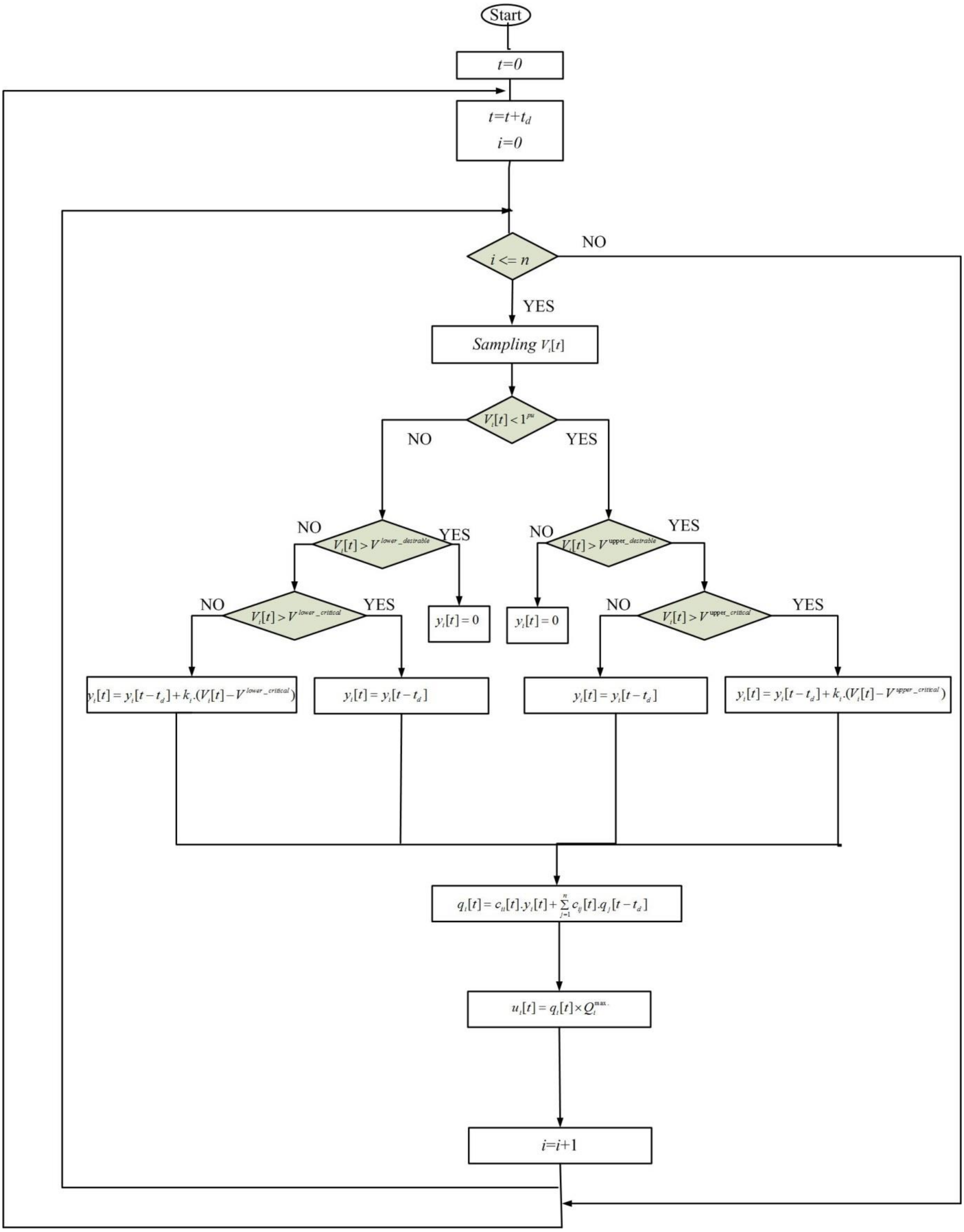


Fig. 7.5 Proposed distributed control strategy flow chart.

7.5. Case Studies

The standard test case of IEEE 33 bus distribution system is used to study the proposed control structure [33]. The network schematic with multiple PV plants is shown in Fig. 7.6. There are 8 PV plants with rating of 800 kW+j500 kVAR connected in this network. The load in each bus is given in Table 7.1. The voltage parameters, for the purpose of this application, are listed in Table 7.2.

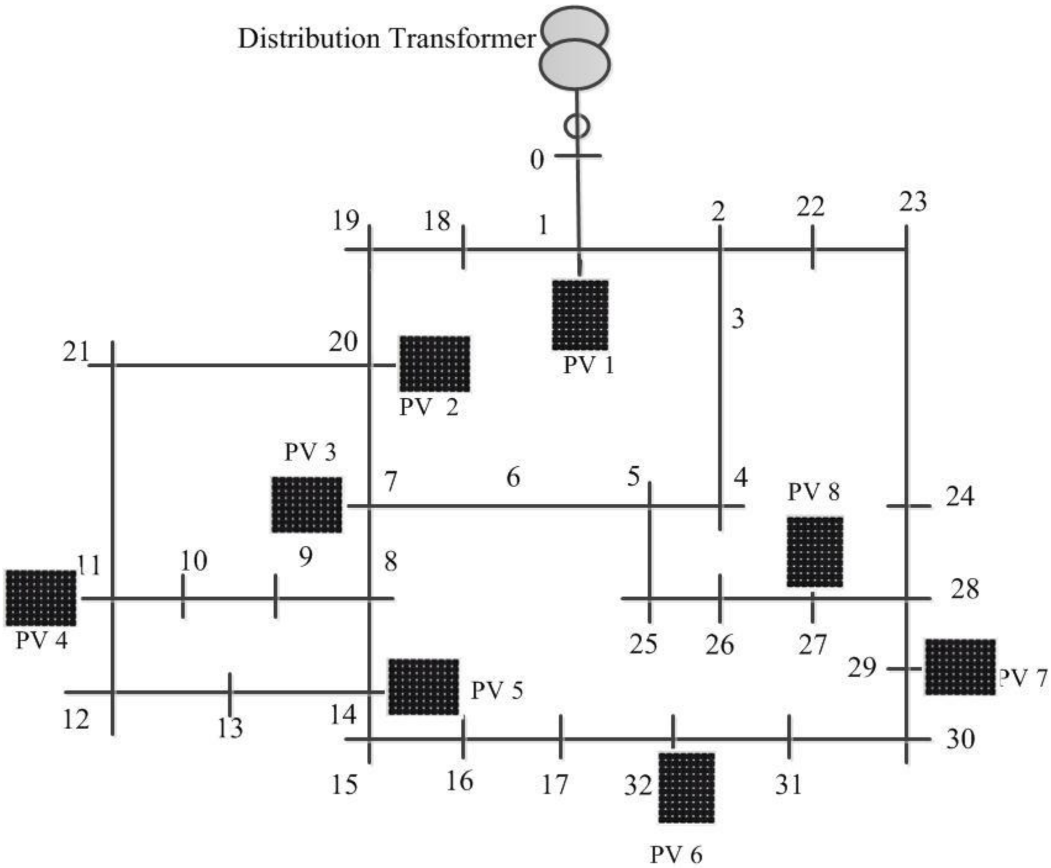


Fig. 7.6 IEEE 33 bus distribution system, case study.

Table 7.1 Loads at each bus.

Bus no.	Active Power (kW)	Reactive Power (kVAR)
1	100	60
2	90	40
3	120	80
4	60	30
5	60	20
6	200	100
7	200	100
8	60	20
9	60	20
10	45	30
11	60	35
12	60	35
13	120	80
14	60	10
15	60	20
16	60	20
17	90	40
18	90	40
19	90	40
20	90	40
21	90	40
22	90	50
23	420	200
24	420	200
25	60	25
26	60	25
27	60	20
28	120	70
29	200	600
30	150	70
31	210	100
32	60	40

Table 7.2 Voltage limits for the proposed approach.

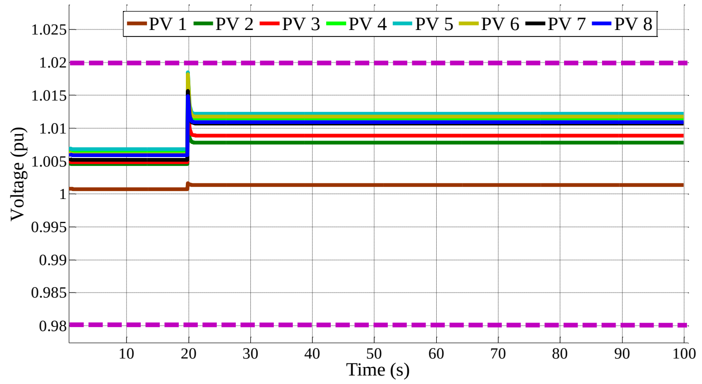
Parameter	Voltage (kV)	Voltage (pu)
$V^{upper\_critical}$	12.91	1.02
$V^{upper\_desirable}$	12.78	1.01
$V^{lower\_desirable}$	12.53	0.99
$V^{lower\_critical}$	12.40	0.98

7.5.1. Case 1

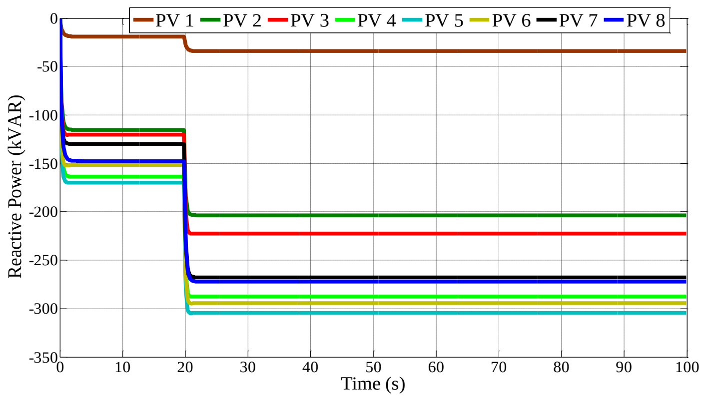
In this case, the advantage of the proposed control is examined compared with droop-based control for PV inverter [30]. It is assumed that the load in all buses are 25% of their maximum value and PVs generation is increased from 400 kW to 700 kW at t=20s. The results for the case of droop-based control are shown in Fig.7. 7. It is assumed that PVs need to regulate their bus voltage in a range of 0.98-1.02 pu using droop-based control of reactive power. It can be seen that for both states (before and after generation rise), the PV bus voltages are kept in the desired range, using PV inverter reactive power contribution as shown in Fig. 7.7 (b).

The same case was examined using the proposed control structure in this paper, where Fig. 7.8 shows the bus voltages and PVs reactive power contribution. The cyber layer is modelled as in equation (7.11) and the PVs interaction in this layer is happening at each 100 ms.

$$C(t)=\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{7.11}$$



(a)

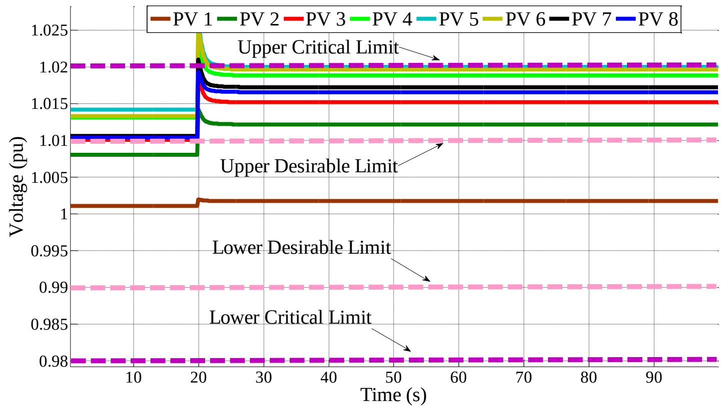


(b)

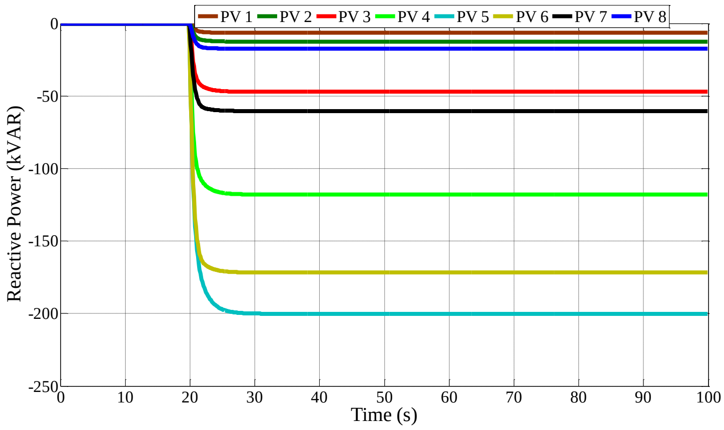
Fig. 7.7 Droop- based voltage control, (a) PV bus voltages, (b) PVs reactive power contribution.

Before generations increase, all voltages are less than critical limit without any reactive support in this strategy, as compared with the case of droop-based control with total required reactive power of 1026 kVAR. However, after generation step change, the voltage at buses 4, 5, 6 and 7 passes the upper critical limit. Therefore, control agents at these buses initialize the coordination of PVs for voltage support. After 13 s, the voltage of all PV buses reduced to less than the upper critical limit.

For both examined control approaches, PVs reactive power are listed in Table 7.3. As shown in this table, the proposed control structure results in much less reactive power contribution, compared with the droop based control, which proves to be an attractive proposition.



(a)



(b)

Fig. 7.8 Proposed approach, (a) bus voltages, (b) PVs reactive power contribution.

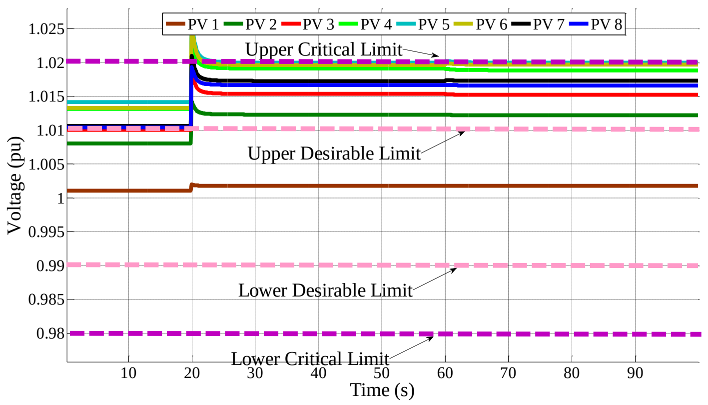
Table 7.3 PVs reactive power (kVAR) after generation step change.

PV no.	Droop-based approach	Proposed approach
1	-34.21	-6.46
2	-203.53	-12.50
3	-222.25	-47.13
4	-287.56	-117.96
5	-304.35	-200.14
6	-294.24	-171.73
7	-267.90	-60.37
8	-272.33	-17.39
Total	-1886.4	-633.68

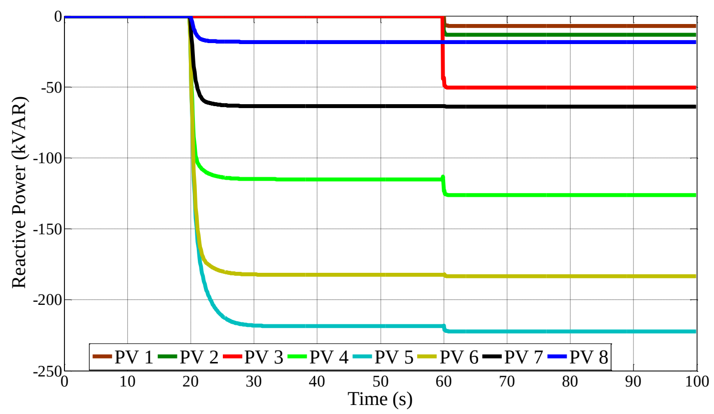
7.5.2. Case 2

There are two types of failure in the proposed control structure which include failure in physical layer and failure in cyber layer. In this case, the effect of failure in cyber layer is studied. The same example as in case 1 is considered, while it is assumed that the communication link between PVs 3 and 4 is not available during t=10-60s. As shown in Fig. 7.9, at t=20s, voltages at bus 4, 5, 6 and 7 pass the upper critical limits. However, due to the noted failure, voltage support can only be coordinated by PVs 4, 5, 6, 7 and 8, and they can reduce the violated voltage less than critical limit. At t=60 s, communication between PV 2 and 3 become available. At this stage, again PVs update their reactive power contribution. The total required reactive power needed at steady state of coordination equals to -684.69 kVAR which is more than the case with no communication failure.

Based on results in this case, it can be said that the failure in cyber layer does not impact the robustness of voltage control. However, it may reduce the utilization of available resources which can cause efficiency reduction.



(a)



(b)

Fig. 7.9 Proposed approach with communication drop, (a) bus voltages, (b) PVs reactive power contribution.

7.5.3. Case 3

The same system with combination of different network operation states, is simulated to examine the proposed control structure. The same generation and load profiles are considered for PVs and buses, with different percentages of their maximum value as given in Fig. 7.10. The results for different time intervals are shown in Fig. 7.11. The operation process is explained as follows:

1- In period of 0s-200s, no reactive contribution is needed as all voltages are fine.

2- At t=200s, injections to the grid rise while voltage at buses 5, 6 and 7 pass $V^{upper\_critical}$. Consequently, PVs reduce all the voltages less than critical limit at t=210s.

3- At t=300s, all voltages go to the desirable range which stop the PVs coordination.

4- At 500s, as the network is in peak load period, voltages at buses 3 to 8 violate the lower critical limit. Therefore, the PVs coordination starts to support the network voltage in peak load period.

5- Finally, at t=600s, voltages go to desirable range and coordination stops.

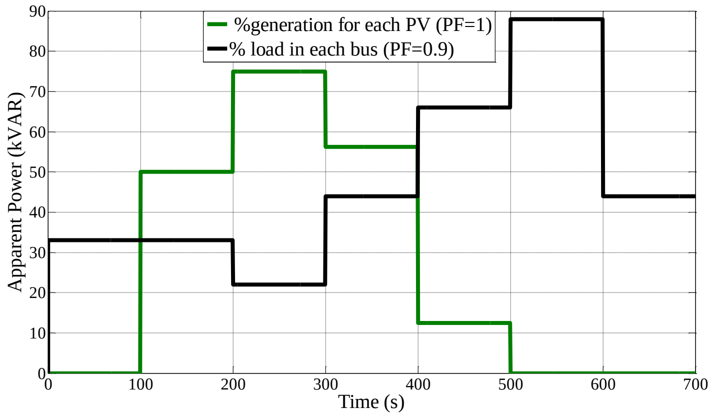
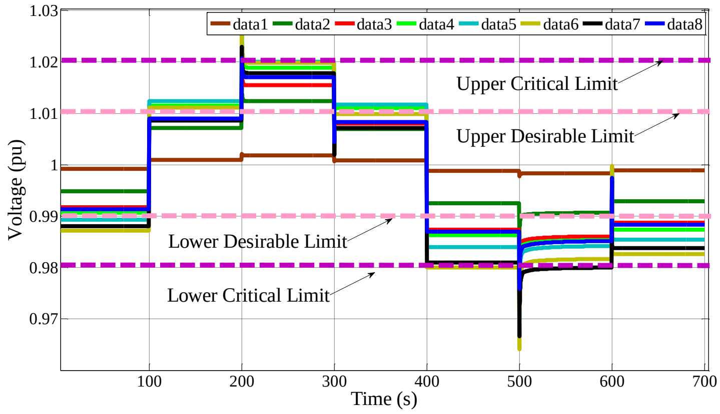
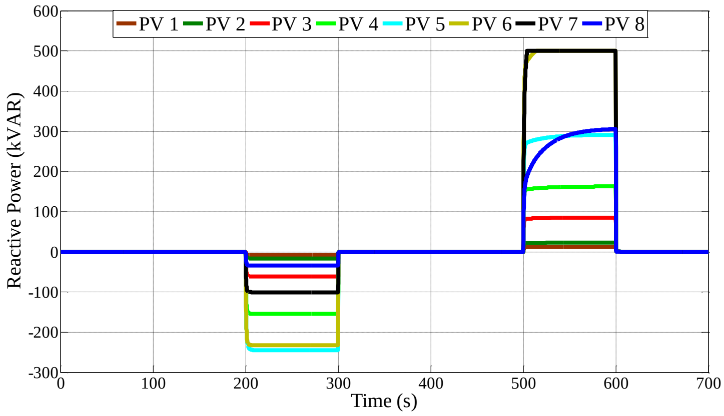


Fig. 7.10 Load and generation profiles.



(a)



(b)

Fig. 7.11 Proposed control approach, (a) bus voltages, (b) PVs reactive power contribution.

7.5.4. Case 4

In the last case, the aim is to show that the operation of the proposed approach can be in close coordination with other voltage supporter such as OLTC and AVR control loop. Case 3 is considered with the exception that it is assumed the distribution transformer is provided with OLTC and AVR control loop. The OLTC can operate in such a way that the secondary transformer voltage can be varied with a range from 0.94 pu to 1.06 pu, with 12 steps. The OLTC is considered to regulate the voltage at bus 32 as the critical bus voltage. The reference value for this voltage is set to 1 pu while the dead-band is set to 1%. To limit the simulation time, the delay time is set to 5s.

For the case with OLTC and AVR control loop, Fig. 7.12 shows the voltage at transformer secondary side and the voltage in all PV buses. It can be seen that the voltage at critical bus is nearly regulated in desirable range. However, the transformer tab is changing 6 times during the operation period.

The result for the case with proposed control structure and OLTC is given in Fig. 7.13. It can be seen that the number of transformer tap changing decreases to 3 times, which is attractive. In addition, it can be seen that the required reactive power in this operation mode is less than the case with no OLTC (case 3), for both high generation and peak load periods.

The results of this case showed that the proposed control structure in this paper can operate in great harmony with OLTC and AVR control loop to provide more effective voltage support.

7.6. Conclusion

This paper proposed an effective voltage support control structure to utilize multiple PV reactive power. The suggested approach mixed the localized and distributed control using communication facilitates to achieve robust and effective voltage control. This approach was applied to the IEEE 33 bus distribution system with various operational situations including cyber layer failure, and the results proved the effectiveness of the proposed control structure. Furthermore, it was also shown that this approach can operate in great harmony with other control scheme, to increase the overall effectiveness.

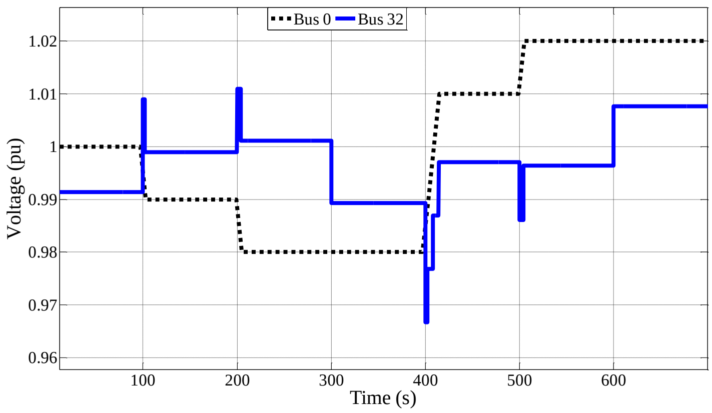
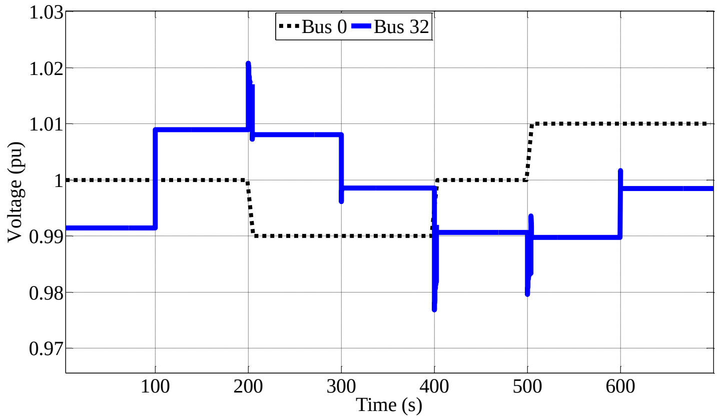
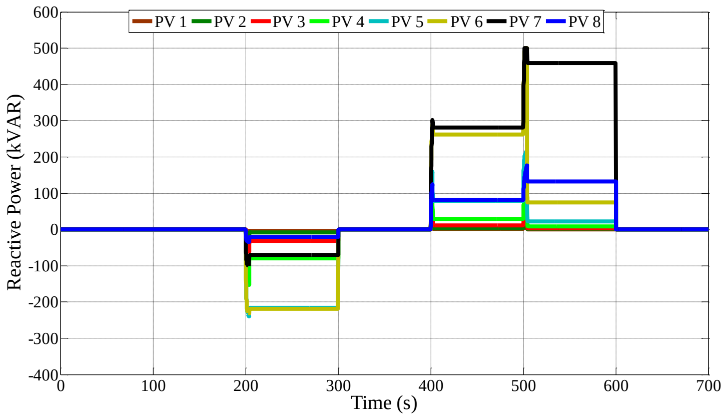


Fig. 7.12 Voltage profile when AVR is applied.



(a)



(b)

Fig. 7.13 Voltage profile when both the proposed approach and AVR are applied.

7.7. References

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Statement of Contribution of Co-Authors

The authors listed below have certified that:

6- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;

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8- There are no other authors of the publication according to these criteria;

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Smart Coordination of Energy Storage Units (ESUs) for Voltage and Loading Management in Distribution Networks

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Contributor	Statement of contribution
Ghassem Mokhtari G. Mokhtari 21 May 2014	Proposed the control strategy. Develop the control strategy regarding the simulation and data analysis. Wrote the manuscript.
Ghavam Nourbakhsh	Aided data analysis and writing the paper
Arindam Ghosh	Aided data analysis and writing the paper

Supervisor Confirmation

I have sighted email or other correspondence from all Co-authors confirming their certifying authorship.

Prof. Arindam Ghosh A ghosh
Name Signature Date: 2 Jan. 2014

Chapter 8

Smart Coordination of Energy Storage Units (ESUs) for Voltage and Loading Management in Distribution Networks

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Abstract- This paper proposes a distributed control approach to coordinate multiple ESUs to avoid violation of voltage and thermal constraints, which are some of the main power quality challenges for future distribution networks. ESUs usually are connected to a network through voltage source converters. In this paper, both ESU converters active and reactive power are used to deal with the above mentioned power quality issues. ESUs' reactive power is proposed to be used for voltage support, while the active power is to be utilized in managing network loading. Two typical distribution networks are used to apply the proposed method, and the simulated results are illustrated in this paper to show the effectiveness of this approach.

8.1. Index Terms

Distribution Network, Distributed Control, Network Loading management, ESU, Voltage support, Consensus Algorithm.

8.2. Introduction

As a sustainable solution for future energy crisis, it is anticipated that future distribution networks will see a widespread use of renewable energy sources such as PV, wind turbine and fuel cell [1]. Distribution networks with renewable energy sources can encounter two main challenges. A typical load curve for NSW in Australia [2] shows that during the peak load period, generation is normally low or zero, which may cause voltage drop along the network [3]. On the other hand, in peak generation period, when generated power exceeds the load, surplus power is injected to the grid. This will cause reverse power and hence may result in voltage rise along the network [4-6]. Additionally, in both peak generation and peak load periods, thermal constraints for line and power transformer can be violated [7].

The strategies suggested by researchers to avoid these issues can be divided in the following categories:

1- Network upgrading. References [8-10] propose the increase of conductor cross section to deal with voltage rise. This approach requires high investment cost which is not attractive for utilities.

2- Changing network static set points such as transformer tap changers [9, 11]. This approach is not practical due to randomness of load and generation which needs frequent changes of set points.

3- Active power curtailment [12], which reduces the energy efficiency.

The unbalance between the generated power and load, during both the high load and high generation periods, causes the noted issues [13]. As a result, the introduction of ESU as a buffer can be a promising solution which can store surplus power during the peak generation periods and use it in peak load periods [14-16].

The main challenge in the utilization of multiple ESUs is the coordination control strategy [17]. There are three types of coordination strategies that can be taken. The first strategy can be provided through centralized manner in which a central controller coordinates ESUs [18, 19]. The drawback of this approach is that it would require extensive data base with high speed and fast calculating computers, along with broadband networks. This can be too expensive for the current state of art. This can also be less reliable due to communication failure and computer freezing [20]. The second approach is the localized control strategy, based on local measurements only, such as the ones proposed in [12, 21]. This control strategy is robust in the sense that only local measurements are utilized. However, it cannot effectively utilize all available resources in the network due to the lack of broader information. A distributed control strategy, the third approach, can be as efficient as a centralized approach while avoiding its drawbacks [22]. However, the robustness of this approach still depends on the communication links.

This paper proposes an effective and robust approach which can coordinate multiple ESUs to manage and control voltage and loading in distribution networks. As voltage needs fast and robust control, a combined localized and distributed control approach is proposed to regulate the ESUs reactive power to deal with voltage issues. In addition, a distributed control strategy based on consensus algorithm is proposed to manage network loading, which divides the required active power equally among ESUs with respect to their maximum available active power.

8.3. Proposed Approach

National standards usually allow a maximum of ±6% voltage variation in distribution network [12]. Consider the distribution network with PV as the renewable energy sources, as shown in Fig. 8.1. Distribution network is designed in such a way that the voltage level of different nodes is within the standard limits, in normal operating condition. However, practical measurements show that the lower permissible voltage limit ($V^{min\_permissible}$) in critical buses is usually violated in peak load periods, which usually occur in the evenings when PVs do not generate any active power. In addition, the lower permissible limit for network loading ($S^{min\_permissible}$) may also be violated during this period, which is not acceptable.

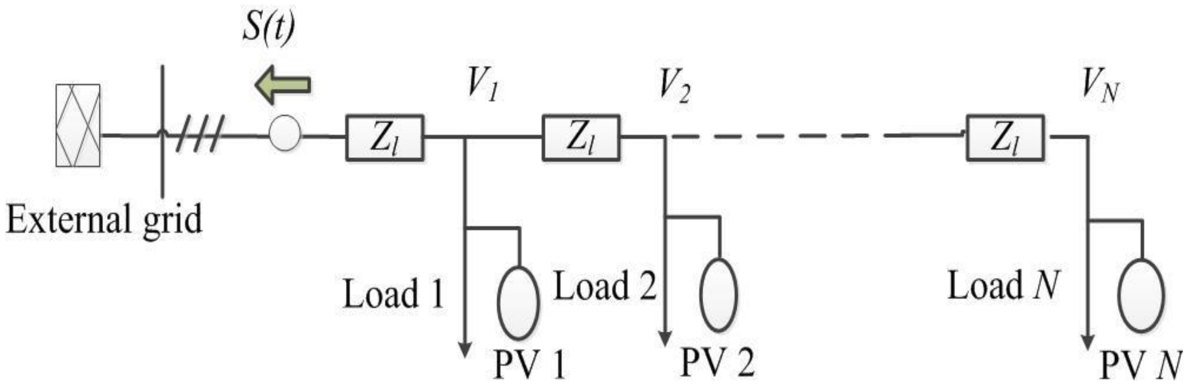
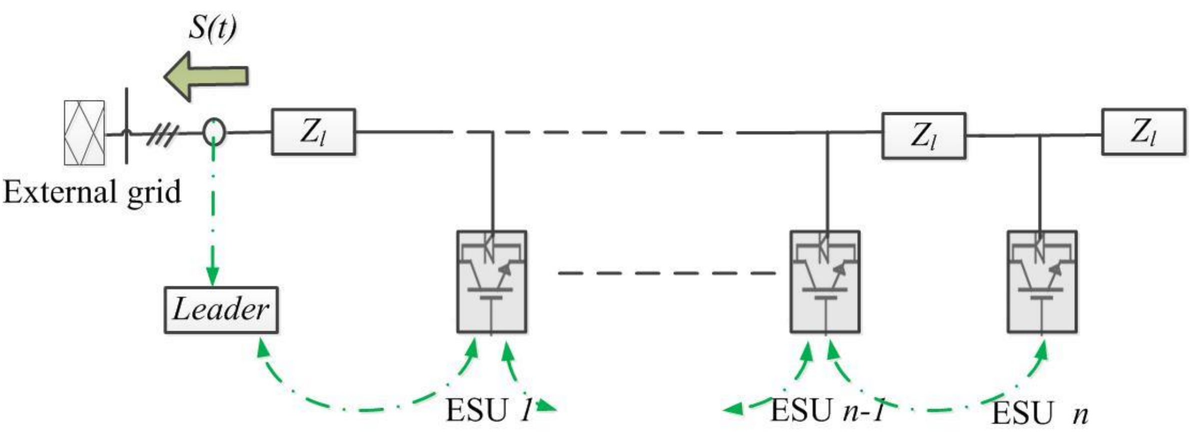


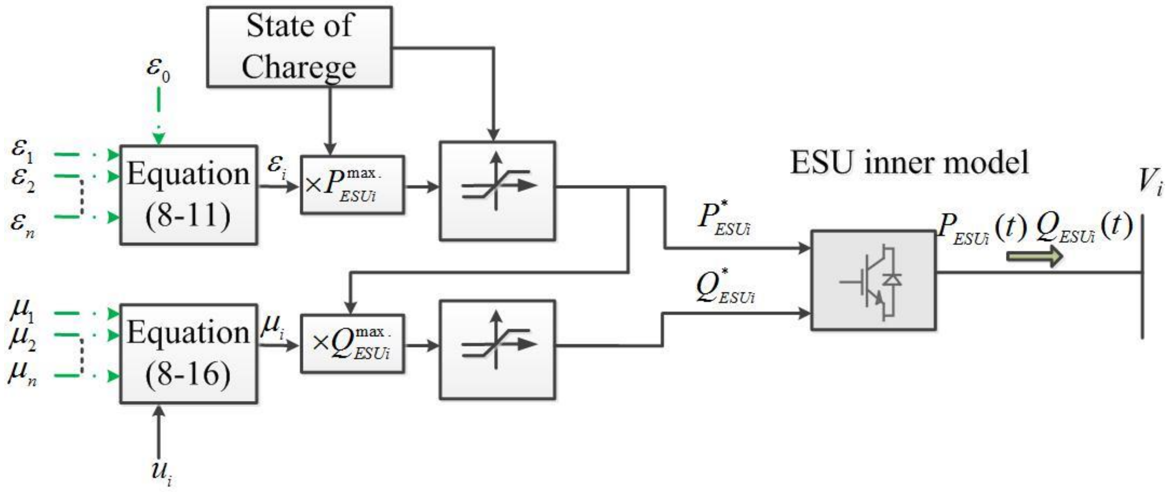
Fig. 8.1 A radial distribution network with multiple PVs.

Similarly, the violations can occur during the midday when network is in its low load period, while the PVs are in their maximum generation mode. During this period, the upper permissible voltage limit ($V^{max\_permissible}$) and upper permissible network loading limit ($S^{max\_permissible}$) can be reached. The approach of this paper is to coordinate ESUs' active and reactive power to avoid these problems.

ESUs are added to the network of Fig. 8.1 to cope with the problems. The proposed distributed control structure for coordination of ESUs is shown in Fig. 8.2. The dashed arrows in Fig. 8.2 (a) show the information flow, where the neighbouring ESUs are communicated to coordinate their operation. The proposed internal control structure for each ESU is shown in Fig. 8.2 (b). The reference value for ESU's active and reactive power ($P^*_{ESUi}(t)$ and $Q^*_{ESUi}(t)$) depend on information state of each ESU and its neighbour. As noted before, the proposed control structure includes voltage and network loading management. Details of the proposed approach are presented below.



(a)



(b)

Fig. 8.2 Proposed approach, (a) distributed control structure, (b) Internal control structure for each ESU.

8.3.1. Network Loading Management

In this paper, a consensus algorithm is proposed to be used to share the required active power with the same ratio among ESUs, for network loading management. In this algorithm, consensus is achieved by sharing variable of interest, called the information state. Consensus algorithm has been used in different applications of distributed control. In [23, 24], it is used to align multiple wheeled mobile robots. Reference [25] applied this algorithm to coordinate unmanned air vehicles for fire monitoring.

In this application, a higher control level named the leader is defined to initiate the ESUs coordination. The internal control structure of leader is shown in Fig. 8.3. The leader monitors *S(t)*, the drawn power from (-) or injected to (+) the external grid (higher voltage level network), and use this as the controllable variable for the network loading management. Four threshold limits; $S^{min\_desirable}$ and $S^{min\_critical}$ with negative values and $S^{max\_desirable}$ and

$S^{max\_critical}$ with positive values are considered to determine the network operation mode. In peak load period, if *S(t)* is more than $S^{min\_desirable}$, the network is in its normal operation mode and ESUs coordination is not needed. However, if *S(t)* violates $S^{min\_critical}$, ESUs coordination is initiated by leader and it is continued until the value of *S(t)* becomes more than $S^{min\_desirable}$. The same procedure is applied for high generation period.

The proposed distributed control strategy for ESUs active power can be written in a general form as:

$$\varepsilon_i(t) = f_i(c_{i0}(t).\varepsilon_0(t), c_{i1}(t).\varepsilon_1(t), ..., c_{in}(t).\varepsilon_n(t)) \quad (8\text{-}1)$$

where ε_0 is the information state of leader, ε_i is the information state of i^{th} ESU active power which is communicated among neighbouring ESUs, c_{ij} denotes the communication link between i^{th} and j^{th} ESUs, c_{ij} =1; if j^{th} ESU sends information to the i^{th}, otherwise c_{ij} =0. In addition, c_{i0}=1; if the i^{th} ESU can get information from the leader, otherwise c_{i0}=0, and c_{ii}=1 for all ESUs.

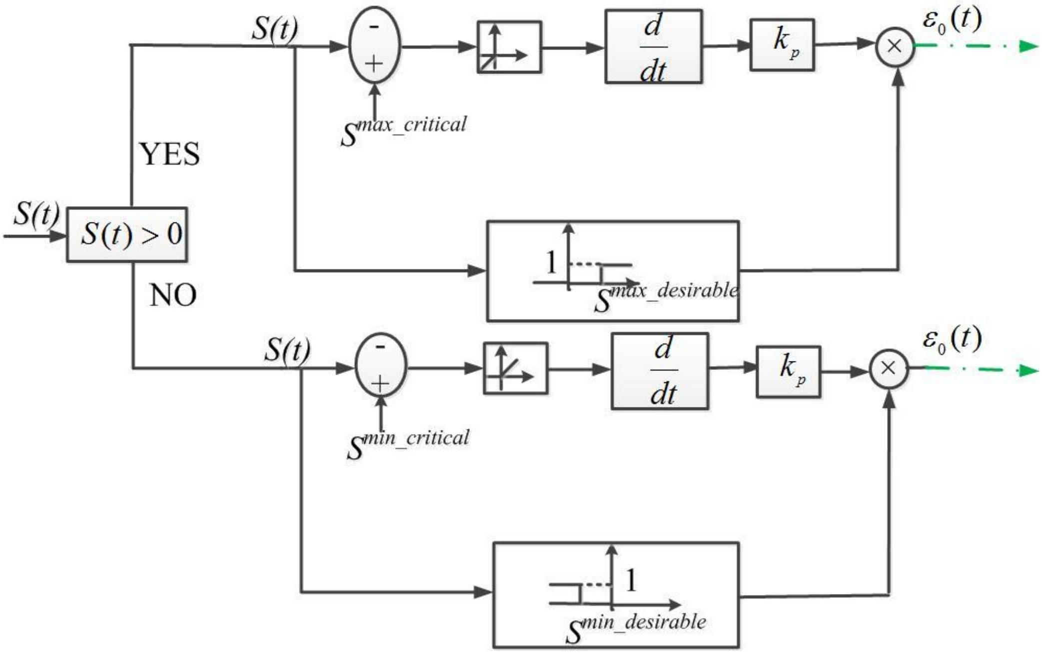


Fig. 8.3 Proposed control structure for leader.

The time-varying coefficients can be organized in a matrix of the complete communication topology as

$$C(t) = \begin{bmatrix} c_{10}(t) & c_{11}(t) & ... & c_{1n}(t) \\ . \quad . & & & . \quad . \\ . \quad . & & & . \quad . \\ c_{n0}(t) & c_{n1}(t) & ... & c_{nn}(t) \end{bmatrix} \quad (8\text{-}2)$$

Two general objectives need to be achieved to coordinate ESUs for network loading management. The first objective is to design a control for each ESU to reduce the network loading less than the critical limits. In other words, in peak generation period equation (8-3) and in peak load period equation (8-4) needs to be met at equilibrium point of ESUs coordination.

$$S(t) < S^{\max\_critical} \tag{8-3}$$

$$S(t) > S^{\min\_critical} \tag{8-4}$$

The second objective is to design a control for each ESU in such a way that the relationship in equation (8-5) is met at equilibrium point of ESUs coordination. In other words, the required active power is to be shared at the same ratio as its maximum available active power for each ESU ($P_{ESUi}^{\max.}$). As shown in Fig. 8.2 (b), the value of $P_{ESUi}^{\max.}$ depend on ESU state of charge and can be considered for a specified period of time (for example 15 minutes). In other words, for 15 minutes, the value of $P_{ESUi}^{\max.}$ is the maximum active power which *i*th ESU can continuously support. In this way, it can be said that the required active power will be shared with respect to ESU state of charge which is an important parameter for the ESU.

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{P_{ESU2}}{P_{ESU2}^{\max.}} = \ldots = \frac{P_{ESUn}}{P_{ESUn}^{\max.}} \tag{8-5}$$

The following procedures need to be followed to achieve the noted control objectives.

If *S(t)* passes $S^{max\_critical}$ limit, the leader should initiate the consensus algorithm of

$$\dot{\varepsilon}_0(t) = k_p.(S^{\max\_critical} - S(t)) \tag{8-6}$$

Similarly, if *S(t)* violates $S^{min\_critical}$ limit, the leader should also initiate

$$\dot{\varepsilon}_0(t) = k_p.(S^{\min\_critical} - S(t)) \tag{8-7}$$

Based on consensus algorithm, the information state of each ESU can be determined as:

$$\dot{\varepsilon}_i(t) = -\sum_{j=0}^{n} a_{ij}(t).(\varepsilon_i(t) - \varepsilon_j(t)) \tag{8-8}$$

where $a_{ij}(t)$ is the *(i,j)* entry of adjacency matrix $A_{n+1}(t) \epsilon R^{(n+1)\times(n+1)}$; $a_{ij}(t)>0$ *if* $c_{ij}(t)=1$ and $a_{ij}(t)=0$ otherwise.

In real case, the interaction among ESUs and leader occurs at discrete time steps. So, equations (8-6), (8-7) and (8-8) are replaced with equations (8-9), (8-10) and (8-11), respectively.

$$\varepsilon_0[t] = \varepsilon_0[t - t_d] + k_p.(S^{\max\_critical} - S[t]) \tag{8-9}$$

$$\varepsilon_0[t] = \varepsilon_0[t - t_d] + k_p.(S^{\min\_critical} - S[t]) \tag{8-10}$$

$$\varepsilon_i[t] = \sum_{j=0}^{n} d_{ij}[t].\varepsilon_j[t - t_d] \tag{8-11}$$

where $d_{ij}[t]$ can be found in each discrete time data exchange by

$$d_{ij}(t) = \frac{c_{ji}[t - t_d]}{\sum_{j=0}^{n} c_{ji}[t - t_d]} \tag{8-12}$$

For the entire network, $d_{ij}[t]$ can be considered as the *(i,j)* entry of a row stochastic matrix in which the sum of each row is equal to 1.

Finally, the required contribution of each ESU at each time step is updated by

$$P^*_{ESUi}[t] = \varepsilon_i[t] \times P^{\max.}_{ESUi} \tag{8-13}$$

8.3.2. Voltage Constraints Management

Similar to network loading control, four limits are considered for voltage control. To avoid overvoltage, $V^{max\_desirable}$ and $V^{max\_critical}$ determine the network operation mode. If all ESU bus voltages are less than $V^{max\_critical}$, the network is in normal operation mode and ESUs reactive power coordination is not needed. However, if the bus voltage of any ESU violates the limit, it initiates the distributed algorithm to support the voltage. The coordination will continue until all voltages are reduced to less than $V^{max\_desirable}$. In this situation, all ESUs decrease their reactive power step by step. The same procedure is applied to avoid under-voltage, in which case $V^{min\_desirable}$ and $V^{min\_critical}$ determine the network operation.

Two objectives need to be achieved to coordinate ESUs' reactive power when required. The first is to design a control for each ESU to keep the voltage within critical limits (between $V^{max\_critical}$ and $V^{min\_critical}$). The ESU control as given in (8-14) and (8-15).

$$V_i(t) < V^{\max\_critical} \qquad i = 1, \ldots, n \tag{8-14}$$

$$V_i(t) > V^{\min\_critical} \qquad i = 1, \ldots, n \tag{8-15}$$

The voltage limit violation is a local problem, not a network wide problem. Therefore, it is well suited to design a distributed control such that the most effective ESUs on the violated voltage(s), should contribute more in the reactive power sharing. This strategy is expected to provide the optimum voltage support mechanism.

As shown in Fig. 8.2 (b), the reference value for reactive power of each ESU is a function of its bus voltage and the information state of its neighbouring ESUs. Based on this internal control structure, it is proposed that the information state of each ESU reactive power is updated in discrete time interval t_d as given by

$$\mu_i[t] = s_{ii}[t].u_i[t] + \sum_{j \in N_i} s_{ij}[t].\mu_j[t - t_d] \tag{8-16}$$

where; μ_i is the information state for i^{th} ESU's reactive power which is communicated to its neighbouring ESUs, u_i is a localized control term to assure a robust control of ESU bus voltage. This value is determined based on a control structure shown in Fig. 8.4. In addition, s_{ij} represents transition weights which are potentially time-varying and dependent on communication structure. The weights, determined based on the bus voltage sensitivity to the reactive power, share the required reactive power in efficient way among ESUs (objective 2). This is discussed below.

The relationship between changes in power (active and reactive) with changes in bus voltage can be determined by Jacobian matrix as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} . \begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} \tag{8-17}$$

where,

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix}^{-1} . \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} . \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{8-18}$$

The approximate sensitivity of the ESU bus voltage to the reactive power can be given by

$$\frac{\partial V}{\partial Q} = D \tag{8-19}$$

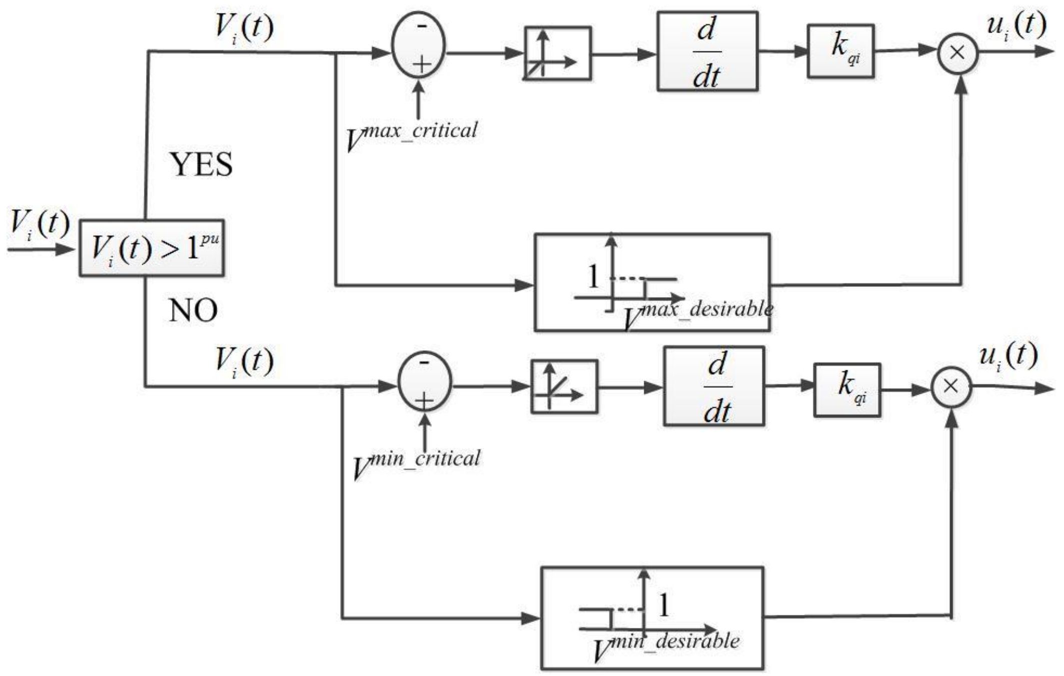


Fig. 8.4 Proposed localized voltage control for each ESU.

With the proposed communication structure, the customers are only aware of the value of D_{ji} corresponding to their neighbours. Therefore, the sensitivity matrix is modified as:

$$\overline{D_{ji}} = \begin{cases} D_{ji} & i \in \{N_j \cup j\} \\ 0 & i \notin \{N_j \cup j\} \end{cases} \tag{8-20}$$

Finally, the transition weights are calculated by the following equation:

$$s_{ij}[t] = \frac{\overline{D_{ji}}.c_{ij}[t]}{\sum_{k=1}^{n} \overline{D_{ki}}.c_{ki}[t]} \tag{8-21}$$

It is worth noting that the voltage sensitivities do not change much with respect to the changes in the operating point [26]. Therefore their nominal values are used in this paper to design the transition weights. As a result, the weights are predetermined for each ESU and its neighbours.

If either of the critical voltage limits is violated for any ESU, its localized control term initiates the distributed control strategy based on

$$\dot{u}_i(t) = k_{qi}.(V^{\max\_critical} - V_i(t)) \tag{8-22}$$

$$\dot{u}_i(t) = k_{qi}.(V^{\min\_critical} - V_i(t)) \tag{8-23}$$

Following the control initiation, the information states of ESUs are updated in each discrete time interval based on equation (8-16). Finally, the required reactive power contribution of each ESU at each time interval is updated by:

$$Q^{*}_{ESUi}[t] = \mu_i[t] \times Q^{\max.}_{ESUi} \tag{8-24}$$

By applying this control structure, both objectives for voltage support can be achieved and ESU inverters will contribute with their reactive power. The complete set of system equations (8-25 – 8-33) for this coordination strategy is given in the followings:

$$u_i[t] = \begin{cases} u_i[t-t_d] + k_{qi}.(V^{\max\_critical} - V_i[t]) & V_i[t] > V^{\max\_critical} \\ u_i[t-t_d] & V^{\max\_desirable} < V_i[t] < V^{\max\_critical} \\ 0 & V^{\min\_desirable} < V_i[t] < V^{\max\_desirable} \\ u_i[t-t_d] & V^{\min\_critical} < V_i[t] < V^{\min\_desirable} \\ u_i[t-t_d] + k_{qi}.(V^{\min\_critical} - V_i[t]) & V_i[t] < V^{\min\_critical} \end{cases} \quad i = 1,2,...,n \tag{8-25}$$

$$\varepsilon_0[t] = \begin{cases} \varepsilon_0[t-t_d] + k_p.(S^{\max\_critical} - S[t]) & S[t] > S^{\max\_critical} \\ \varepsilon_0[t-t_d] & S^{\max\_desirable} < S[t] < S^{\max\_critical} \\ 0 & S^{\min\_desirable} < S[t] < S^{\max\_desirable} \\ \varepsilon_0[t-t_d] & S^{\min\_critical} < S[t] < S^{\min\_desirable} \\ \varepsilon_0[t-t_d] + k_p.(S^{\min\_critical} - S[t]) & S[t] < S^{\min\_critical} \end{cases} \tag{8-26}$$

$$\mu_i[t] = s_{jj}[t].u_i[t] + \sum_{j \in N_i} s_{ij}[t].\mu_j[t-t_d] \tag{8-27}$$

$$\varepsilon_i(t) = \sum_{j=0}^{n} d_{ij}(t-t_d).\varepsilon_j(t-t_d) \tag{8-28}$$

$$Q^{*}_{ESUi}[t] = \mu_i[t] \times Q^{\max.}_{ESUi} \qquad i = 1,2,...,n \tag{8-29}$$

$$P^{*}_{ESUi}[t] = \varepsilon_i[t] \times P^{\max.}_{ESUi} \qquad i = 1,2,...,n \tag{8-30}$$

$$Q_{ESUi}[t] = Q^{*}_{ESUi}[t] \qquad i = 1,2,...,n \tag{8-31}$$

$$P_{ESUi}[t] = P^{*}_{ESUi}[t] \qquad i = 1,2,...,n \tag{8-32}$$

$$g(P_{ESU1}, P_{ESU2}, ..., P_{ESUn}, Q_{ESU1}, Q_{ESU2}, ..., Q_{ESUn}, \chi, X) = 0 \tag{8-33}$$

where; equations (8-25)-(8-28) model the proposed distributed control strategy for ESUs, equations (8-29) and (8-30) model the ESUs internal control. Equation (8-33) gives the load flow equations where χ denotes the internal dynamics of network such as state variable of ESUs etc., and X is the algebraic variables of network such as bus voltages.

It is worth noting that the internal dynamics of network (χ) are not considered here. This is because, the dynamic of internal variables are much faster compared with output power. So, it can be said that the value of these variables diminish much faster than the output power. As a result, the dynamic of ESU output power is determined by the controller designed in this paper while the inner dynamic of ESUs is ignored. Consequently, the ESUs reactive and active power are modelled as in (8-31) and (8-32).

8.4. Case Studies

8.4.1. Case 1

A typical radial distribution network is selected, as the first case, to show the effectiveness of the proposed approach. The network parameters and load details can be found in [20]. There are 5 PVs connected in this network with rating listed in Table 8.1. The network structure with three ESUs and its communication topology is shown in Fig. 8.5. It is assumed for the period of study, all ESUs can continuously support the power shown in Table 8.2. It is assumed that ESU inverter rating is increased by just 11.8% to have the ability to supply nearly 50% reactive power while supplying full rated active power. The limits for voltage and network loading are listed in Table 8.3 and 8.4.

In addition, it is stipulated that the power factor of ESUs should be more than 0.9 and the upper limit of the reactive power output is dependent of the active power output as

$$Q_{ESUi}^{\max.} = 0.4843 \times P_{ESUi} \qquad i = 1,2,3 \tag{8-34}$$

It is assumed that all loads are in 15% of their maximum. In addition, the PVs generation change from 75% to 95% at t=100 s. the result for this case is shown in Fig. 8.6.

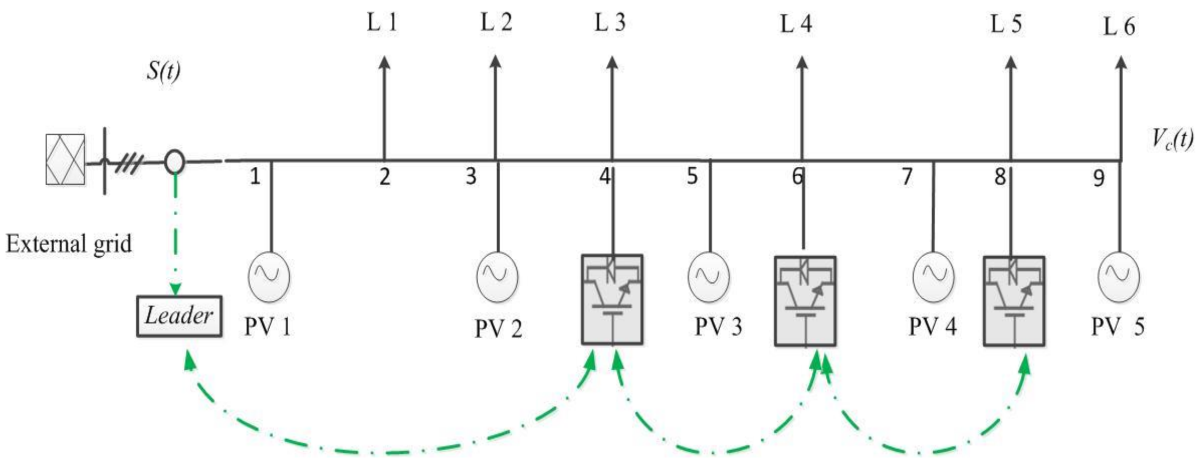


Fig. 8.5 A radial distribution network with multiple ESUs.

Table 8.1 PVs rating.

PV	PV1	PV2	PV3	PV4	PV5
Active power (kW)	550	600	500	450	650

Table 8.2 Available active power for ESUs.

ESU	ESU1	ESU2	ESU3
Active power (kW)	150	200	250

Table 8.3 Voltage limits in the proposed approach.

Parameter	Voltage (pu)
$V^{max\_permisIable}$	1.06
$V^{max\_critical}$	1.03
$V^{max\_desirable}$	1.02

Table 8.4 Network loading limits in the proposed approach.

Parameter	Power (kVA)
$S^{max\_permissible}$	2200
$S^{max\_critical}$	1800
$S^{max\_desirable}$	1500

It can be seen between t= 0s and t= 100s, all voltages and network loading are in the desirable range. Therefore, no ESUs coordination is needed. However, at t=100s, as the PV generation increases, the upper critical limit for voltage of ESUs 2 and 3 and network loading is violated. Therefore, the proposed control approach for both voltage and thermal constraints management is initiated. For network loading management, it can be seen that, at the equilibrium point, its value is less than upper critical limit (the first aim is achieved). In addition, the ESU contribution is as follow based on the second objective.

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{-74.75}{150} = -0.49$$

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{-99.67}{200} = -0.49$$

$$\frac{P_{ESU1}}{P_{ESU1}^{\max.}} = \frac{-124.59}{250} = -0.49$$

In addition, after the generation step change, the ESU voltages follow the pattern based on equation (8-35). Accordingly, reactive power sharing among ESUs needs to follow as in (8-36) to have effective voltage support.

$$V_3 > V_2 > V_1 \tag{8-35}$$

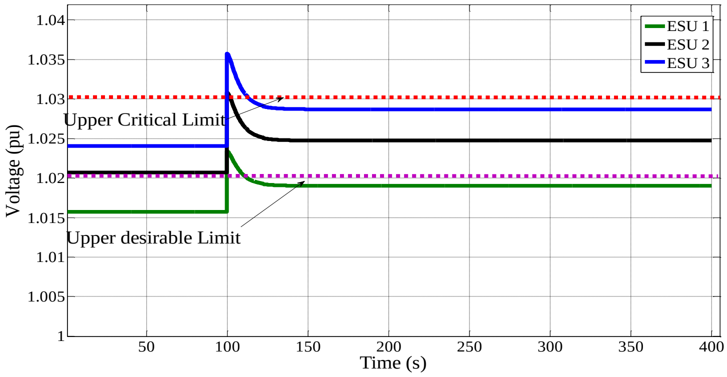
$$\left|\frac{Q_{ESU3}}{Q_{ESU3}^{\max.}}\right| > \left|\frac{Q_{ESU2}}{Q_{ESU2}^{\max.}}\right| > \left|\frac{Q_{ESU1}}{Q_{ESU1}^{\max.}}\right| \tag{8-36}$$

The reactive power sharing at the equilibrium point of coordination is as follows. It can be seen that the proposed approach follow the second objective aimed in this paper.

$$\left|\frac{Q_{ESU1}}{Q_{ESU1}^{\max.}}\right| = \left|\frac{Q_{ESU1}}{0.4843 \times P_{ESU1}}\right| = \left|\frac{-2.016}{0.4843 * 124.59}\right| = 0.033$$

$$\left|\frac{Q_{ESU2}}{Q_{ESU2}^{\max.}}\right| = \left|\frac{Q_{ESU2}}{0.4843 \times P_{ESU2}}\right| = \left|\frac{-5.28}{0.4843 * 124.59}\right| = 0.087$$

$$\left|\frac{Q_{ESU3}}{Q_{ESU3}^{\max.}}\right| = \left|\frac{Q_{ESU3}}{0.4843 \times P_{ESU3}}\right| = \left|\frac{-14.05}{0.4843 * 124.59}\right| = 0.232$$



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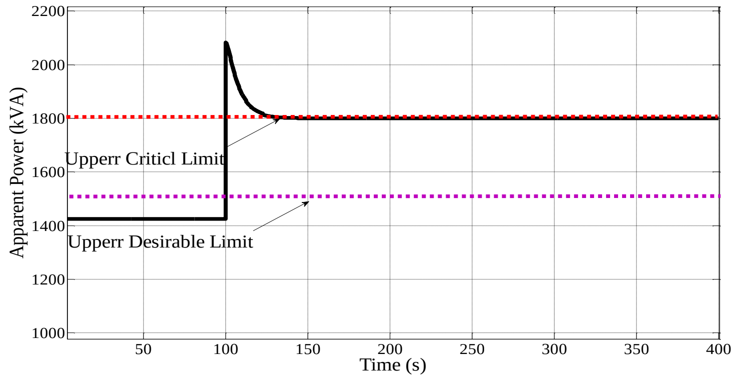

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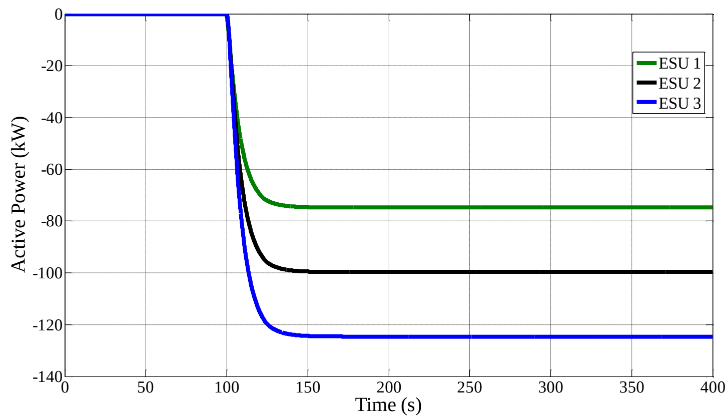

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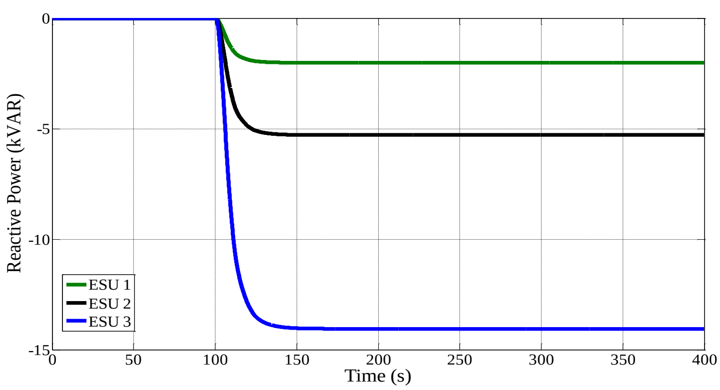


(d)

Fig. 8.6 Proposed control approach (a) ESUs bus voltage, (b) network loading, (c) ESUs active power, (d) ESUs reactive power.

8.4.2. Case 2

The IEEE 33 bus is used as the second case study to show the effectiveness of the proposed approach in different operation modes. In addition, the effect of communication drop on the proposed approach is studied as well. This is a 12.66 kV loop system with parameters listed in [27]. The network structure and the multiple ESUs are shown in Fig. 8.7. For the studied period of time, it is assumed that the ESUs can support the active power listed in Table 8.5 continuously. In addition, the apparent power than can be supplied by the ESU inverter is assumed to be the same as the ESU rating, i.e., no over-rated inverter is necessary. Therefore, the upper limit of the reactive power output is dependent of the active power output as

$$Q_{ESUi}^{\max.} = \sqrt{S_{ESUi}^2 - P_{ESUi}^2} \qquad i = 1, 2, ..., 8 \tag{8-37}$$

where S_{ESUi} is the rating of i^{th} ESU inverter. In this case, the power factor can vary depending on the ESU active power.

Moreover, For the sake of simplicity, it is assumed that the maximum generation power in each bus is equal to maximum load active power in that bus. With respect to these values, it is assumed that all buses have the same generation and load profiles, as shown in Fig. 8.8. The limits for voltage and network loading are listed in Table 8.6 and 8.7.

For the system of Fig. 8.7, it is assumed that ESU information states are updated at each t_d=100 ms. Moreover, it is assumed that the communication link between ESU 4 and 5 is not available during t=300-400s. Using the proposed control approach, Fig. 8.9 shows the bus voltages, network loading, ESUs active power, ESUs reactive power in different time steps. The time sequences of the operation are detailed as follows:

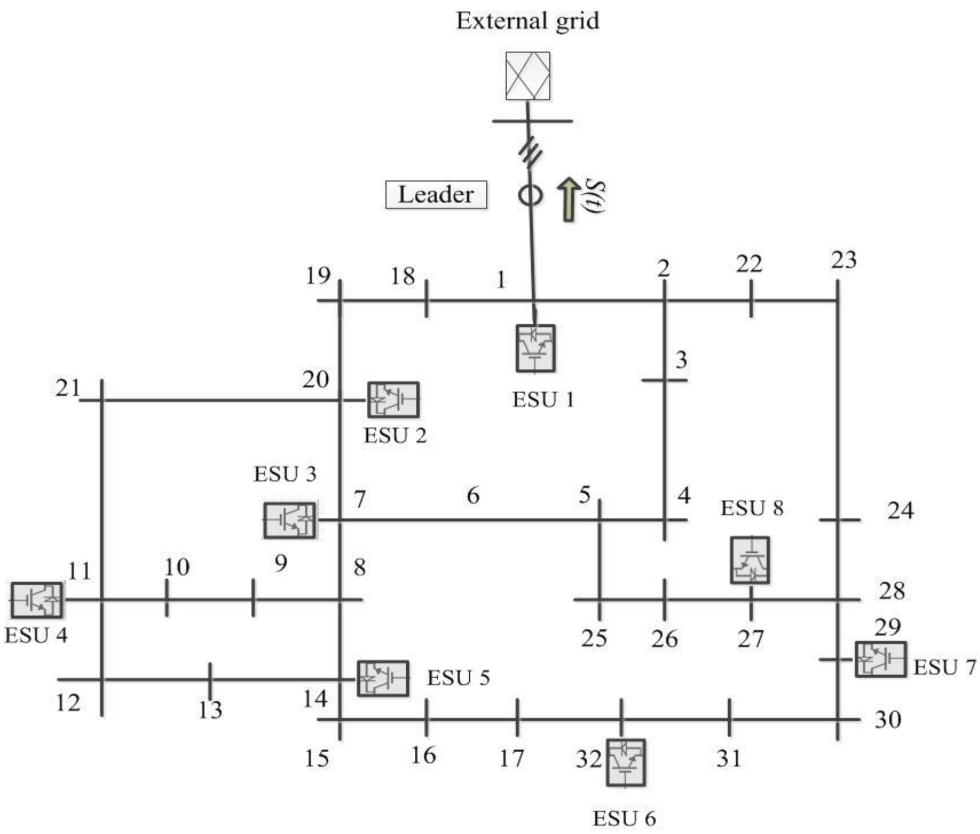


Fig. 8.7 Loop distribution network with multiple ESUs.

Table 8.5 ESUs rating.

ESU	1	2	3	4	5	6	7	8
Active power (kW)	150	60	120	80	100	140	50	40

Table 8.6 Voltage limits in the proposed approach.

Parameter	Voltage (kV)	Voltage (pu)
$V^{max\_permisIable}$	13.41	1.06
$V^{max\_critical}$	13.03	1.03
$V^{max\_desirable}$	12.91	1.02
$V^{min\_desirable}$	12.40	0.98
$V^{min\_critical}$	12.28	0.97
$V^{min\_pwermiisible}$	11.90	0.94

Table 8.7 Network loading limits in the proposed approach.

Parameter	Power (kVA)	Power (pu)
$S^{max\_permissible}$	3000	30
$S^{max\_critical}$	2700	27
$S^{max\_desirable}$	2000	20
$S^{min\_desirable}$	-2000	-20
$S^{min\_critical}$	-2700	-27
$S^{min\_permissible}$	-3000	-30

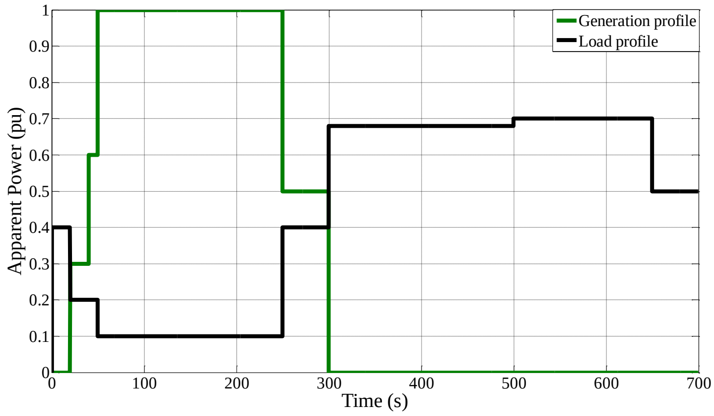


Fig. 8.8 Load and generation profiles at each node.

1- Between 0 s and 50 s, the network loading and all ESUs voltages are in desirable range and no ESUs coordination is needed.

2- At 50 s, injection increases while the network loading passes $S^{max\_critical}$. As a result, the leader initiates the coordination of ESUs active power to reduce the network loading. At t=68 s, the network loading become less than $S^{max\_critical}$ (the first objective is achieved). It can be seen that, at the equilibrium point, the ESUs contribute at the same ratio as their available power (the second objective is achieved).

3- At 250 s, network loading goes to the desirable range. As a result, ESUs reduce their active power contribution step by step, until they stop operating.

4- At 300s, critical limits for network loading and the voltage at bus 32 are violated. Consequently, ESUs start to coordinate their active and reactive power. However, due to the communication links drop between ESUs 4 and 5, voltage support can only be coordinated for ESUs 5, 6, 7 and 8. Using their localized control term, they can keep the violated bus voltage (ESU 6 bus) in the range. Moreover, only ESUs 1, 2, 3 and 4 are coordinated for loading reduction. At t=400s, communication links become available between ESUs 4 and 5. Consequently, the ESU information states for active and reactive power are updated again. At this stage, the information states of ESUs active power are as follows;

$$\varepsilon_0 = \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = 0.51 \quad \varepsilon_5 = \varepsilon_6 = \varepsilon_7 = \varepsilon_8 = 0$$

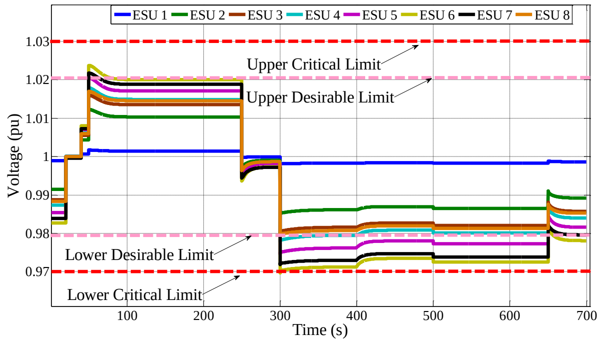
As can be seen, at the equilibrium point of this coordination, information states of all ESUs active power converge to the value of 0.51. The total required active power therefore is 379.21 kW. This value is more than the case with no communication drop (the result is not shown due to space limitation) which is 291.41kW.

These results show that the communication malfunction does not affect the robustness of the proposed approach, even though it limits the available resources for coordination and may somewhat reduce the efficiency of management.

5- At 650 s, the network loading and all voltages go to the desirable range. At this point, ESUs stop their contribution for voltage support and network loading management.

8.5. Conclusions

This paper proposes a new approach to coordinate multiple ESUs to manage voltage and loading in distribution networks. ESU's active power is used to manage network loading, and ESU reactive power is utilized for voltage support. As the voltage needs fast and robust control, a combined localized and distributed control approach is used to coordinate the ESU reactive power. This method is designed to use the most adjacent ESUs to the violated bus voltage. For loading management, a distributed control strategy based on consensus algorithm is employed to coordinate ESUs' active power. The proposed consensus algorithm has been designed to share the required active power with the same ratio among ESUs with respect to their available active power. This approach has been tested on two systems and the results show that the algorithm works effectively.



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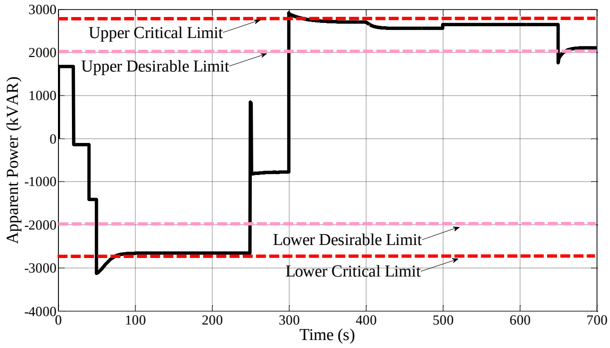

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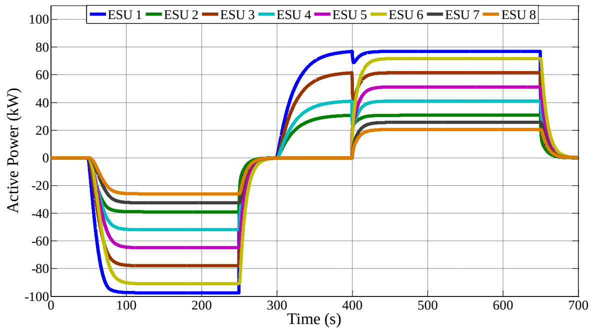

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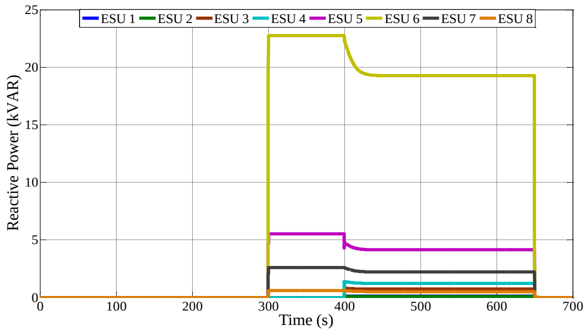

(d)

Fig. 8.9 Proposed control approach with communication drop, (a) ESUs bus voltage, (b) network loading, (c) ESUs active power, (d) ESUs reactive power.

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Chapter 9

Conclusions and Further Research

9.1. Conclusions

In the past 10 years, smart grid and new innovative approaches have been introduced to deal with different power quality issues caused by high penetration of PVs. Therefore, this research area is very wide and covering this wide range of all related topics is not possible. Therefore, the main aim of this research project is narrowed to investigate new approaches to deal with voltage and network loading issues caused by high penetration of PV in distribution networks. In order to develop the approaches, LV and MV networks are identified as the main location for PVs. As a result, the main research objectives were identified as below:

- Developing new approaches to deal with voltage and loading issues in LV network
- Developing new approaches to deal with voltage and loading issues in MV network

Considering the above noted objectives, this dissertation set out to investigate new smart control approaches to deal with noted issues in LV and MV network. In LV network, distributed customer resources are proposed to be used and coordinated to deal with noted issues. Moreover, novel approaches are introduced for MV network with concentrated resources.

9.1.1. Developing new approaches to deal with voltage and loading issues in LV network

In LV network, distributed resources are proposed to be used to deal with voltage and network loading problems. In chapter 2 a new mixed localized-distributed control approach was proposed to deal with voltage rise. The main resources identified in this chapter include PV inverter active power, PV inverter reactive power and distributed ESU connected to customer DC link.

The idea along with the simulation results are published in a journal paper entitled *"Smart Robust Resources Control in LV network to Deal with Voltage Rise Issue" in IEEE Transaction on Sustainable Energy*.

In addition to the noted resources, smart controllable devices such as electric vehicle and dishwasher can be another option to be coordinated to deal with noted issues. In Chapter 5, a new commutation structure is proposed for smart meters to coordinate these resources and avoid overvoltage in LV network. This study was published as a part of a journal paper entitled *"Overvoltage Prevention in LV Smart Grid Using Customer Resources Coordination"* in *Energy and Buildings journal*.

To deal with both voltage and loading issues simultaneously, two new approaches were proposed in Chapters 3 and 4. In Chapter 3, load leveling is proposed to be used and coordinate customers ESUs and avoid any overloading and voltage issues. The idea and results for a LV network was presented as a conference paper entitled *"Load Leveling in LV Network Using Coordinated Energy Storage Units"* in *AUPEC Conference* in October 2013.

In addition, in Chapter 4, connection of customer DC link is proposed as pathway to accommodate customer power exchange and avoid power quality issues. A comprehensive study of this method was published with title of *"Improving the penetration Level of PVs Using DC link for Residential Buildings"* in *Energy and Buildings journal*.

9.1.2. Developing new approaches to deal with voltage and loading issues in MV network

In MV network, resources are in concentrated layout such as PV plant and ESU in three-phase scheme. Therefore, distributed control approach should apply in three-phase basis.

To start with, PV plant active and reactive power are introduced to be used to deal with voltage and loading problems, respectively. A distributed scheme is proposed in Chapter 6 to use PV plant active and reactive to keep the voltages and network loading in an acceptable range. The main aim of this approach is to share the required active and reactive power equally among PVs. The idea and results of this case was prepared to be submitted to the IEEE IECON 2014 with title of *"Overvoltage and Overloading Prevention Using Coordinated PV Inverters in Distribution Network"*

As the voltage is a local problem rather than wide area problem, the approach which shares the required reactive power equally among PVs may not be efficient. Therefore, to avoid these drawbacks, a new distributed approach is proposed in Chapter 7. The idea and analysis of this approach is prepared as a journal paper with title of "*A New PV Reactive Power Control to Improve Voltage Profile of Distribution Network*".

Finally, ESU as a promising resource for future smart grid is considered for coordination and a new control structure is proposed to coordinate these resources for voltage and loading support. This study entitled *"Smart Coordination of Energy Storage Units (ESUs) for Voltage and Thermal Constraints Management in Distribution Networks"* was published in *IEEE Transactions on Power Systems Journal*.

9.1.3. Critical aspects of this research work

This section tries to address some critical aspects regarding this research project.

A. Relevance of this research to the current state of electrical industry

Current electricity grids have been operating for many years in which traditional methods are used to control their operation. For instance, to avoid overvoltage in current distribution networks, inverters are operating based on IEEE recommended practice for the utility interface of PV systems. Based on this standard, PV inverters should be supported with overvoltage protection relay which will trip if the PV bus voltage violates the permissible voltage limit, and will reconnect after a while (10 minutes) if the bus voltage is within permissible range. Such a traditional control strategy is not suitable for future electricity networks in which the power quality and efficiency are the main concerns. Therefore, in the last decade, significant effort has been put to change the control and operation of current network to achieve greater efficiency. A smart grid paradigm is proposed to improve the performance and control by applying IT and communication technologies in the power system. Based on this paradigm, this research project tries to address new smart control structure which can be applied to change the current network operation to a more efficient and smart one.

B. The effect of Network size on convergence and computing time

One of the important aspects which need to be addressed for the proposed approaches is the effect of network size on computing time. When the network size increases, the time to catch steady state coordination could increase as well. However, as shown in the algorithm, the computing time for resources information state is a function of the neighbouring resource numbers, approximately in the range of 2 – 5 resources, and therefore has little effect on the computing time. Therefore, computing time is not a critical issue in the proposed strategy.

C. Advantages and disadvantages of the proposed approaches

Smart Robust Resources Control in LV network to Deal with Voltage Rise Issue	
Advantages	✓ Allowing every owner of renewable energy sources to utilize all available resources (e.g. ESU, inverter active and reactive power) for voltage rise control. ✓ design a method using combined localized and distributed algorithms to achieve an efficient voltage reduction ✓ A new robust control approach even with communication drop
Drawbacks	➢ Efficiency of this approach depends on communication links ➢ Requires communication among neighbouring ESUs

Load Leveling in LV Network Using Coordinated Energy Storage Units	
Advantages	✓ Avoiding network overloading ✓ Avoiding over and under voltage ✓ Sharing the required active power equally among customers ✓ Avoiding renewable energy losses
Drawbacks	➢ Required communication among neighbouring customers

Improving the Penetration Level of PVs Using DC link for Residential Buildings	
Advantages	✓ Improving the customer injection ✓ Improving the redundancy in LV network ✓ Improving the reliability in LV network ✓ Improving customer satisfaction ✓ Reducing the losses in network
Drawbacks	➢ Investment cost for the DC link

'Overvoltage Prevention in LV Smart Grid Using Customer Resources Coordination	
Advantages	✓ Utilization of all available resource to avoid voltage rise ✓ Improving the customer injection to the grid ✓ Keeping robustness to any communication drop
Drawbacks	➢ Need a new communication structure for smart meter

Overvoltage and Overloading Prevention Using Coordinated PV Inverters in Distribution Network	
Advantages	✓ Sharing the required contribution equally among PVs ✓ No need for any investment cost
Drawbacks	➢ May not be efficient for voltage support

A New PV Reactive Power Control to Improve Voltage Profile of Distribution Network	
Advantages	✓ Efficient for voltage control comparing droop control ✓ Improving the utilization of other voltage support equipments ✓ Robust to any communication drop
Drawbacks	➢ Requiring communication among PVs

Smart Coordination of Energy Storage Units (ESUs) for Voltage and Thermal Constraints Management in Distribution Networks	
Advantages	✓ Sharing the required active power equally among ESUs ✓ Efficient for voltage support ✓ Robust voltage support approach
Drawbacks	➢ Requiring communication among ESUs

9.2. Further Research

This research study has focused on developing new control approaches for future smart grid with high penetration of PVs. Regarding this objective, suggestions for further research work are discussed in five specific areas.

- **Hardware implementation of the proposed approaches**

To investigate the performance of the proposed approaches, a hardware implementation is required. The hardware setup can be implemented for different approaches with different resources.

- **Cost-benefit analysis for each control approach**

In this study, some preliminary economic studies have been done to show the effectiveness of the approaches. However, comprehensive studies are needed to analyse the effectiveness of these approaches for whole network. In the other word, for each approach, it is needed to analyse how much cost it has and how much benefit can be brought by that.

- **Designing the control parameters for each approach**

As shown in the studies, each approach has some parameters which need to be designed carefully. In this research, acceptable value has been used for these parameters. However, a study is required to find out the efficient value for these parameters.

- **Reliability analysis of the proposed approaches**

As shown in the thesis, the proposed approach aims to improve the customer injection and decrease the probability of loss of generation. To show the effectiveness of these approaches in better way, reliability analysis is needed and maybe new indices can be helpful to show the results better.

- **Considering these approaches in the planning of a network**

The proposed approaches can be considered in network planning program. In other words, to have efficient and better control, these control structure can be considered as the backbone of future grid and network planning can be considered based on these approaches.