A New DER Coordination in LV network Based on the Concept of Distributed Control

G. Mokhtari*, F. Zare*, *Senior Member, IEEE*, G. Nourbakhsh*, A. Ghosh*, *Fellow Member, IEEE*

Abstract- **Given the paradigm of smart grid as the promising backbone for future network, this paper uses this paradigm to propose a new coordination approach for LV network based on distributed control algorithm. This approach divides the LV network into hierarchical communities where each community is controlled by a control agent. Different level of communication has been proposed for this structure to control the network in different operation modes.**

***Keywords; LV Network, Community, Smart-metering system,* DER, Power Quality Issues**

I. Introduction

Future Low Voltage (LV) networks will include widespread Renewable Energy (RE) generators Like PV, wind turbine and fuel cell. The high penetration of RE generators may introduce new challenges for LV networks. The main challenges include voltage rise, voltage regulation problem, voltage unbalancing, line overloading and LV transformer overloading [1-8]. Consequently, the traditional operation will impose limitation to the hosting capacity of LV network for more RE generation and needs to be modified with new strategies.

Different approaches have been suggested by researchers to minimize these challenges which can be summarized as follow:

1- Network upgrading, such as increasing conductor size to reduce the line impedance. This approach needs new expensive investment by utilities for upgrading the networks which is not attractive [9-11].

2- Changing network static set points, such as reduction of secondary LV transformer tap. 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 acceptable [10, 12].

3- Curtailing RE generator output power. This approach is based on decentralized control which is attractive, but contradicts the main purpose of installation of theses generators which is the maximum use of renewable energy [12-14].

4- Utilization of Distributed Energy Resources (DERs) such as battery [15-24] and Controllable load [25] in customer side to deal with power quality issues. In other words, in period of high generation (for example, mid day for residential area with solar PVs), these resources should be utilized to improve the hosting capacity of LV network for more RE generation.

The main challenge for utilization of these resources is their coordination. There are two approaches for coordination of these resources. The first way is a centralized approach which needs communication link between central controller and the various devices [26]. The main problem of this approach is the need of knowledge for each resource which needs high memory space and high calculations. In addition, “plug and play” functionality through centralized approach is difficult. As a result, these issues motivate the second approach which is known as peer-to-peer, multi-agent, or distributed control [27]. This paper proposes an approach with a modular and flexible communication structure to utilize distributed control algorithm for DER coordination in LV network.

There are a lot of large-scale project around the world for smart-metering system to make the network more intelligent. The frontrunner countries are Italy and Sweden (nearly 100% installations at the end of 2011). The primary role of smart-metering system is to generate customer consumption data to the utility [28]. In addition, It can give the customers the ability to control their load, local generation and battery storage [29]. The present smart-metering systems offer a new level of functionality which can communicate through communication infrastructure (like wireless technology) with a center to deal with different issues. It is proposed that a new functionality can be added to the smart-metering system in which they can communicate with each other. Therefore, this technology can give the flexibility to customers in a local area to collaborate with each other for different operational goals such as DERs coordination. Reference [30] proposed the term of “collaborative customer” for the industrial customers who join together to buy a power plan and collaborate in sharing and selling power based on this concept. In future, the LV networks, with high penetration DERs, can similarly operate to bring benefits to customers and utilities.

This paper proposes a new approach for LV network which can help to coordinate customer’s DERs in different operation modes. This approach suggests that the LV network can be divided into different hierarchical communities and communication level. Through this scheme, the control agent of each community can coordinate the DERs based on its own objective function or any command from other control agents. Normal, alert and emergency states are associated with all hierarchical levels. However, these states do not have the same

*Ghassem Mokhtari, Firuz Zare, Ghavameddin Nourbakhsh and Arindam Ghosh are with the School of Electrical Engineering and Computer Science, Science and Engineering Faculty, Queensland University of Technology, Brisbane, Australia,

Email: g.mokhtari@qut.edu.au

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definition for all hierarchies. The operation in normal state is communicated from the higher level in hierarchies. However, the alert and emergency states are resolved in the same level of hierarchies. This approach enables the coordination of DERs in different operation states.

II. Prposed Aproach

This paper presents a new arrangement for LV networks in which they can be divided into hierarchical communities. The customers within and between communities can collaborate with each other through different communication levels.

The proposed structure is shown in Fig. 1. The same structure is suggested for other LV networks as well. As an application, residential customers have been considered in this paper; however, industrial and commercial customers can also be considered in this new arrangement.

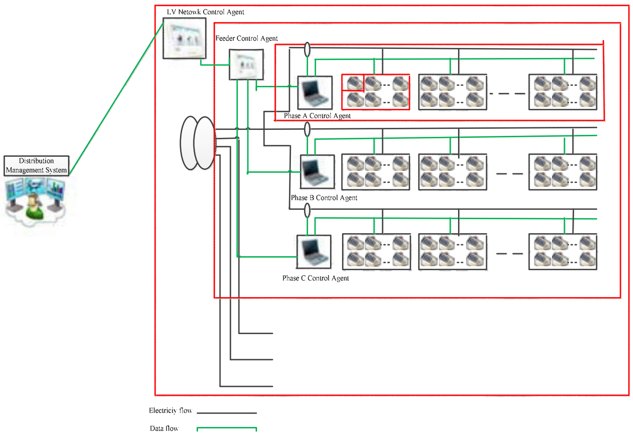

Fig. 1: Proposed structure for LV residential network base on local communities

As it can be seen in Fig. 1, there is a modular structure for coordination of this network. In this approach, Individual customers are controlled by their smart-metering system as the Individual Customer Control Agent (CCCA). However, individual customers are part of a community including its neighbors named neighboring community which is controlled based on master-slave control. The master is the Neighboring Community Control Agent (NCCA). Neighboring communities in one phase form a phase community which is controlled by Phase Community Control Agent (PCCA). Moreover, Phase communities in one feeder form the feeder community which is coordinated by Feeder Community Control Agent (FCCA). This modular structure can be expanded to the whole LV network which is controlled by LV Network Community Control Agent (LVNCCA). Any command from Distribution Management System (DMS) is sent to NCCA for any aggregation or coordination.

In this paper, the coordination among communities is based on the developing standard of Foundation for Intelligent Physical Agent (FIPA). FIPA defines standards for creating, locating, removing and communication with agents [31]. The modular architecture of a control agent, in proposed approach, has been shown in Fig. 2. Signal from the sensors or the messages from other control agents are received and filtered by perception module. Considering the local and social model of each community, the interpretation module translates this signal for decision making module. Decision making module make decisions based on this signal and the agent's objective. Finally, the execution module carries out the action.

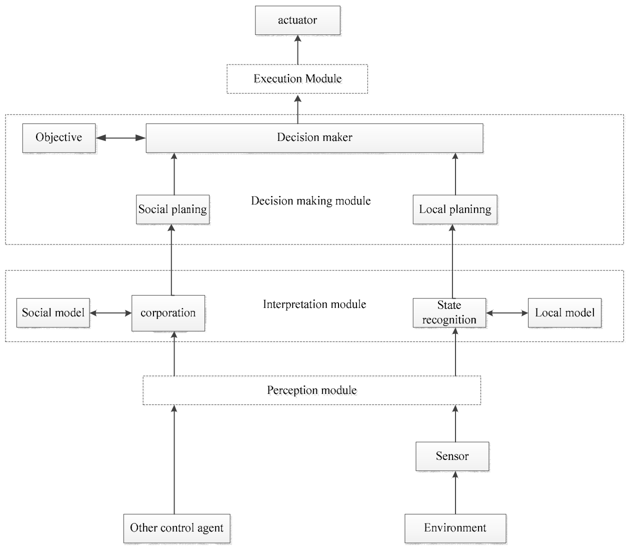

Fig. 2: Control agent's architecture in proposed approach

A. *Individual customer*

Each individual customer is controlled by its smart-metering system as ICCA. There is a communication link between ICCA and each customer's resources (RE generator, Battery and controllable load and critical load) as shown in Fig. 3. ICCA receives the component's information such as State of Charge (SOC) of battery, the generated power of RE generator and the value of critical load and send back the command to each management unit considering its own objective function or any external command from NCCA.

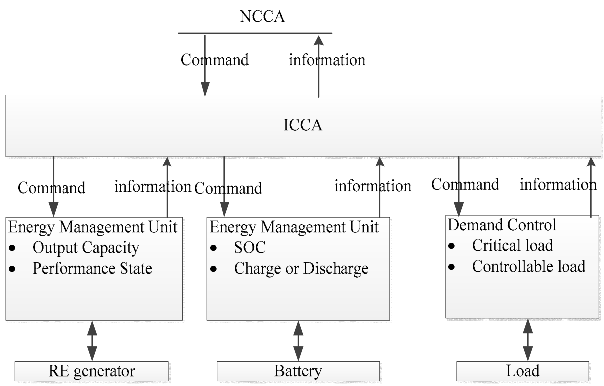

Fig. 3: Individual customer architecture

B. Neighboring community

The strategy of control for each neighboring community can be through the master/slave control. Master/slave is a model of communication where one device or process has unidirectional control over one or more other devices [32]. In this model, one of the customer within each neighboring community is appointed as the NCCC to coordinate the operation of customers within this community. The architecture of a neighboring community has been shown in Fig. 4. NCCC will receive the working parameters of each customer (RE generator output power, total critical load and controllable active power) and send back the control command to each customer within that community. It should be noted that NCCA of each neighboring community exchange data and command with NCCA of its adjacent neighboring communities (right and left) as shown in Fig. 4.

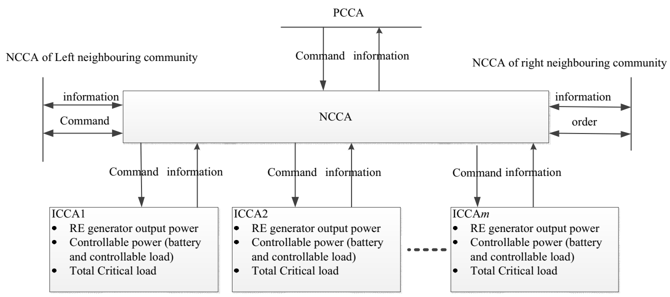

Fig. 4: Neighboring community architecture

Neighboring communities are responsible to coordinate their operation for the under-voltage and over-voltage problems in their phases. Consequently, the operation states of neighboring communities are defined based on the voltage of all customers within the community as shown in Fig. 5. If all customers within the neighboring community are working within desirable range, neighboring community is operating in normal state. In normal state, the aim is to maximize the RE injection to the grid. The management of controllable loads and batteries is only considered whenever there is a command from PCA to the NCCA. As a result, these resources are coordinated with that command.

However, a neighboring community goes to alert state whenever the voltage of one customer violates the desirable level. In this state, depends on the type of voltage problem, the NCCA take the action as follow:

- Over-voltage problem

In this operation mode, NCCA should control the neighboring community injection to the network. In other words, this value can be decreased, but NCCA should prevent the increase of this value by controllable active power within the community. Consequently, if the RE generation increased, the active load (controllable load and battery) of neighboring community would increased to keep the injection to a fixed level (in this state the RE generation should not be curtailed).

- Under-voltage problem:

In this operation mode, NCCA should control the drawn active power from the network. In other words, this value can be decreased, but NCCA should prevent the increase of this value by using the battery discharging within the community. Consequently, if the critical load increased, the the active power of battery would increase to keep the drawn power to a fixed level.

Finally, if the action in alert sate could not keep the voltage of customers within than permissible limits, the emergency state start for neighboring community and the contribution of other neighboring communities are needed. In this state, the distributed control algorithm needs to be initiated to find the contribution of other communities which will be discussed in next section.

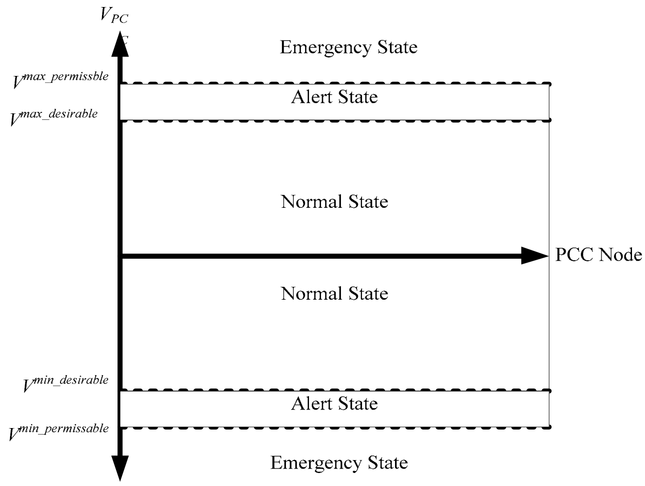

Fig. 5: Operation states of a neighboring community

C. Phase community

Phase communities for each feeder are controlled by PCAs. The architecture of one phase community has been shown in Fig. 6.

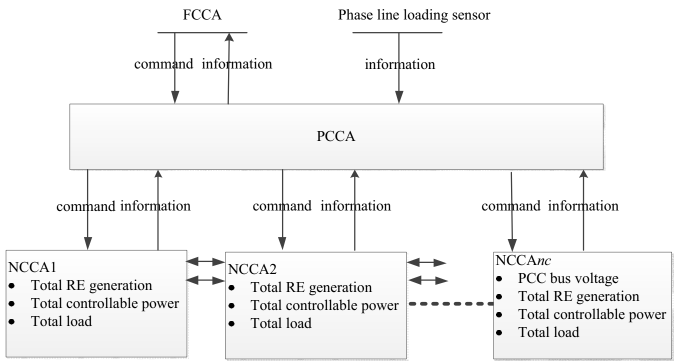

Fig. 6: Phase community architecture

In each phase, PCA is responsible for the voltage regulation (VR_x) and the phase line loading (S_x) parameters. As a result, PCA gets the information of voltage at the last node, total load, RE generation and available controllable power from each NCCA besides the line loading power from the allocated sensor (s). With a simple calculation, if the parameters are in desirable range as shown in (1) and (2), phase community is operating in normal state.

$$VR_x \leq VR^{desirable} \quad (1)$$

$$|S_x| \leq S^{desirable} \quad (2)$$

However, if any of these two parameters for the phase go beyond the limits, phase community goes to the alert and emergency state as shown in (3) and (4), respectively.

$$VR^{desirable} < VR_x \leq VR^{permissable} \; or \; S^{desirable} < |S_x| \leq S^{permissable} \quad (3)$$

$$VR_x > VR^{permissable} \; or \; |S_x| > S^{permissable} \quad (4)$$

In alert state, phase community sent a command to the NCCAs and ask them to control the injection or drawn power of neighboring community by contribution of their controllable loads (no RE generation curtailment).

However, in emergency state, the PCA initializes the distributed control algorithm to find the contribution of each neighboring community to deal with these two problems. Considering each problem, the initialization process for distributed control algorithm has been shown in next section.

D. Feeder community

FCCA is the responsible control agent for feeder community and tries to coordinate the resources on different phases through the PCAs. The architecture of one feeder community is shown in Fig. 7. PCAs of each phase provide the information of voltage at the last node in addition to the total controllable power in phase communities for any aggregation goal.

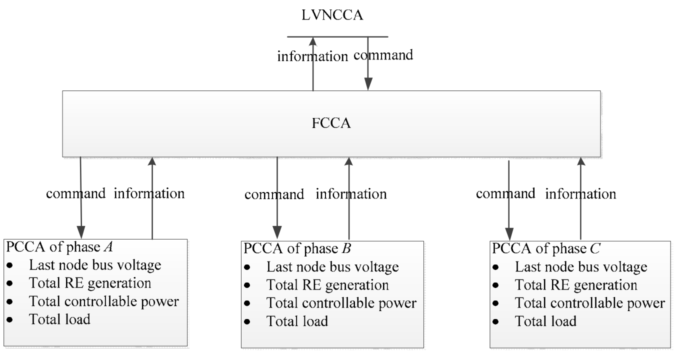

Fig. 7: Feeder community architecture

Different operation states of feeder community are associated with Voltage Unbalancing Factor (VUF) at the last node. If the VUF of the last nodes (VUF_n) is in desirable range as shown in (5), feeder community is working in normal state and FCA coordinates the resources of feeder community based on any command from LVNCA.

$$VUF_n \leq VUF^{desirable} \quad (5)$$

However, alert state starts if VUF_n goes beyond its desirable limit as shown in (6). In this operation mode, FCCA asked neighboring communities in phase with maximum voltage deviation from average (through PCA of that phase) to control their injection or drawn power by their controllable load.

$$VUF^{desirable} < VUF_n \leq VUF^{permissable} \quad (6)$$

However, if the VUF of last node passed the permissible limit, the feeder community goes to emergency sate as shown in (7) and the distributed control algorithm initialized to deal with this operation mode.

$$VUF^{permissable} < VUF_n \quad (7)$$

E. Network community

LV Network community is controlled by LVNCA to coordinate and aggregate the resources in all feeders connected to the LV power transformer as shown in Fig. 8. For this type of community, different operation state is defined base on the LV transformer loading. If transformer loading is in desirable range, LV network community is working in normal state. Otherwise, it goes to alert or emergency state based on the desirable and permissible limit. The only provided information to LVNCCA by FCCAs are the available RE and controllable power in their feeder community for any aggregation aim.

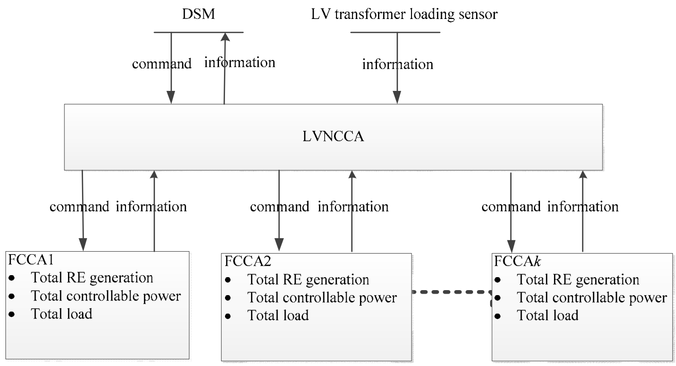

Fig. 8: LV network community architecture

Considering the structure of the proposed approach, the hierarchical communication levels for this structure can be shown in Fig 9. It can be seen that the flow of measuring data is from lower level to the upper level. However, the flow of command is from upper level to the lower level. As noted before, for neighboring communities (NC1, NC2,…,NCn), there is a two-way information and command exchange between adjacent NCCAs.

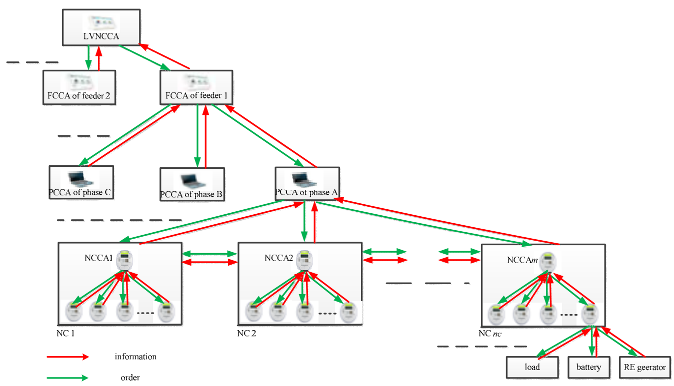

Fig. 9: Communication structure for the proposed approach

III. Distributed Control

A general form of distributed algorithm has been introduced in literatures [33-37]. This paper utilizes distributed control algorithm to coordinate the operation of customers in a LV network. In this approach, network parameters are measured at step $r=\{1,2,\ldots\}$ (r depends on smart-metering system sampling time which can be set to a special value) and for any emergency state, the distributed algorithm allocated k step between r and r+1 to find the value of needed resources in each node to bring the network parameter to desirable range. In addition, in normal state, this algorithm is used to aggregate resources for predetermined operational goal such as load shaving. In distributed algorithm, the first k/2 steps compute the unconstrained allocation and the second half modify the results to account the capacity constraints in each node. In [37] distributed algorithm has been used to coordinate the reactive power contribution to voltage control in sub-transmission network. In LV network, customers cannot contribute in reactive power. Therefore, active power needs to be utilized for any power quality control in LV network. As a result, a modified version of the distributed algorithm in [37] has been utilized for active power contribution of DERs in LV network in different operation modes. A summary of this algorithm is as follows:

In proposed approach, The communication links between different levels of communities can be shown by a graph $G=\{V,E\}$, where, $V=[1,2,\ldots,n]$ is the node set and E is the edge set and $(j,i)\in E$ if node j can receive information from node i. all node that can send information to node j are said to be neighbors of node j and are shown by the set $N_j=\{i\in V:(j,i)\in E\}$. For a simple single phase residential feeder with 2 neighboring communities (NC1 and NC2) and 4 customer communities in each, the proposed communication structure can be shown as Fig. 10:

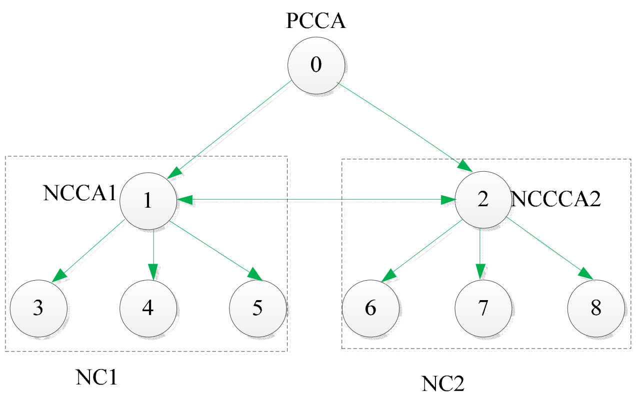

Fig. 10: Communication structure

Let $\pi_j[k]$ be the value of active power demanded from the resources in node j at the k round of information exchange between nodes. Based on distributed algorithms, this value will be updated by (8):

$$\pi_j[k+1]=p_{jj}[k].\pi_j[k]+\sum_{i\in N_j} p_{ji}[k].\pi_i[k] \tag{8}$$

where p_{jj} represents the amount of its value that node j keeps from time-step k, and p_{ji} represents the amount of its value that node i transmits to node j from time-step k.

This linear set of equations for the whole network can be shown as:

$$\pi[k+1]=P[k].\pi[k] \tag{9}$$

Where:

$$\pi=[\pi_1,\pi_2,\ldots,\pi_n] \tag{10}$$

and P is the transition matrix, which depends on the network constraints, and will be calculated, in proposed approach, based on voltage sensitivity to active power as shown in following part.

A. Transition matrix for the network

For the proposed approach, the transition weights of transition matrix (P) are determined based on the bus voltage sensitivity to the active power as follow:

The relation of changes to the power (active and reactive) to changes in bus voltage can be determined by Jacobin matrix as follow:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J1 & J2\\ J3 & J4\end{bmatrix}.\begin{bmatrix}\Delta\theta\\ \Delta|V|\end{bmatrix} \tag{11}$$

$$\begin{bmatrix}\Delta\theta\\ \Delta|V|\end{bmatrix}=\begin{bmatrix}J1 & J2\\ J3 & J4\end{bmatrix}^{-1}.\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}A & B\\ C & D\end{bmatrix}.\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} \tag{12}$$

Considering no contribution of reactive power of DERs in LV network, equation (12) can be written as:

$$\begin{bmatrix}\Delta\theta\\ \Delta|V|\end{bmatrix}=\begin{bmatrix}A & B\\ C & D\end{bmatrix}.\begin{bmatrix}\Delta P\\ 0\end{bmatrix} \tag{13}$$

As a result, the sensitivity of the nodes voltage to the active power can be shown by C matrix as follow:

$$\Delta|V|=C.\Delta P \tag{14}$$

Considering the proposed communication structure, the nodes are only aware of the value of C_{ij} corresponding to their neighbors. As a result to sensitivity matrix is modified as:

$$\overline{C_{ji}}=\begin{cases}C_{ji} & i\in\{N_j\cup j\}\\ 0 & o.w\end{cases} \tag{15}$$

Finally, the component of transition matrix is calculated by the following equation:

$$pij=\frac{\overline{C_{ji}}}{\sum_{i\in(N_j\cup j)}\overline{C_{ji}}} \tag{16}$$

These weights are predetermined and constant for each node of LV network considering the communication structure.

B. *Initialization process of distributed control algorithm in proposed approach*

The initialization process for distributed control algorithm in the proposed structure depends on the operation state of communities. In two operation states (normal and emergency state), distributed control algorithm need to be initialized as follows:

1. Normal state

As noted before, in normal states, the predetermined parameter(s) of community is (are) in desirable range and community is working based on any upper level command. For example, if LVNCCA need a *P* kW which needs contribution of all DERs in LV network, it sends the following order to FCCAs:

$$\pi_y[0] = P.\frac{P_{y\max\_cl}}{\sum_{k=1}^{n_y} P_{k\max\_cl}} \qquad for\ y=1,2,...,n_y \tag{17}$$

Where π_y is the command for the FCCA of *y*th feeder, P_{ymax_cl} is the maximum controllable power of *y*th feeder and n_y is the number of feeders in LV network.

Considering allocated contribution for *y*th feeder community, FCCA of this community send the command as (18) to each PCCA for determining the contribution of each phase.

$$\pi_p[0] = \pi_y[0].\frac{P_{p\max\_cl}}{\sum_{k=a,b,c} P_{k\max\_cl}} \qquad for\ p=a,b,c \tag{18}$$

Where π_p is the command of FCCA to *p*th phase and P_{pmax_cl} is the maximum controllable power of *p*th phase.

Finally, PCA of each phase send the command as shown in (19) to each NCCA to initialize the distributed control algorithm and equation (9) starts to iterate to find the contribution of each node in DER aggregation.

$$\pi_j[0] = \frac{\pi_p[0]}{nc} \qquad for\ j=1,2,...,n_{nc} \tag{19}$$

2. Emergency state

The power quality parameters of network have been sampled in interval of *r*. if any parameter violates its permissible value; the responsible community of that parameter goes to the emergency state and start to communicate with its component to bring the community to normal state by coordination the DERs on that community. Initialization process of distributed algorithm depends to the type of power quality problem which is explained as follow. It should be noted that in initialization process, considering the low distances between nodes which are communicate together, it is assumed for each node *j:*

$$\Delta V_j \approx \Delta V_i \qquad \forall i \in N_j \tag{20}$$

$$\Delta P_j \approx \Delta P_i \qquad \forall i \in N_j \tag{21}$$

$$\frac{\partial V_j}{\partial P_j} \approx \frac{\partial V_i}{\partial P_i} \qquad \forall i \in N_j \tag{22}$$

- Under-voltage and over-voltage problem

As noted before, neighboring communities are responsible for under-voltage or over-voltage problem. Therefore, if there is any voltage problem in node *j*, the initialization of needed active power in that node can be shown as follows:

To correct under voltage an active power need to be injected to node as equation (23):

$$\pi_j[0] = \begin{cases} \dfrac{V^{desirable\_\min} - V_j}{n_j.C_{jj}} & V_j < V^{permissable\_\min} \\ 0 & o.w. \end{cases} \tag{23}$$

Where n_j is the number of elements in the set $\{N_j \cup j\}$.

To correct overvoltage an active power load need to be added in node *j* as follow:

$$\pi_j[0] = \begin{cases} \dfrac{V^{desireable\_\max} - V_j}{n_j.C_{jj}} & V_j > V^{permissable\_\max} \\ 0 & o.w. \end{cases} \tag{24}$$

- Voltage regulation problem

The PCCA are responsible for voltage regulation problem in each phase and initialize the distributed control algorithm to coordinate the DERs in each phase to deal with this problem as follow:

The voltage regulation is defined as follow:

$$VR = \frac{|V_s - V_n|}{V_s} \tag{25}$$

Where V_s is the voltage at the beginning of phase and V_n is the voltage at the last node of phase.

If *VR* violates the $VR^{permissable}$, the phase community will go to emergency state and the PCCA sends the command to the NCCAs based on the following equations:

$$V_n^{update} = V_s.(1 + VR^{desirable}) \tag{26}$$

$$\pi_j[0] = \begin{cases} \dfrac{V_n^{upadate} - V_j}{C_{jj}} & j = nc \\ 0 & o.w. \end{cases}$$

(27)

- Line loading problem

PCCA also has the responsibility for phase line loading. If there is any line loading problem, the PCCA sends the commands to the NCCAs as follow :

$$P^{desirable} = \sqrt{(S^{desirable})^2 - Q_l^2} \tag{28}$$

$$P^{update} = \pm | P^{l} - P^{desirable} | \quad (29)$$

$$\pi_j[0] = \frac{P^{update}}{n_{nc}} \qquad for\, j = 1,2,...,n_{nc} \quad (30)$$

Where: Q_l and P_l are the reactive and active power flowing in line.

- Voltage unbalancing problem

voltage unbalancing is when the voltage amplitude of phases are different or their phase difference are not exactly 120 [38]. FCCA of each feeder is responsible for coordination the DERs in each feeder to deal with any voltage unbalancing problem. Usually the voltage unbalancing problem is due to the voltage amplitude difference on different phases. Consequently, to consider this problem, the VUF can be approximated as shown in (31)

$$VUF_y^n = \frac{Max_{dev.}^n}{V_{ave.}^n} \quad (31)$$

Where VUF_y^n is the voltage unbalancing factor of feeder number y at nth node, $Max_{dev.}^n$ is the maximum voltage deviation from average voltage at nth node and $V_{ave.}^n$ is the average voltage at nth node.

As it can be seen, the phase with maximum voltage deviation should be considered for DERs contribution. Therefore, for any unbalancing voltage problem, the FCCA finds the phase with maximum voltage deviation (for example phase C) and ask the PCCA of that phase to sends command to the neighboring communities in last node as follows:

$$VUF_y^{n\_desireable} = \frac{\left| V_c^{n\_update} - \dfrac{V_a^n + V_b^n + V_c^{n\_update}}{3} \right|}{\dfrac{V_a^n + V_b^n + V_c^{n\_update}}{3}} \quad (32)$$

$$V_c^{n\_update} = \frac{(1 + VUF^{desireable})}{(2 - VUF^{desireable})} . (V_a^n + V_b^n) \quad (33)$$

$$\pi_j[0] = \begin{cases} \dfrac{V_c^{n\_update} - V_c^n}{C_{jj}} & j = nc \\ 0 & o.w. \end{cases} \quad (34)$$

- Transformer loading problem

LVNCA should monitor the LV transformer loading and if there is any problem, it should initiate distributed control algorithm as follows:

In any operation mode, the permissible active power passing from the transformer can be determined as follow:

$$P^{permissable} = \sqrt{S_{rating}^2 - Q_T^2} \quad (35)$$

Where S_{rating} is the transformer rating and Q_T is the reactive power flowing in transformer.

If the active power passing from the transformer (P_T) passed this limit, the LVNCCA send the command to the FCCAs as follows:

$$P^{update} = \pm | P^{T} - P^{permissable} | \quad (36)$$

$$\pi_y[0] = P^{update} . \frac{P_{y\max\_cl}}{\sum_{k=1}^{n_y} P_{k\max\_cl}} \qquad for\ y = 1,2,...,n_y \quad (37)$$

After determining the needed contribution of each feeder, equations (18) and (19) are repeated here to initialize the distributed control algorithm for this operation mode.

After the initialization process for different operation modes, the nodes start to exchange data with their neighbors and they should converge to a feasible solution after *k/2* steps for unconstrained case and after the second *k/2* steps for constrained one between step *r* and *r+1*. At step *r+1*, network parameters are sampled again and if there is still a need for DERs contribution, the initialization and iteration process continue until this process bring the community out of emergency state. Based on the proposed initialization process for each problem and the accuracy of weighted coefficient, just one step (*r=1*) is enough to make the system out of emergency state.

IV. Conclusion

This paper proposed a new paradigm for operation of a LV network to coordinate the DERs in residential area in different operation modes. It can be seen that the proposed approach avoid the complexity of centralized control for LV network while improving the utilization of DERs in LV network by avoiding any renewable energy losses. In addition, the proposed approach has control on different power quality issues like voltage regulation and voltage balancing by the customer's resources (no need for any investment for custom power in LV network).

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