IMPROVED DROOP CONTROL FOR PARALLEL INVERTER SYSTEM WITH LOAD

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ABSTRACT

DC-AC converters are electronic devices used to change DC direct current to alternating current. Three-phase inverter is widely used in power electronics system applications consequently, the DC-AC converters requires a controller with a high degree. Therefore the structure of two parallel three phase inverter with load system has presented. In order to achieve load sharing between parallel inverters, the linear transformed droop control is applied. This control strategy combines frequency and voltage droop method and inverter voltage regulation control scheme. In the external power control structure, the references frequency and magnitude of inverter output voltage are obtained according to the droop characteristics. The improvement of the droop control is made to obtain a more stable voltage and better load sharing between two parallel inverters. The performance of the control strategy is verified in simulation using Matlab/Simulink.

ABSTRAK

Pengubah adalah peranti elektronik yang digunakan untuk menukar aras terus DC kepada arus ulang alik AC. Penyongsang tiga fasa digunakan secara meluas dalam aplikasi sistem kuasa electronik. Oleh yang demikian, pengubah DC-AC memerlukan sebuah pengawal mempunyai tahap yang tinggi. Oleh itu,struktur dua selari penyongsang tiga fasa dengan sistem beban telah dibentangkan. Dalam usaha untuk mencapai perkongsian beban di antara penyongsang selari, kawalan linear pengubah berat digunakan. Stategi kawalan ini menggabungkan frekuensi dan kaedah voltan jatuh dan skim kawalan penyongsang voltan. Dalam struktur kawalan kuasa luaran, frekuensi rujukan dan magnitud voltan keluaran penyongsang diperolehi mengikut ciri-ciri bebanan. Peningkatan kawalan bebanan itu dibuat untuk mendapatkan voltan yang lebih stabil dan perkongsian beban yang lebih baik di antara dua penyongsang selari. Prestasi strategi kawalan ini telah disahkan dalam simulasi dengan menggunakan Matlab Simulink.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
DC	Direct current
VSI	Voltage source inverter
CSI	Current source inverter
DER	Distributed energy resources
DG	Distributed generation
UPS	Uninterruptible power supply
WC	Wireless control
RES	Renewable energy system
ASD	Adjustable speed drive
PCM	Power control mode
VCM	Voltage control mode
PMS	Power management system
EMC	Electromagnetic compatibility
CM	Common mode
PI	Proportional- integral
PID	Proportional- integral -derivative
PM	Permanent magnet
PV	Photo voltaic
PWM	Pulse width modulation
L	Self-inductance
E	Electromotive force
v	Phase terminal voltages
v_f	Field terminal voltage
P	Real power
Q	Reactive power
IGBT	Insulated Gate Bipolar Translator

CHAPTER 1

INTRODUCTION

1.1 Introduction

Distributed generation has attracted people's attention greatly due to its reducing the emission of greenhouse gases, increasing the reliability of the system and alleviating the pressure of power transmission, but output power is affected by the environment, and when there is a fault in the power system, the distributed generation must be quitted [1] which has restricted its application.

The Distributed energy resources (DERs) based microgrid is able to deliver electric power to the grid and able to supply the local loads to ensure reliable power supply of some important and sensitive loads when the grid fails [10]. Most of the DERs need power electronics interfaces to be connected to the microgrid [8, 9]. Consequently, inverters or ac-dc-ac converters are adopted to connect the DERs to the local ac bus with the aim to share loads properly.

Distributed generation systems and microgrids are taking importance when trying to increase the renewable energy penetration. In this sense, the use of intelligent power interfaces between the sources and the grid is mandatory. Usually, in order to inject energy to the grid current-source inverters (CSI) are used, while in island or autonomous operation voltage-source inverters (VSI) are used [2].

Voltage sources inverters are very interesting since they don't need any external reference to stay synchronized [3], they can operate in parallel with other inverters by using frequency and voltage droops, forming autonomous microgrids [4]. When these inverters are required to operate in grid-connected mode, they often change its behavior from voltage to current sources [5]. To achieve flexible microgrids, which are able to operate in both grid connected and island mode.

In distributed generation (DG) systems, there may be more than one inverter acting in parallel. Therefore, distributed uninterruptible power supply (UPS) systems as well as the parallel operation of voltage source inverters with other inverters or with the grid, are sensitive to disturbances from the load or other sources and can easily be damaged by over current. Hence, careful attention should be given to system design and the control of parallel operation of inverters. When two or more inverters operate in parallel, the following features must be achieved: (1) amplitude, frequency and phase synchronization among the output voltages of inverters, (2) proper current distribution according to the capacities, (3) flexibility and (4) hot-swap feature at any time [6].

The conventional control strategies for the parallel-connected inverters can be classified into two types; active load sharing or current distribution. The droop control method for the parallel-connected inverters can avoid the communication mismatch of reference current. It is also defined as wireless control (WC) with no interconnection between the inverters. In this case, the inverters are controlled in such a way that the amplitude and frequency of the reference voltage signal will follow a droop as the load current increases and these droops are used to allow independent inverters to share the load in proportion to their capacities [7].

The main task of this project is to design the control of the parallel inverter system of standalone microgrid, and the droop control is applied to achieve good load sharing in low voltage microgrid. Improvement of the droop control is to keep the voltage more stable meanwhile to get a better reactive power sharing the block.

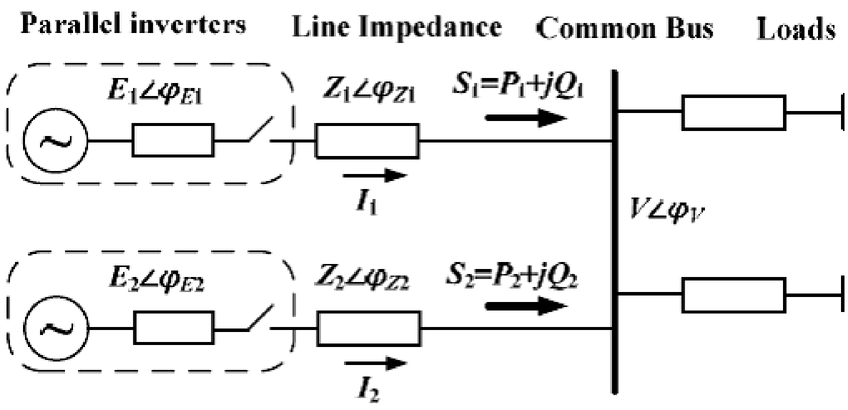

Figure 1.1 Equivalent circuit of parallel-inverters-based microgrid

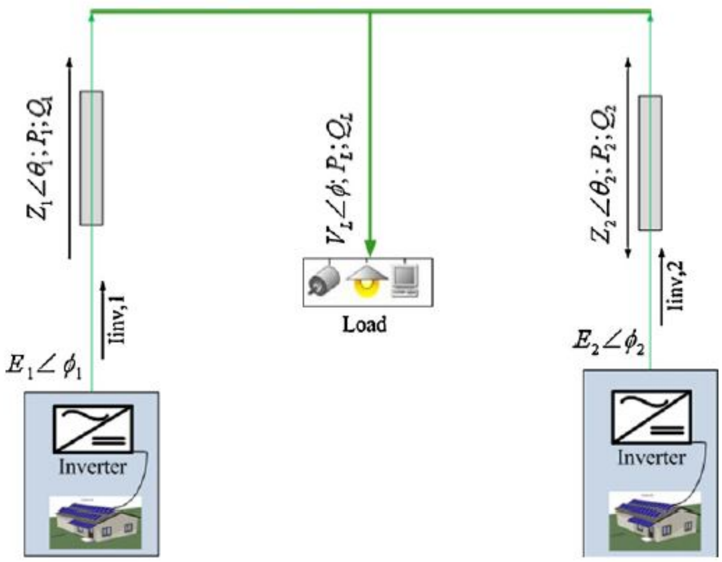

Figure 1.2 Power sharing through droop control method.

1.2 Problem statement

There is two type to connecting between parallel inverters are wire communication between inverters and droop control. For first type it has disadvantages if one of parallel inverter fail it will effect to the other, the cost of these connecting will be high so the droop control method for the parallel-connected inverters can avoid the communication mismatch of reference current. It is also defined as wireless control (WC) with no interconnection between the inverters. In this case, each inverter has different power and when connecting two parallel inverters to load, the output of voltage of inverter not stable and the inverters did not sharing the load. The inverters need controller to control and make the voltage stable and sharing the current to the load. The droop method controlled inverter by parameters for this control in such a way that the amplitude and frequency of the reference voltage signal will follow a droop as the load current increases and these droops are used to allow independent inverters to share the load in proportion to their capacities.

1.3 Objective

The main objectives of this project are:

1. To design two parallel inverter system of standalone mode.
2. To control two parallel inverters by using droop control method.
3. To control voltage and current for the inverters to load.

1.4 Scope of project

This project is improving droop control for parallel inverters.

The scopes of this project are:

1. The parallel inverters with load will be designed in MATLAB.
2. The droop control method to control parallel inverter using MATLAB.

3. To get a better voltage and current output sharing between parallel inverters using MATLAB.

CHAPTER 2

LITERATURE REVIEW

2.1 Distribution generation

Distribution generations (DG) are electric power generators that produce electricity at a site close to customers or that are tied to an electric distribution system. Distributed generators include, but are not limited to synchronous generators, induction generators, reciprocating engines, micro turbines (combustion turbines that run on high-energy fossil fuels such as oil, propane, natural gas, gasoline or diesel), combustion gas turbines, fuel cells, solar photovoltaic, and wind turbines.

The concept of DG has been recently become commercially extensive. distributed generation is the interconnection of alternative energy resources to the utility grid system close to the load Point to mitigate the request for and expansion of the electric transmission system [11]. DG is meant to shift the structure of the utility system from a centralized, radial system to energy source connected on the distribution level.

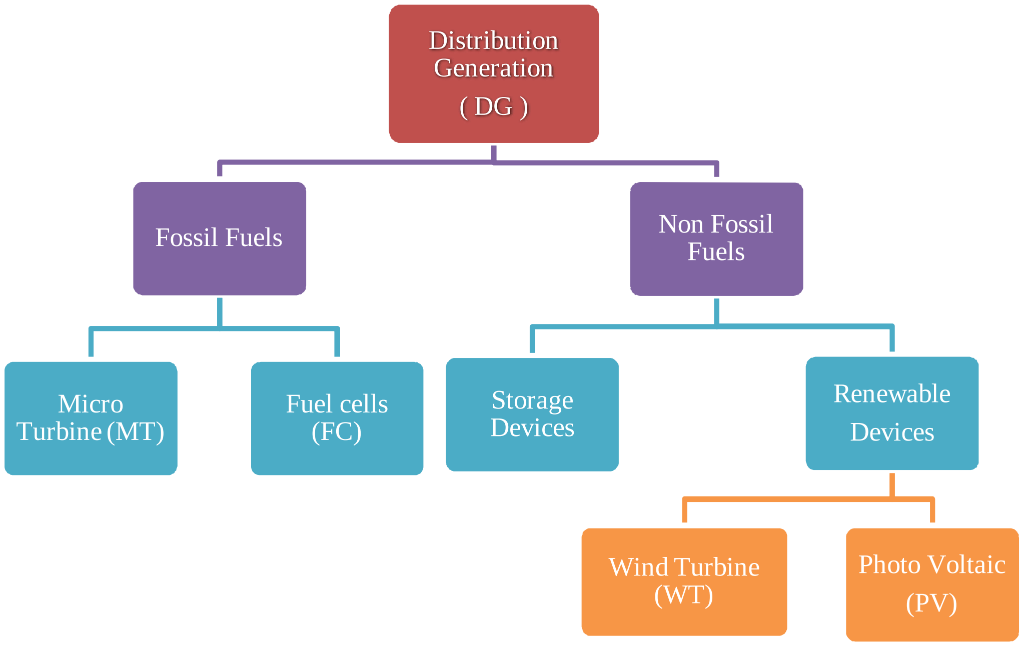

Figure 2.1: Distribution generation technology

2.1.1 Benefits of Distributed Generating Systems

Distributed Generation:

- Has a lower capital cost because of the small size of the DG
- May reduce the need for large infrastructure construction because the DG can be constructed at the load location.
- If the DG provides power for local use, it may reduce pressure on distribution and transmission lines.
- With some technologies, produces zero or near-zero pollutant emissions over its useful life.
- With some technologies such as solar or wind, it is a form of renewable energy.

The main advantage of renewable energy systems (RES) is no fossil fuels involved because it is free like sun and wind. This decreases the operational cost of renewable energy systems and reduces operational risks. The major drawback is the initial investment in renewable energy systems, which is often larger than for non-RES. For instance, a gas turbine system may be built for 500 EUR per kW, while for a wind turbine the investment is more than 900 EUR per kW.

Other disadvantages of RES are the specific requirements of the site and the unpredictability of the power generated. The availability of renewable energy (sun, wind, water) largely determines the feasibility of a renewable energy system and this may raise environmental issues. Figure 2.2 shows renewable energy sources. The unpredictability of RES also means a higher cost for balancing the electricity grid and maintaining reserve capacity e.g. in the event that the wind drops or increases above the operating area of wind turbines. DG and RES have advantages and disadvantages that might be energy-related, grid-related or environmental which need to be evaluated on a case-by-case basis.

Most of the distribution energy resources need power electronics interfaces to be connected to the microgrid [8, 9]. Consequently, inverters are adopted to connect the DERs to the local ac bus with the aim to share loads properly.

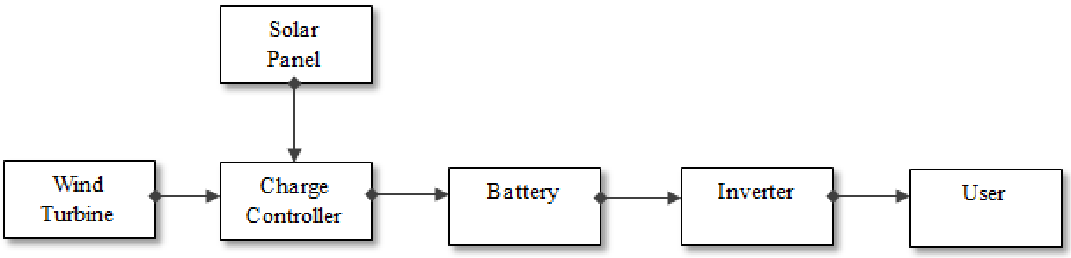

Figure 2.2: renewable energy sources

2.2 Inverter

Power inverter, or inverter, is an electrical power converter that changes direct current (DC) to alternating current (AC). The converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

Solid-state inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries. Figure 2.3 shows the general block diagram.

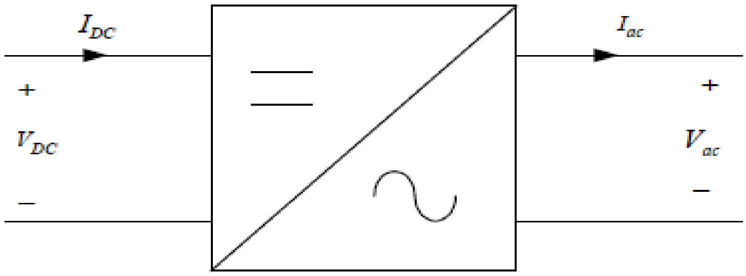

Figure 2.3: General block diagram

2.2.1 Voltage Source Inverter

The type of inverter that most commonly used is voltage source inverter (VSI) where AC power provides on the output side function as a voltage source. The input DC voltage may be an independent source such as battery, which is called a ’DC link’ inverter. These structure are the most widely used because they naturally behave as voltage source as required by many industrial application, such as adjustable speed drives (ASDs), which are the most popular application of inverters. Figure 2.4 shows the voltage source inverter. Single phase VSIs are used in low range power application where the three phase VSIs is used in medium to high-power application. The main purposes of three-phase VSIs are to provide a three-phase voltage source, where the amplitude, phase and frequency of the voltage should be controllable [18].

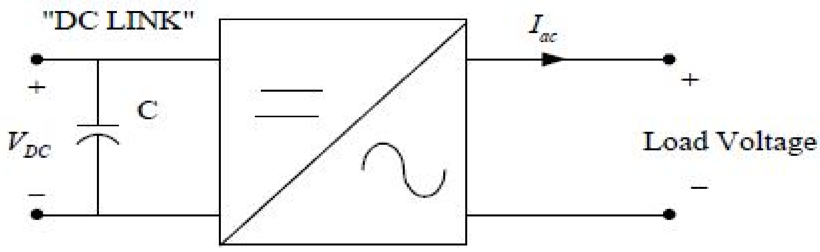

Figure 2.4: Voltage Source Inverter (VSI)

2.2.2 Current Source Inverter

Respectively, CSI the DC source appears as a constant current and the voltage is changing with the load. The protection filter is normally a capacitance in parallel with the DC source The main advantage of the current source inverter is that it increases the voltage towards the mains itself. Figure 2.5 shows the current source inverter [18].

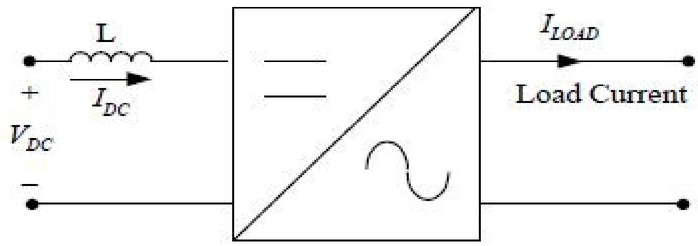

Figure2.5: Current Source Inverter (CSI)

2.2.3 Three Phase Inverter

Three-phase counterparts of the single-phase half and full bridge voltage source inverters are shown in Figures 2.6 and 2.7. Single-phase VSI cover low-range power applications and three-phase VSI cover medium to high power applications. The main purpose of these topologies is to provide a three-phase voltage source, where the amplitude, phase and frequency of the voltages can be controlled.

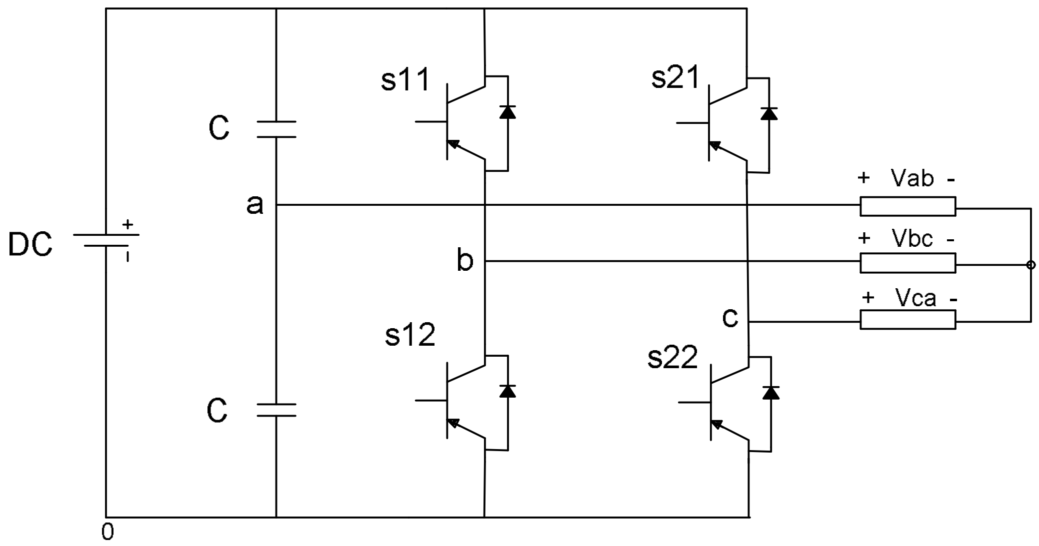

Figure 2.6: Three-Phase Half Bridge Inverter

The three-phase dc/ac voltage source inverters are extensively being used in motor drives, active filters and unified power flow controllers in power systems and uninterrupted power supplies to generate controllable frequency and ac voltage magnitudes using various pulse width modulation (PWM) strategies.

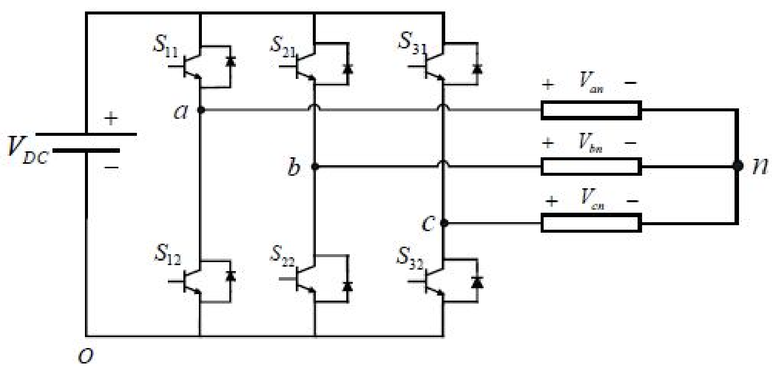

Figure 2.7: Three-phase Full –Bridge Inverter

The input dc is usually obtained from a single-phase or three phase utility power supply through a diode-bridge rectifier and LC or C filter.

2.3 Control of inverter

When interfacing distributed energy resources with the utility grid, a single inverter can typically operate in two modes: one is the grid-connected mode and the other is the isolated mode. Corresponding to these two modes, the controller has two distinct modes of operation: power-control mode (PCM) and voltage-control mode (VCM) [16].

2.3.1 PCM control

The grid-connected mode of operation requires that the power management system (PMS) shall not actively regulate the voltage; hence the logical choice of control is a form of current regulation. Here we use power flow control as a means of current regulation. The control calculates current references for the system by the measured voltage and desired power levels, as described in Figure 2.8, which shows the block diagram of the power control system, where the current references are produced by the outer power control loops.

2.3.2 VCM control

The isolated mode of operation requires the control operation to differ from that of the grid-connected mode. In this mode, the system has already been disconnected from the utility grid; therefore the voltage is no longer regulated by the grid. Because of this, the control now needs to actively regulate the voltage of the local load, hence a VCM control is o be used to regulate the output of the VSI. Figure 2.8 also shows a block diagram of this control mode, where the current references are produced by the inner voltage control loops.

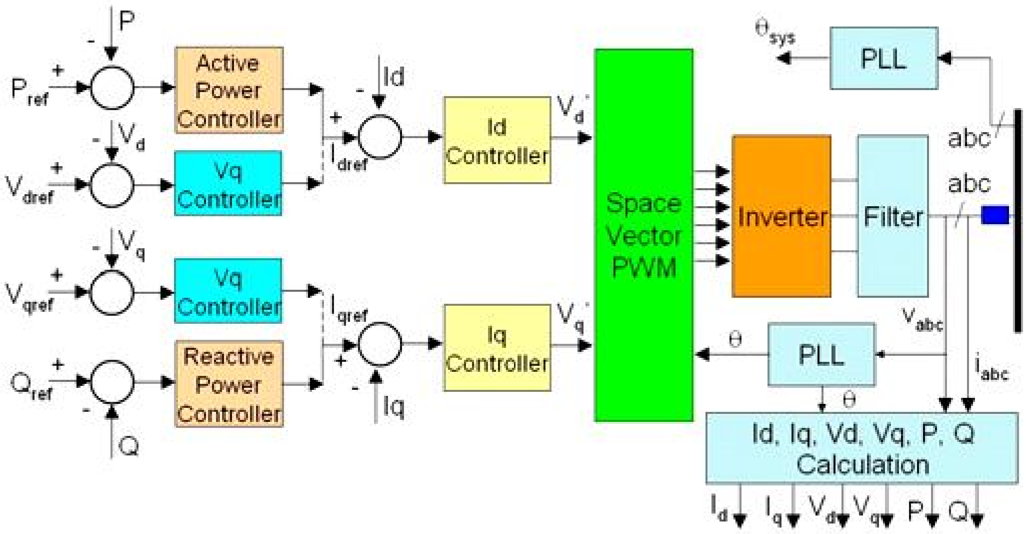

Figure 2.8: Block Diagram of Space Vector PWM Control of Single Voltage Source Inverter.

2.4 Multilevel parallel inverters

In the following will present a control method for multiple parallel connected inverters operating in the isolated mode. Figure 2.9 depict the main circuit of the system and the system parameters. The system comprises three inverters each of which can operate in the PCM mode or the VCM mode. The DC components in the microgrid could be a smaller-scale DC microgrid, or a DC voltage bus linking several distributed generation and energy storage units.

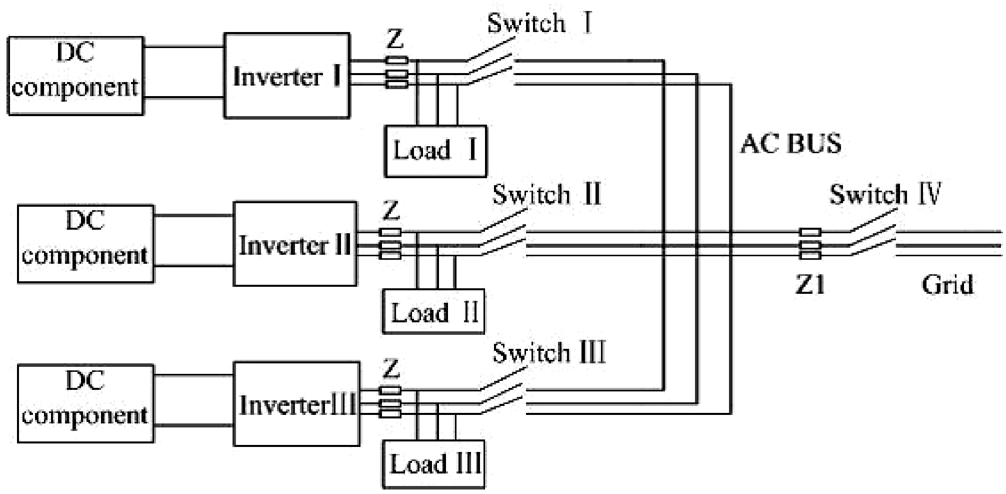

Figure 2.9: Main Circuit of a Microgrid Formed by three Parallel Inverters.

In Figure 2.9, when the switch IV is on, all these three inverters can be connected to the grid. They can operate in PCM and their output power can be controlled respectively. While the switch IV is off, all these three inverters are operating in the isolated mode. Based on the single inverter control, we know that a single inverter can operate in two modes. When the inverter connects to the grid, the inverter can operate in the PCM mode. While the inverter disconnects from the grid, the inverter may need to maintain the bus voltage. When these three inverters all operate in the isolated mode, it is possible to selectively operate Inverter I in the VCM mode to maintain the AC bus voltage. If the AC bus voltage is constant, from the viewpoint of the other inverters, it is the same situation as the utility grid. So Inverters II and III can work in PCM and their control aim is still the PCM mode.

2.4.1 Advantages and disadvantages of multilevel inverter

A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of a multilevel converter can be briefly summarized as follows.

- Staircase waveform quality: Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stresses; therefore electromagnetic compatibility (EMC) problems can be reduced.
- Common-mode (CM) voltage: Multilevel converters produce smaller CM voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive can be reduced. Furthermore, CM voltage can be eliminated by using advanced modulation strategies.
- Input current: Multilevel converters can draw input current with low distortion.
- Switching frequency: Multilevel converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency.

- One particular disadvantage is the greater number of power semiconductor switches needed. This may cause the overall system to be more expensive and complex

2.5 Control system

A control system is a device or set of devices to manage, command, direct or regulate the behaviour of other devices or systems. A control mechanism is a process used by a control system. There are many controller systems user in the inverter controller such as PI controller, PID controller and droop controller.

2.5.1 PI control

PI controller is proposed is to improve the performance of the soft switched inverter. The duty ratio of the inverter is controlled by PI controller. To provide optimal performance at all operating conditions of the system PI controller is developed to control the duty ratio of the inverter.

PI control is a traditional linear control method used in industrial applications. The linear PI controller controllers are usually designed for dc-ac inverter and dc-dc converters using standard frequency response techniques and based on the small signal model of the converter. A Bode plot is used in the design to obtain the desired loop gain, crossover frequency and phase margin. The stability of the system is guaranteed by an adequate phase margin. However, linear PID and PI controllers can only be designed for one nominal operating point. A boost converter's small signal Model changes when the operating point varies. The poles and a right-half plane zero, as well as the magnitude of the frequency response, are all dependent on the duty cycle. Therefore, it is difficult for the PID controller to respond well to changes in operating point. The PI controller is designed for the boost converter for operation during a start-up transient and steady state respectively [15].

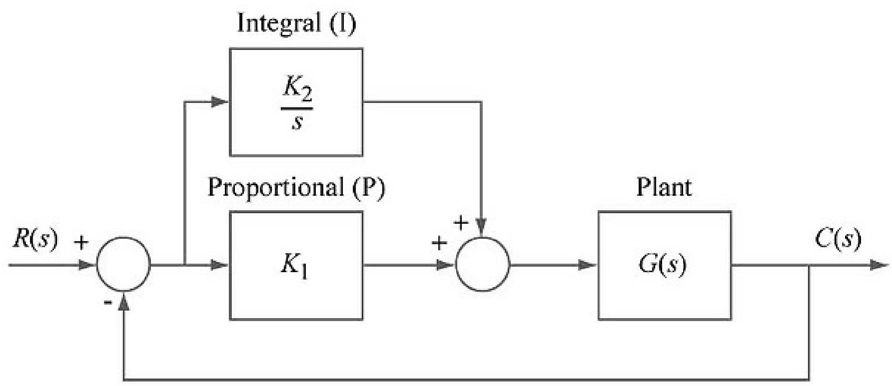

Figure 2.10 Block diagram of the PI controller.

2.5.2 PID controller

Proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs.calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, a damper, or the power supplied to a heating element.

In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the best controller. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability.

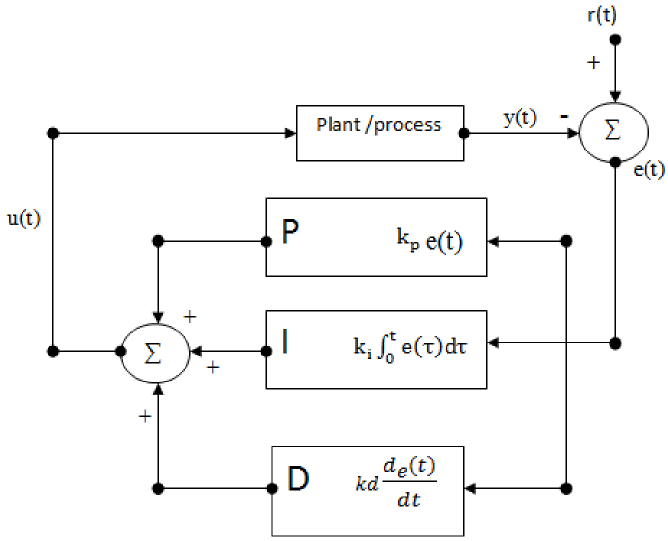

Figure2.11: A block diagram of a PID controller in a feedback loop

2.6 Droop control

Droop control strategy is proposed to enhance the dynamic performance of the parallel inverters in micrograds without communication wire interconnections. A wireless controller is developed by taking the active and reactive current as the control variables, the droop control variables is taken to ensure the power sharing accuracy, and additional terms are added to the droop controller to enhance the dynamic performance.

2.6.1 Review of the conventional droop control

A typical microgrid is shown in Figure 2.12, which includes PV panels, wind turbines, batteries and super capacitors. Since most of the micro sources are DC form or need to be converted to DC form first, voltage source inverters are used for each of the micro sources. The inverters can be modelled as a voltage source connected to the ac bus through complex impedance, as shown in Figure 2.13

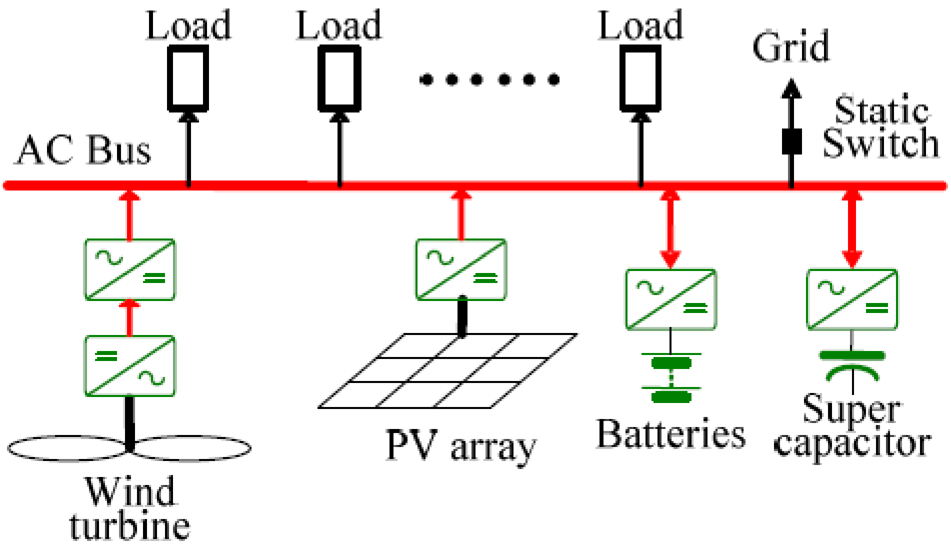

Figure 2.12: Typical Microgrid Diagram [17]

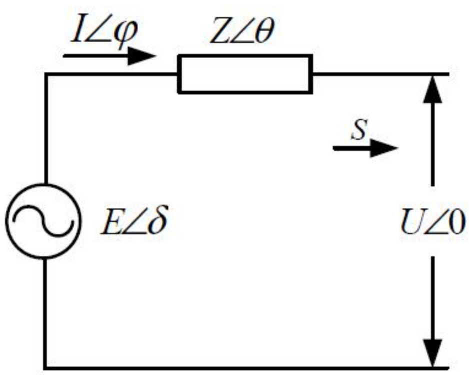

Figure 2.13: Equivalent model of voltage source inverter connected to an ac bus.

The active and reactive power can be expressed as. [13]

$$P = \frac{U}{Z^2}[R(E\cos\delta - U) + XE\sin\delta] \qquad (2.1)$$

$$Q = \frac{U}{Z^2}[X(E\cos\delta - U) + RE\sin\delta] \qquad (2.2)$$

Where $Z\angle\theta = R + jX$ is the sum of inverter output impedance and line impedance for the overhead lines, the line impedance mainly exhibits inductive characteristic, that is X>>R, and hence $\theta \approx 90^{o}$, then the equations (2.1) and (2.2) can be simplified as

$$P = \frac{EU}{X}\sin\delta \qquad (2.3)$$

$$Q = \frac{U(E\cos\delta - U)}{X} \qquad (2.4)$$

In practical applications, the phase error δ of the voltage source and the ac bus is usually small, then $\sin\delta \approx \delta$ and $\cos\delta \approx 1$. In this way, it can be derived that the active power is predominantly dependent on the phase error δ, while the reactive power mainly depends on the voltage amplitude E. At the same time, changing frequency causes dynamic change of the phase error δ. Consequently, the conventional droop control method is developed based on the decoupled control of the active power and reactive power via output frequency and voltage amplitude.

$$\omega - \omega_0 = -k_p.(P - P_0) \qquad (2.5)$$

$$E - U_0 = -k_q.(Q - Q_0) \qquad (2.6)$$

In equations (2.5) and (2.6), ω_0 and U_0 are the inverter output angular frequency and voltage amplitude without load, P_0 and Q_0 are the reference of the active and reactive power, k_p and k_q are the droop coefficients for the frequency and voltage amplitude, respectively.

For a given operation point, only two droop coefficients k_p and k_q can be adjusted to change the power sharing accuracy and dynamic response of the conventional droop control, and the resistance of the inverter output impedance or line impedance is ignored which must be considered under low voltage microgrids conditions. Therefore, the conventional droop control method needs to be improved for microgrids applications.

2.6.2 Droop control strategy

The droop control technique is commonly used in rotating interfaces of power sources. The (P, f) droop loop allows parallel connected generators to operate in a safe way sharing variations in the load/demand in a pre-determined way without any dedicated communication means. Similarly, the (Q, V) droop loop is used to minimize the circulation currents that would appear if the impedance between the inverters and a common load were not the same [19]. To limit the current spikes due to the initial phase error or grid fault, active current and reactive current are obtained in equation (2.7) as the control variables. In low voltage microgrids, the line resistance can't be ignored, therefore, the active and reactive currents are coupled by line resistance and inductance. An orthogonal convert is taken to obtain the decoupled control variables as given by equation (2.8). It can be seen that the new control variables I_a' and I_r' are proportional to the inverter output voltage phase error δ and amplitude E respectively when δ is small. As mentioned in part 2.6.1, the conventional droop control method presents a decoupled characteristic between P, Q and δ, E at the expense of ignoring the line resistance. The proposed strategy decouples I_a' and I_r' with consideration of the line resistance, therefore, it is appropriate for microgrid use.

$$\begin{bmatrix} I_a \\ I_r \end{bmatrix} = \frac{1}{U}\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \frac{1}{Z^2}[R(E\cos\delta - U) + XE\sin\delta] \\ \frac{1}{Z^2}[X(E\cos\delta - U) + RE\sin\delta] \end{bmatrix} \tag{2.7}$$

$$\begin{bmatrix} I_a' \\ I_r' \end{bmatrix} = T\begin{bmatrix} I_a \\ I_r \end{bmatrix} = \begin{bmatrix} \frac{E\sin\delta}{Z} \\ \frac{E\cos\delta - U}{Z} \end{bmatrix} \tag{2.8}$$

Where $T = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} = \begin{bmatrix} \frac{X}{Z} & -\frac{R}{Z} \\ \frac{R}{Z} & \frac{X}{Z} \end{bmatrix}$

The Figure2.14, shows I_{a0}'and I_{r0}' are the transformed active and reactive current reference, ω_0 and U_0 are the inverter output angular frequency and voltage amplitude without load, v_{ref} is the inverter output voltage reference which is synthesized by ω and E. Three phase instantaneous power theory [14] is used to calculate the inverter output active power P and reactive power Q. The matrix T is the orthogonal transformation in equation (2.8). The droop functions of the proposed strategy are given by equations (2.9) and (2.10).

$$\omega - \omega_0 = -k_{ap}.(I'_a - I'_{a0})$$

$$-k_{ai}.\int_{-\infty}^{t}(I'_a - I'_{a0})d\tau - k_{ad}.\frac{d(I'_a - I'_{a0})}{dt} \qquad (2.9)$$

$$E - U_0 = -k_{rp}.(I'_r - I'_{r0}) - k_{rd}.\frac{d(I'_r - I'_{r0})}{dt} \qquad (2.10)$$

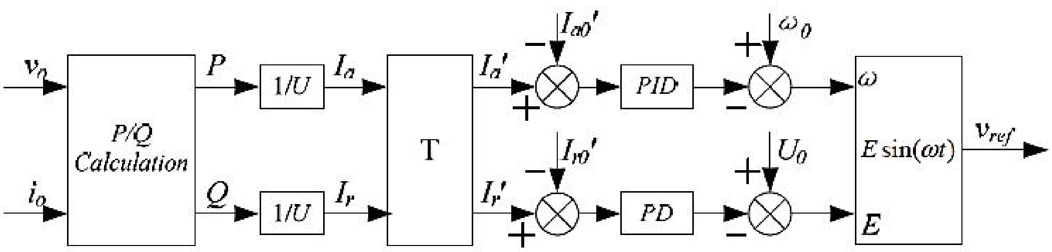

Figure 2.14: The control scheme

As illustrated, the droop control strategy takes the transformed active current I_a' and reactive current I_r' as the control variables, and integral derivative terms are added to the droop functions to enhance the dynamic response of the inverters. The coefficients of the controller can be designed by calculating the small signal function of $\boldsymbol{\delta}$ through equation (2.8) to equation (2.10), and using root locus method to observe the impact of these coefficients over the system dynamics.

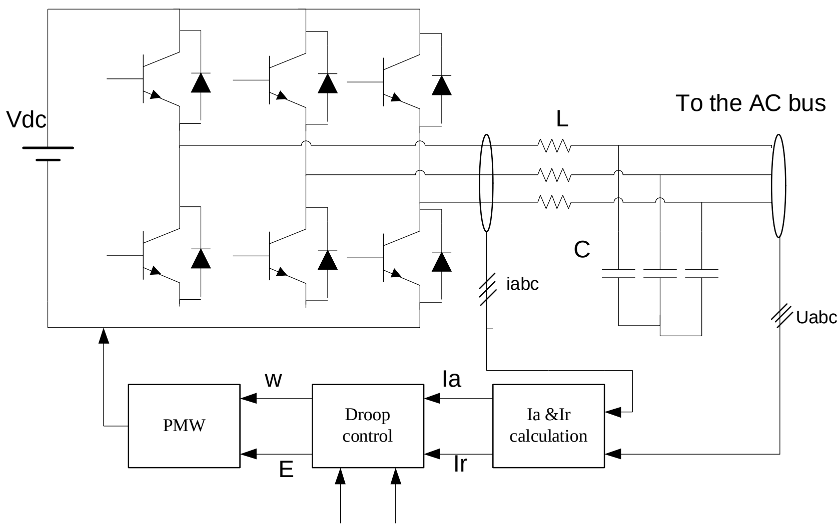

Figure 2.15: Example of control scheme using in three phase voltage source inverter

The overall diagram of the control scheme using in three phase voltage source inverter applications is given graphically in Figure 2.15. As seen, only the inverter output voltage u_{abc} and output current i_{abc} which are locally measurable are using to implement the control scheme, and then the transformed active and reactive current are calculated to realize the droop control algorithm, finally the PWM driving signals are produced through the PWM generator.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, it presents the block diagram and the flow chart of this project. Also it will prove the equation for droop controller to share the loading for two parallel inverters.

3.2 Droop control

The analysis will be done for the $Q - \omega$ and $P - E$ droop. The sketch of two inverters with resistive output impedances R_{o1} and R_{o2} operated in parallel is shown in Figure. 3.1. The line impedances are omitted because the output impedances of the inverters can be designed to dominate the impedance from the inverter to the ac-bus. The reference voltages of the two inverters are, respectively

$$v_{r1} = \sqrt{2}E_1 \sin(\omega_1 + \delta_1)$$
$$v_{r2} = \sqrt{2}E_2 \sin(\omega_2 + \delta_2)$$

Here, E1, E2 are the RMS voltage set-points for the inverters. The power ratings of the inverters are $S^*_1 = E^*I^*_1$ and $S^*_2 = E^*I^*_2$. They share the same load voltage.

$$v_0 = v_{r1} - R_{o1}i_1 = v_{r2} - R_{o2}i_2 \qquad (3.1)$$

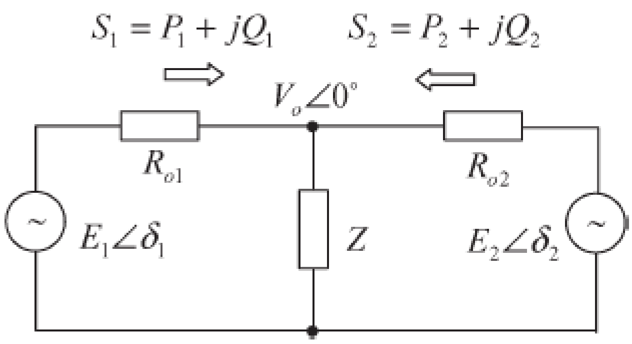

Figure 3.1 Two parallel inverters connecting to the load

The active and reactive powers of each inverter injected into the bus are

$$P_i = \frac{E_i V_o \cos\delta_i - V_o^2}{R_{oi}} \qquad (3.2)$$

$$Q_i = \frac{E_i V_o}{R_{oi}} \sin\delta_i \qquad (3.3)$$

To share the loads of order the inverter, the normal droop controller

$$E_i = E^* - n_i P_i \qquad (3.4)$$

$$\omega_i = \omega^* - m_i Q_i \qquad (3.5)$$

As shown in Figure. 3.2, is widely used to generate the amplitude and frequency of the voltage reference v_{ri} for Inverter I, where ω^* is the rated frequency. Note that, from equation (3.3), the reactive power Q_i is proportional to$-\delta_i$ for a small power angle (δ_i) in order to make sure that the $Q - \omega$loop is a negative feedback loop so that it is able to regulate the frequency, the sign before m_iQ_i in equation (3.5) is positive, which makes it a boost term. The droop coefficients n_i and m_i are normally determined by the desired voltage drop ratio $n_iP^*_i$ /E* and frequency boost

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