

Integrating Droop and Direct Current Vector Control for Control of Parallel inverters in Islanded Microgrid

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ABSTRACT

Now a days Reactive power sharing between parallel units in microgrid is most important challenge associated with the droop control of parallel inverters. To overcome this challenge we integrate Direct Current Vector Control (DCVC) method with the droop control method. However, maintaining microgrid voltage stability while sharing active power between parallel inverters should be the primary objective for a microgrid. This study proposes to integrate droop and direct-current vector control (DCVC) techniques for active power sharing and bus voltage control within a microgrid. Voltage level drop associated with reactive power sharing is another problem in droop control of parallel inverters in islanding mode. To maintain voltage level of the microgrid by injecting needed reactive power we use DCVC controlled units, power that is determined automatically from the droop-DCVC controllers. The Proposed system is made connection with PV source and MLI fed Induction motor. The performance of system was evaluated through MATLAB/SIMULINK software.

Index Terms – droop control, microgrid, vector control, reactive power sharing

I.INTRODUCTION

Any time a micro grid is implemented in an electrical distribution system, it must be well planned to avoid problems. For microgrids to work properly, a switch must open and the DER must be able to carry the load on the islanded section. This includes maintaining suitable voltage and frequency levels for all islanded loads. Depending on the switch technology, momentary interruptions may occur during transfer from grid-parallel to islanded mode. If power is lost, the DER assigned to provide power to the intentional island should be able to restart and pick up the island load after the switch has opened. Power flow analysis of island scenarios should be performed to ensure that proper voltage regulation is maintained and establish that the DER can handle inrush currents from large loads. The DER must be able to load- follow during islanded operation and sense if a fault current has occurred downstream of the switch location. When power is restored on the utility side, the switch must not close unless the utility and islanded portions are in synchronism. This requires measuring the voltage on both sides of the switch to allow synchronization of the island and the utility.

Islanded operation can be considered as one of the most attractive features of a microgrid, since it ensures service continuity in the event of a grid interruption [1]. When islanded, distributed generation (DG) units must be able to cooperatively regulate the voltage and frequency, and maintain the generation/load power balance

within the microgrid. Accordingly, droop control concepts have been widely adopted in [2]–[4] to provide decentralized power sharing control without relying on communications. Moreover, communications can be used, in addition to droop control, as a noncritical element in a higher control layer known as secondary control to enhance the performance of the islanded microgrid without reducing the system reliability. A microgrid (MG) reflects a new way of designing and building future smart grids [1]. A microgrid can be described as a cluster of loads, Distributed Generation (DG) units and Energy Storage Systems (ESSs) operated in coordination to reliably supply electricity and connected to the host power system at the distribution level at the Point of Common Coupling (PCC). It is expected that the development of MGs has the potential to bring a number of benefits into the electric power system [2]

Microgrids have received increasing attention as a means of integrating distributed generation such as combined heat and power (CHP) into the electricity network. Usually described as confined clusters of loads, storage devices and small generators (< 500 kW), these autonomous networks connect as single entities to the public distribution grid [1]–[3]. The low-voltage non-50/60-Hz power output of many forms of small-scale distributed generation—including wind turbines, fuel cells, reciprocating gas engines, and energy storage—means that power-electronic converter interfaces are required. While such low-inertia interfaces tend to make microgrids sensitive to disturbances, they enable flexible operation of the connected generators

In recent years, in order to solve the power shortage and environmental pollution problems using traditional fossil fuels, the development and the use of solar, wind and other polluting renewable energy is increasingly subject to people's attention[1]. Power electronics rapid development for distributed power supply, has opened up a new path for the renewable energy. With multiple distributed generation units in microgrid can be operated in grid or islanded mode. In islanding mode utilizing multiple distributed power inverter parallel way to achieve high capacity and redundant power supply, can greatly improve the reliability of the power supply system[2].

II.DROOP CONTROL IN ISLANDING MODE

A. Droop Control Method

Assuming a DG unit is connected to a common bus through a transmission line with impedance $Z = R + jX$ as shown by Fig.1 [13], in which the common bus voltage is taken as the reference. The apparent power S delivering to the bus from the DG equals:

$$S = P + jQ = (E \angle \phi) I^* \quad (1)$$

where P and Q are active and reactive powers delivering to the bus from the DG, respectively, and I is the current flowing through the transmission line from the DG unit to the bus, which is given by:

$$I = \frac{E \angle \phi - V \angle 0}{Z \angle \theta} \quad (2)$$

where E and V are the magnitude of the inverter output voltage and common bus voltage, respectively, φ is inverter output voltage's phase angle, $\theta = \tan^{-1}(X/R)$ is the line impedance's phase, and Z is the line impedance magnitude.

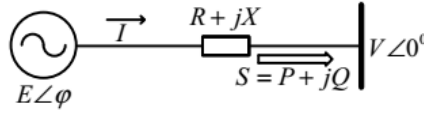


Fig. 1.DG unit connected to AC bus

After some mathematical manipulation, the active and reactive powers are defined as below [13]:

$$P = \frac{EV}{Z} \cos(\theta - \varphi) - \frac{V^2}{Z} \cos \theta \quad (3)$$

$$Q = \frac{EV}{Z} \sin(\theta - \varphi) - \frac{V^2}{Z} \sin \theta \quad (4)$$

According to Eqs.(3) and (4) ,it is obvious that output active and reactive powers of the inverter unit are strongly dependent on line impedance . if the line is inductive dominant ,i.e. $\theta = 90^\circ$ $Z = X$,inverters output active and reactive powers are expressed as (5)and (6);

$$P = \frac{EV}{X} \sin \varphi \quad (5)$$

$$Q = V/X \cdot (E \cos \varphi - V) \quad (6)$$

From Eqs. (5) and (6), it could be concluded that for a small phase angle of the inverter output voltage (i.e. $\sin \varphi, \cos \varphi \cong 1$), the active power is influenced by the phase angle while the reactive power is dependent on voltage magnitude difference between the inverter output voltage and the common bus voltage [3]. Thus, similar to a synchronous generator behavior in power systems, the frequency of the DG should drop when its active power increases and the voltage amplitude of the DG should drop when its reactive power increases [13].

The governing equations of the droop method for wireless control of parallel inverters are expressed as [14], [6]:

$$\omega = \omega_0 - k_\omega P \quad (6)$$

$$E = E_0 - k_E Q \quad (7)$$

Where ω_0 and E_0 are the reference angular frequency and amplitude of inverter output voltage, respectively, and k_ω, k_E are called droop coefficients. Eqs. (7), (8) are depicted in Fig. 2, graphically.

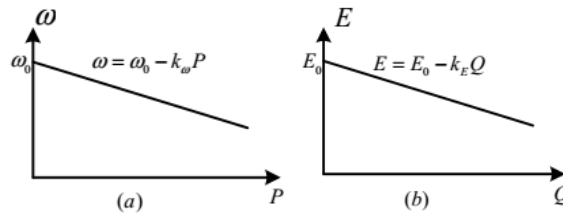


Fig. 2.(a) $P - \omega$, (b) $Q - E$

POWER SHARING BETWEEN PARALLEL INVERTER UNITS BASED ON THEIR DROOP CHARACTERISTICS

Assume two inverter units with equal capacity are connected to a common bus through different lines as shown by Fig. 3. If line impedances are inductive dominant and equal ($\theta = 90^\circ, Z_1 = Z_2 \cong X$) [13], then, active and reactive powers normally are shared equally between the two units [3]. However, if the impedances of the inductive dominant lines are different ($Z_1 \neq Z_2$), reactive power could not be shared equally although active power sharing would not be affected [15]. This issue could be proved mathematically. Assuming that the set point for the first unit is (ω_1, P_1) and for the second unit is (ω_2, P_2) , then, the frequency-active power droop equations are as below:

$$\omega_1 = \omega_0 - k_{\omega 1} P_1 \quad (8)$$

$$\omega_2 = \omega_0 - k_{\omega 2} P_2 \quad (9)$$

where droop coefficients should be equal, if the two units have equal capacity, i.e., $k_{\omega 1} = k_{\omega 2} = k_\omega$.

According to the droop characteristics, when the load changes, the active power would be shared between the two units in a new steady state frequency $\omega_1 = \omega_2 = \omega_3$. As a result, the active powers are shared equally between the two units (for units with equal capacity):

$$\omega_1 - \omega_2 = k_\omega (P_2 - P_1) \Rightarrow P_1 = P_2 \quad (10)$$

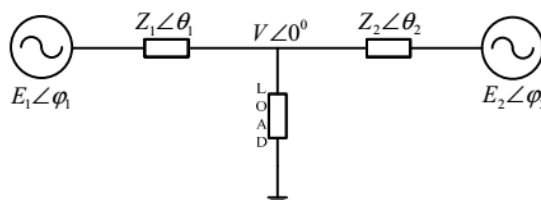


Fig. 3. Two inverter units connected to common bus

However, from reactive power sharing point of view, we have

$$E_1 = E_0 - k_E Q_1 \quad (11)$$

$$E_2 = E_0 - k_E Q_2 \quad (12)$$

$$E_1 = Z_1 I_1 + V \quad (13)$$

$$E_2 = Z_2 I_2 + V \quad (14)$$

Combining Eqs. (12)-(15) results in:

$$Z_2 I_2 - Z_1 I_1 = k_E (Q_1 - Q_2) \quad (15)$$

When Z_1 and Z_2 are not equal, trying to share the reactive power equally between the two parallel inverters would cause a contradiction because the left side of equality cannot be zero. Considering the droop characteristics and Eq. (16), thus, reactive powers cannot be shared equally. Consequently, one of the biggest issues associated with the conventional droop control method is reactive power sharing between DG units which are located at the different place of the micro grid with different distance to a common bus or buses.

Similarly, for a resistive dominant line, i.e. $\theta = 0$ and $Z = R$ [3], [16], it can be derived that reactive power could be shared equally between equal capacity units, but sharing active power equally between the two parallel inverters would cause a contradiction [7]. There is also another case where lines impedance is resistive-inductive. In this case active and reactive power control using the traditional droop method would be more difficult and complicated [6].

All the above issues present a significant challenge for the conventional droop only control strategies. To overcome the challenge, we propose a mechanism to combine conventional droop control technique with a direct-current vector control technique as shown in the following sections.

III. DIRECT CURRENT VECTOR CONTROL

A.LC-Filter Based Converter Model in dq Reference Frame

Fig. 4 shows a converter connected to the point of common coupling (PCC) through an LC filter on its output side. The relation between inverter output voltage and the PCC voltage in dqreference frame is:

$$\begin{bmatrix} v_{di} \\ v_{qi} \end{bmatrix} = R_f \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} + \omega L_f \begin{bmatrix} -i_{q1} \\ i_{d1} \end{bmatrix} + \begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad (17)$$

where v_d and v_q are the PCC voltage in dq reference frame, v_{di} and v_{qi} are inverter output voltage in dq reference frame, R_f and L_f are resistance and inductance of the LC-filter inductor, and ω is the PCC voltage angular frequency.

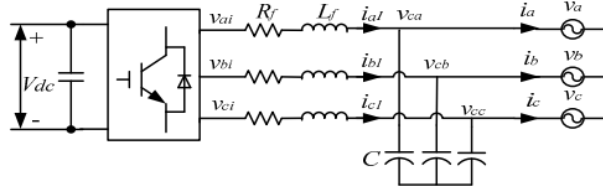


Fig. 4. Voltage source converter connected to the PCC through LC filter

Also based on Norton's theorem, the current balance equation over the LC-filter capacitor in dq reference frame is:

$$\begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} + C \frac{d}{dt} \begin{bmatrix} v_d \\ v_q \end{bmatrix} + C \omega \begin{bmatrix} -v_q \\ v_d \end{bmatrix} \quad (18)$$

where C is the LC-filter capacitance. The space vector representation of Eqs. (17) and (18) are (19) and (20), respectively:

$$v_{dq1} = R_f \cdot i_{dq1} + L_f \frac{d}{dt} i_{dq1} + j\omega L_f \cdot i_{dq1} + v_{dq} \quad (19)$$

$$i_{dq1} = C \frac{d}{dt} v_{dq} + j\omega C \cdot v_{dq} + i_{dq} \quad (20)$$

In the PCC voltage oriented frame, the d -axis voltage would be constant and the q -axis voltage would be zero [12], [17]; therefore, the instantaneous active and reactive powers delivered to the PCC are

$$p(t) = v_d i_d + v_q i_q = v_d i_d \quad (21)$$

$$q(t) = v_q i_d - v_d i_q = -v_d i_q \quad (22)$$

In the steady state condition, the derivative terms in the Eqs. (19) and (20) would be zero, therefore:

$$V_{dq1} = R_f \cdot I_{dq1} + j\omega L_f \cdot I_{dq1} + V_{dq} \quad (23)$$

$$I_{dq1} = j\omega C \cdot V_{dq} + I_{dq} \quad (24)$$

where V_{dq} , I_{dq} , V_{dqi} and I_{dq1} stand for the steady-state space vectors of PCC voltage, grid current, converter output voltage, and LC-filter inductor current in dq reference frame. Neglecting the voltage drop on R_f , the steady state current injecting to the PCC from the converter would be:

$$I_{dq} = \frac{V_{dqi} - V_{dq}}{jX_L} - j \frac{V_{dq}}{X_C} = \frac{V_{qi}}{X_L} + j \left(\frac{V_d - V_{di}}{X_L} - \frac{V_d}{X_C} \right) \quad (25)$$

Where $X_L = L_f$ and $X_C = 1/\omega C$ thus the active and reactive powers delivered to the PCC are:

$$P_{ac} = V_{qi} V_d / X_L \quad (26)$$

$$Q_{ac} = V_d (V_{di} - V_d) / X_L + V_d^2 / X_C \quad (27)$$

IV. DIRECT-CURRENT VECTOR CONTROL

The DCVC for a LC-filter based converter is based on Eqs. (21) and (22), that is active power and reactive power are directly controlled according to d - and q -axis current flowing to the PCC, respectively. Fig. 5 shows the block diagram for the DCVC in which the output of d - or q -axis current controller is a current signal. These current signals are used as tuning currents and the controller input error signals would guide the controllers to adjust the tuning currents during dynamic control process [18]. As it could be seen from Fig. 5, the d - and q -axis tuning currents $\dot{i}_d$ and $\dot{i}_q$ outputted from the current-loop controllers are transferred to the d - and q -axis voltage to control voltage source converter. Rearranging the space vector Eqs. (19) and (20) in terms of tuning-current signals will result in:

$$v_{dqi} = R_f \cdot i_{dq1} + L_f \frac{d}{dt} i_{dq1} + j\omega L_f \cdot i_{dq1} + v_{dq} \quad (28)$$

$$i_{dq1} = C \frac{d}{dt} v_{dq} + j\omega C \cdot v_{dq} + \dot{i}_{dq} \quad (29)$$

Substituting (29) in (28), the d - and q -axis converter output voltage for steady state conditions could be shown by:

$$v_{di} = R_f \dot{i}_d - \omega L_f \dot{i}_q + v_d (1 - \omega^2 L_f C) \quad (30)$$

$$v_{qi} = R_f \dot{i}_q + \omega L_f \dot{i}_d + v_d \cdot R_f \omega C \quad (31)$$

As it is obvious from (34) and (35) decoupling terms are appeared in d -axis and q -axis voltages. The whole structure of the DCVC is shown in fig.5, where $R_{eq} = R_f$, $L_{eq} = L_f$,

$$v_{cd} = v_d (1 - \omega^2 L_f C) \text{ and } v_{cq} = v_d R_f \omega C.$$

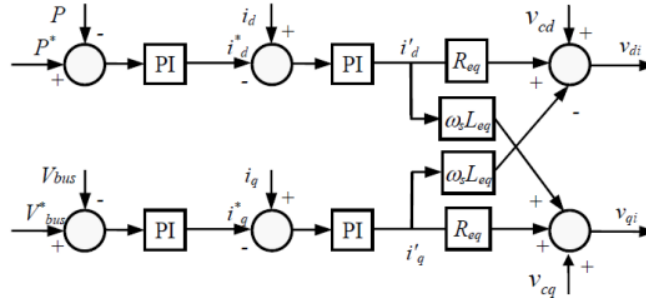


Fig. 5.DCVC system block diagram

C. Control Under Converter's Physical Constraints

In practice, the voltage source converter (VSC) should operate under rated power and PWM saturation limits. To satisfy such conditions, the design strategy of the DCVC [17] is to control the VSC by maintaining the effectiveness of the PCC active power control as the first priority while meeting the PCC reactive power control demand as much as possible when the VSC reaches its rated power or PWM saturation limit. This is expressed as:

$$\text{Minimize: } |Q_{ac} - Q_{ac}^*|$$

Subject to:

$$P_{ac} = P_{ac}^* \sqrt{i_d^{*2} + i_q^{*2}} \leq I_{rated} \sqrt{\frac{v_{di}^2 + v_{qi}^2}{3}} \leq \frac{V_{dc}}{2\sqrt{2}}$$

The requirement is implemented in the following way. To prevent the converter from exceeding the rated current, (32) is employed if the amplitude of the reference current generated by the outer control loop exceeds the rated current limit. According (19) and (20), this represents a strategy of keeping the d -axis current reference i_d^* unchanged so as to maintain active power or dc-link voltage control effectiveness while modifying the q -axis current reference i_q^* to satisfy the reactive power or ac system bus voltage control demand as much as possible [12]. If $|v_{dqi}|$ generated by the current control loops exceeds the PWM saturation limit, v_{d1}^* and v_{q1}^* are modified by (32). According to (26) and (27), this represents a strategy of keeping the q -axis voltage reference v_{q1}^* unchanged so as to maintain the dc-link voltage or active power control effectiveness while modifying the d -axis voltage reference v_{d1}^* to meet the reactive power control demand as much as possible.

$$i_{d_new}^* = i_d^*, i_{q_new}^* = \text{sign}(i_q^*) \cdot \sqrt{(i_{dq_max}^*)^2 - (i_d^*)^2} \quad (32)$$

$$v_{di_new}^* = \text{sign}(v_{di}^*) \cdot \sqrt{(v_{dqi_max}^*)^2 - (v_{qi}^*)^2}, v_{qi_new}^* = v_{qi}^* \quad (33)$$

V.APPLYING DCVC AND DROOP CONTROL METHODS TO PARALLEL INVERTERS

In islanding mode, it is necessary to establish the common bus voltage and simultaneously providing the demanded active and reactive powers. Conventionally, frequency-droop and voltage-droop control strategies without using vector control mechanism were used to share real and reactive powers among two or more DG units. However, this would cause not only a challenge of reactive power sharing but also a bad power quality to the microgrid. With DCVC, it is possible to integrate vector and droop control together for control of parallel inverters with improved power quality and voltage reliability. However, DCVC requires that at least one inverter or DG unit within the microgrid must operate as a grid-forming unit.

A.Grid-Forming Inverter

A grid-forming unit is assigned to regulate the voltage at the PCC, dominantly set the system frequency, and provide a reference to other vector controlled inverters. The unit should be adequately large and have adequate reserve capacity to supply the power balance. Its function is similar to a traditional slack bus generator and is a necessary component for operation of other vector controlled inverters.

Fig. 6 shows the control structure for a grid-forming inverter. The active and reactive powers are calculated based on the measured three-phase voltage and current at the PCC, and then are used to generate frequency and amplitude signals for control of the grid-forming converter through the conventional droop method as shown in Eqs. (7) and (8). The frequency and amplitude from the active and reactive power droop controllers together formulate the three-phase reference control voltage which is used to drive the PWM to control the converter.

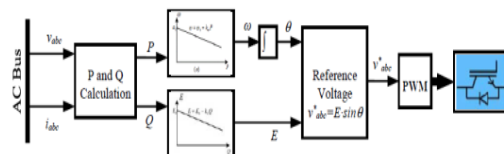


Fig. 6. Control structure of grid-forming inverter

A. DCVC Controlled Inverter

The DCVC controlled inverters combine the DCVC with droop control as shown by Fig. 7, which consists of an external droop control loop, an active power and PCC bus voltage control loop, and an inner current control loop. At the external loop, the droop control is only applied to the PCC active power control. The power reference generated by the droop control mechanism is passed to the active power and PCC bus voltage control loop. At this loop, the DCVC control strategy is operated by maintaining the effectiveness of the PCC active power control as the first priority while meeting the PCC bus voltage control demand as much as possible as explained in Section III-C. Therefore, the reactive generation of the converter is determined by the PCC bus

voltage controller with the consideration of the physical constraints of the converter, which overcomes the challenge of achieving reactive power droop control among parallel inverters as explained in Section II and helps to improve micro grid voltage.

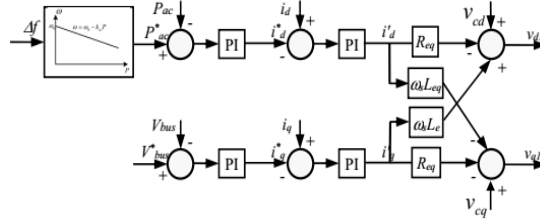


Fig. 7. Control diagram for DCVC controlled inverters

B. Overall System Structure

Fig. 8 shows the overall structure of two parallel units in islanded mode. The active and reactive power balances at PCC are $P=P_1+P_2$ and $Q=Q_1+Q_2$ where P_j and Q_j are the active and reactive power of j th unit, respectively. If the active power droop coefficients for both units are the same, the active power should be shared equally between the two units. The reactive power of the second unit, the DCVC controlled unit, is regulated automatically by its bus voltage controller until the bus voltage is maintained at the nominal value or until the rated power or PWM saturation limit of the converter is reached. The rest of the reactive power demand will be met by the first unit through the droop control mechanism. If the demanded active power at the PCC increases, the MG frequency will drop and the active power of both units will be increased

$$q(t) = v_q i_d - v_d i_q = -v_d i_q$$

In the steady state condition, the derivative terms in the Eqs. (19) and (20) would be zero, therefore:

$$V_{dq1} = R_f \cdot I_{dq1} + j\omega L_f \cdot I_{dq1} + V_{dq} \quad (23)$$

$$I_{dq1} = j\omega C \cdot V_{dq} + I_{dq} \quad (24)$$

where V_{dq} , I_{dq} , V_{dq1} and I_{dq1} stand for the steady-state space vectors of PCC voltage, grid current, converter output voltage, and LC-filter inductor current in dq reference frame. Neglecting the voltage drop on R_f , the steady state current injecting to the PCC from the converter would be:

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Substituting (29) in (28), the d- and q-axis converter output voltage for steady state conditions could be shown by:

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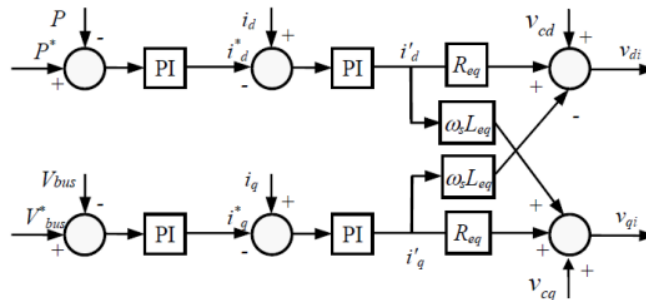


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A grid-forming unit is assigned to regulate the voltage at the PCC, dominantly set the system frequency, and provide a reference to other vector controlled inverters. The unit should be adequately large and have adequate reserve capacity to supply the power balance. Its function is similar to a traditional slack bus generator and is a necessary component for operation of other vector controlled inverters.

Fig. 6 shows the control structure for a grid-forming inverter. The active and reactive powers are calculated based on the measured three-phase voltage and current at the PCC, and then are used to generate frequency and amplitude signals for control of the grid-forming converter through the conventional droop method as shown in Eqs. (7) and (8). The frequency and amplitude from the active and reactive power droop controllers together formulate the three-phase reference control voltage which is used to drive the PWM to control the converter.

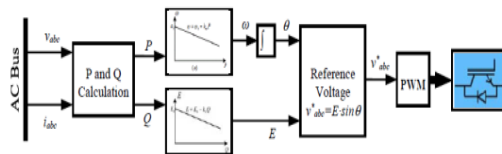


Fig. 6. Control structure of grid-forming inverter

B. DCVC Controlled Inverter

The DCVC controlled inverters combine the DCVC with droop control as shown by Fig. 7, which consists of an external droop control loop, an active power and PCC bus voltage control loop, and an inner current control loop. At the external loop, the droop control is only applied to the PCC active power control. The power reference generated by the droop control mechanism is passed to the active power and PCC bus voltage control loop. At this loop, the DCVC control strategy is operated by maintaining the effectiveness of the PCC active power control as the first priority while meeting the PCC bus voltage control demand as much as possible as explained in Section III-C. Therefore, the reactive generation of the converter is determined by the PCC bus voltage controller with the consideration of the physical constraints of the converter, which overcomes the challenge of achieving reactive power droop control among parallel inverters as explained in Section II and helps to improve micro grid voltage.

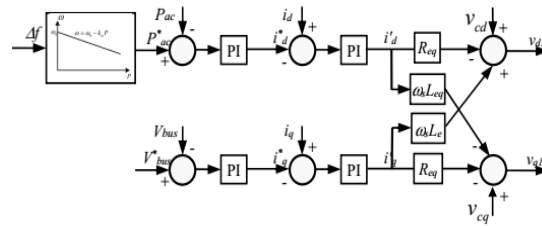


Fig. 7. Control diagram for DCVC controlled inverters

C. Overall System Structure

Fig. 8 shows the overall structure of two parallel units in islanded mode. The active and reactive power balances at PCC are $P=P_1+P_2$ and $Q=Q_1+Q_2$ where P_j and Q_j are the active and reactive power of j th unit, respectively. If the active power droop coefficients for both units are the same, the active power should be shared equally between the two units. The reactive power of the second unit, the DCVC controlled unit, is regulated automatically by its bus voltage controller until the bus voltage is maintained at the nominal value or until the rated power or PWM saturation limit of the converter is reached. The rest of the reactive power demand will be met by the first unit through the droop control mechanism. If the demanded active power at the PCC increases, the MG frequency will drop and the active power of both units will be increased according to their droop characteristics and at the same time the reactive power of the two units will be readjusted.

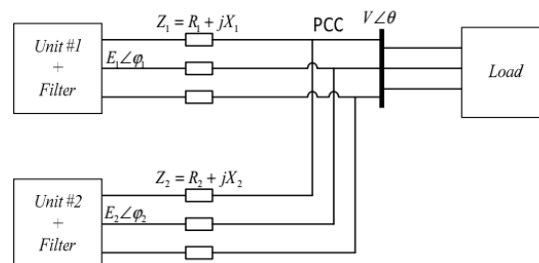


Fig.8. Overall structure for parallel units in islanded mode

VIII. SIMULATION AND RESULTS ANALYSIS

A microgrid with two parallel inverter units and two major loads were built by using MATLAB / SIMULINK. Each inverter is connected to its PCC bus through an LC filter. Two units are considered to have different capacities which are connected through transmission lines having different impedances to the loads. Then, diverse microgrid operation scenario were studied and evaluated.

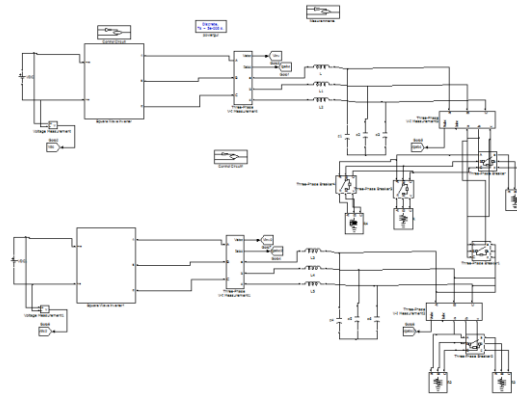


Fig.9. Matlab/simulink model with Droop and DCVC controlled Inverter.

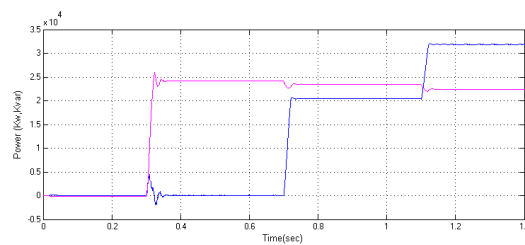


Fig.10. Active and Reactive Powers at unit 1.

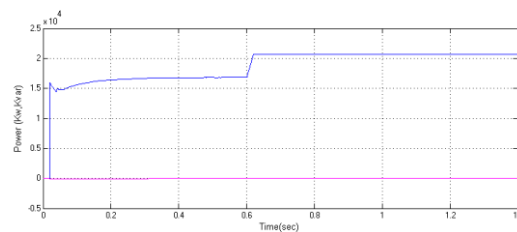


Fig.11. Active and Reactive Powers at unit 2.

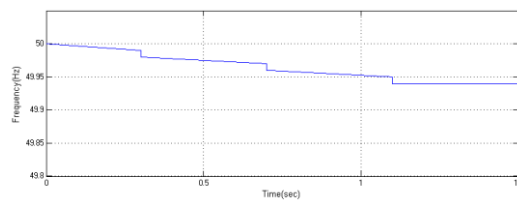


Fig.12. Frequency.

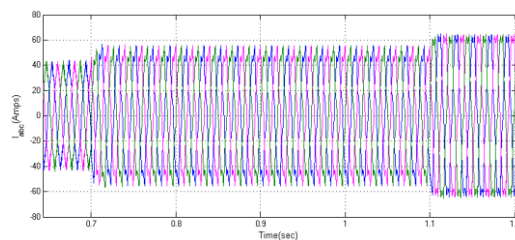


Fig.13.Three phase currents.

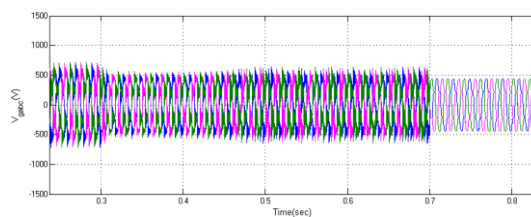


Fig.14.Three Phase Voltages.

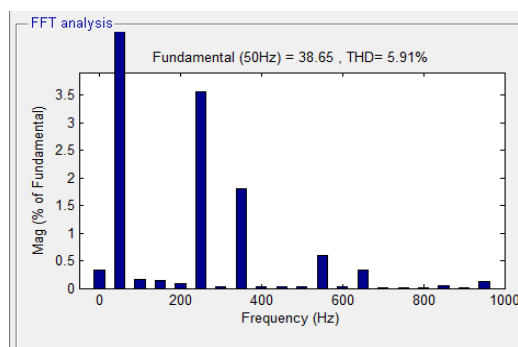


Fig.15.THD of source current with PI Control

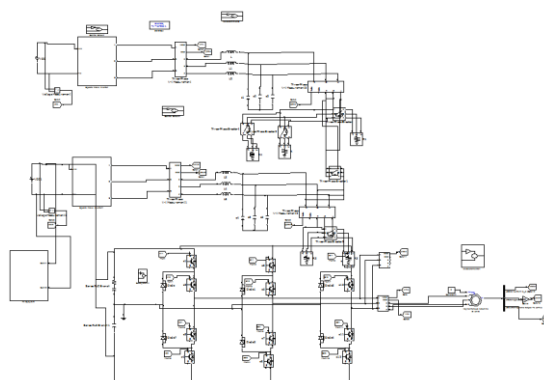


Fig.17. Matlab/simulink model of proposed system with PV source fed Induction Motor.

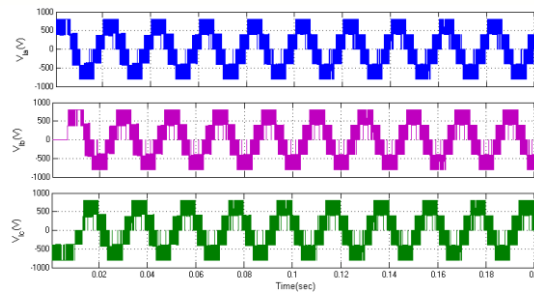


Fig.18.Five level line-line Voltages.

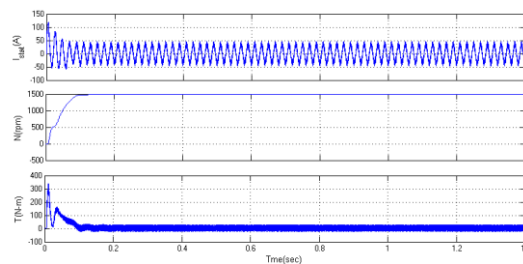


Fig.19. Current, speed and Torque of Induction motor.

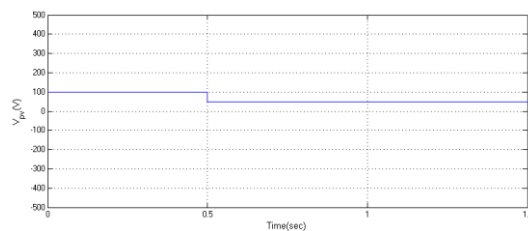


Fig.20. PV voltage.

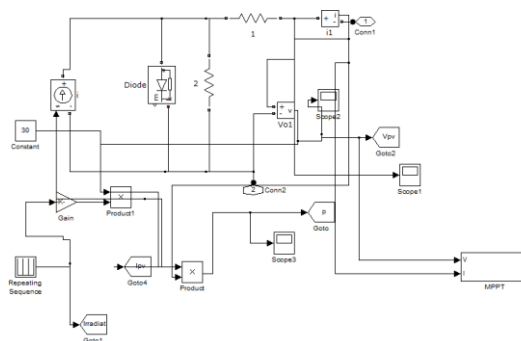


Fig.21. Matlab/simulink Model of PV system.

IX.CONCLUSIONS

This paper proposes to integrate the droop based control method and a novel direct current vector control technique for control of parallel inverter-interfaced DG units in microgrid islanded operating conditions. The

paper reviewed conventional droop control method for control of parallel inverters in a microgrid and analyzed some shortcomings associated with droop based control for parallel DG units in microgrid islanded mode. Also the proposed droop and DCVC for control of parallel inverter with PV system fed Induction motor is simulated and the Performance of the overall system is studied.

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