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# A New Strategy for On-Line Droop Adjustment for Microgrid Connected DGs

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**ABSTRACT**

This paper proposes a simple and effective control technique for interconnection of DG resources to the power grid via interfacing converters based on Phase locked loop (PLL) and Droop control. The behaviour of a Microgrid (MG) system during the transition from islanded mode to grid-connected mode of operation has been studied. A dynamic phase shifted PLL technique is locally designed for generating phase reference of each inverter. The phase angle between filter capacitor voltage vector and d-axis is dynamically adjusted with the change in q-axis inverter current to generate the phase reference of each inverter. During fluctuations in load capacity, the grid-connected system must be able to supply balanced power from the utility grid side and micro-grid side. Therefore, droop control is implemented to maintain a balanced power sharing. The inverter operates in voltage control mode in order to control the filter capacitor voltage. An adjusted droop control method for equivalent load sharing of parallel connected Inverters, without any communication between individual inverters has been proposed. The control loops are tested with aid of MATLAB Simulink tool during several operating conditions.



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## 1. INTRODUCTION

The interconnection of distributed generators (DGs) to the utility grid through power electronic converters has raised concern about proper load sharing between different DGs and the grid. The reduction in global emissions and energy losses make the microgrid (MG) a promising alternative to traditional power distribution systems. However, the design of the MG architecture poses a challenge for an efficient operation. MGs are categorized into two types - AC and DC MGs which can be operated in both islanded and grid-connected modes. Since the existing power system relies on AC systems, the recent literatures on MGs have mostly focused on AC MGs. The microgrid can generally be viewed as a cluster of distributed generators connected to the main utility grid, usually through voltage-source-converter (VSC) based interfaces. It is important to achieve a proper load sharing by DGs for interfacing of MG to the utility system. A load sharing with minimal communication is the best in the distribution level when the network is complex, or it is reconfigured over a large area span [1]-[3].

The DGs encompass a wide range of technologies, such as wind power, micro turbines, internal combustion engines, gas turbines, photovoltaic (PV), fuel cells, and storage systems. However, the challenges have risen up at the same time, in controlling a potentially huge number of DGs and operating the network safely and efficiently. Managing DGs (renewables, conventional, and storage) and loads within MGs during the transition of island and grid-tie modes are challengeable. This challenge can be addressed by proper design and control of power electronic devices [4]. The MG needs to be stable throughout these changes to the demand and the capacities of the energy storage and renewable sources. The MG controller needs a method of commanding the sources and a method of assessing the available capacity of the sources within its command [5].

There are several control methods proposed hitherto for power management and to control voltage and frequency within MG in island mode. MG concept proposed by the Consortium for Electric Reliability Technology Solutions (CERTS) in which, voltage and frequency stability are achieved by drooping the voltage and frequency according to active and reactive power requirement .The natural droop method is not suitable when the MG has nonlinear loads due to the harmonic current [6]-[9]. Another issue relating to the conventional droop is that the frequency and voltage are respectively related to active and reactive power when the output impedance of the generator is mainly inductive, e.g., induction generators. Hence, the power sharing performance is affected by the output impedance of the distributed generation units and the line impedances. It infers that, the active power-voltage (*P-V*) droop control needs to be used instead of the conventional active power-frequency (*P-f*) droop control, which is contrary to the conventional electrical transmission systems or induction generation dominated systems.

A (*Q-V)* droop control method is mostly used to improve reactive power sharing [10]. The voltage and frequency (*V-f*) control was implemented to control DGs in an islanded mode by maintaining voltage and frequency at references. However, pure (*V-f*) controller for DGs in islanded mode is not able to respond to load changes; a master-slave control configuration of a MG is built [11],[12]. In grid-connected mode, all DGs are equipped with PQ controllers, and during islanded mode only the master inverter switches to (*V-f*) control to maintain the MG voltage level and frequency. The drawback of master–slave method is that it also takes large amount of communication. By retrieving the grid parameters such as the voltage, frequency, grid impedance, the inverters based on the droop control method are able to inject real and reactive power to the grid [13],[14].

In order to enhance dynamic performance of the system by utilizing the locally measurable feedback signal, the effective control technique for interconnection of DG to power grid through interfacing converters is proposed in this paper. Since the network system is more complex, a load sharing with minimal communication is to be implemented. Hence, an improved droop control method which is capable of efficiently managing power between DGs and grid is adopted. The proposed control technique depends on reshaping the input impedance of the interfaced converter by injecting an active stabilization signal at the control loop of the converter. The effectiveness of the study in the system is validated by MATLAB/Simulink software during several operating conditions.

## 2. MICROGRID ARCHITECTURE

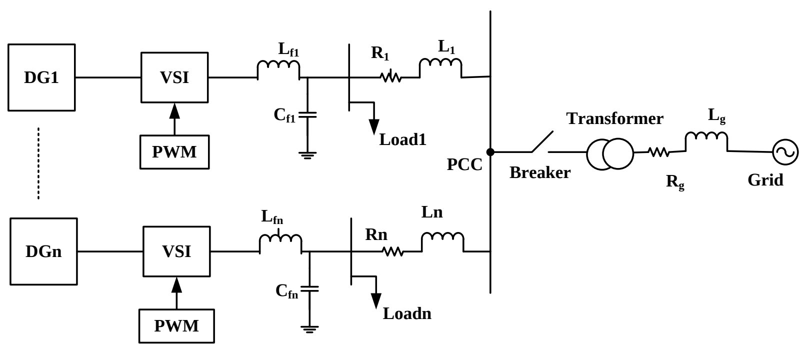



Figure 1. Architechture of Micro-Grid

A simple MG structure is developed in order to test the effectiveness and efficiency of controllers, as shown in Figure 1. $DG_1,\ldots, DG_n$ are connected to the voltage source inverters (VSI) controlled by pulse width modulation (PWM) controller followed by the filters and $load_1,\ldots,load_n$. All these DGS are connected at the point of common coupling (PCC) and then, DGs are connected to the main grid through the transmission line, circuit breakers, and transformers. DGs are implemented through PQ controller under grid-connected mode and droop controller can be implemented under either grid-connected or islanded mode [3].

### 2.1. PV Model

A PV cell can be modeled as a current source connected with one diode and two resistors as shown in figure 2. A PV module is built by simply connecting many PV cells in series and parallel. The characteristic equation for a single PV cell is given as

$$I_{pv} = I_{ph} - I_o \left\{ exp\left[\frac{q\left(V_{pv} + R_s I_{pv}\right)}{nkT}\right] - 1 \right\} - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \tag{1}$$

where $V$ is output voltage, $I$ is output current, $I_0$ is cell reverse saturation current, $I_{ph}$ is light-generated current, $q$ is electron charge $1.6 \times 10^{-23}$(C), $T$ is cell temperature in Celsius, $k$ is Boltzmann's constant $1.38 \times 10^{-19}$(J/k), $R_{sh}$ is shunt resistance, $R_s$ is series resistance, ideality factor $n$ is introduced in the denominator of the exponent, which ranges from 1 to 2, representing the defects from ideal diode.

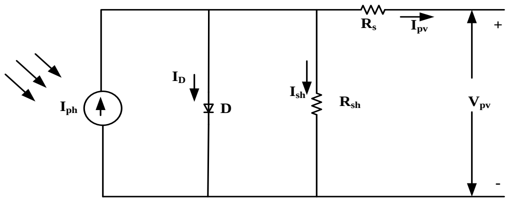



Figure 2. Single Diode Model of PV cell

## 3. MODELING OF THE THREE-PHASE GRID-CONNECTED VSI SYSTEM

A typical model of a three-phase grid connected VSI with an LC filter is depicted in Figure 3, whereas *Rf, Lf, Cf,* represent the equivalent lumped resistance, an inductance of the filter and capacitance of the filter, respectively. *Iabc* is the grid current and *Vabc* is the grid voltage [13].

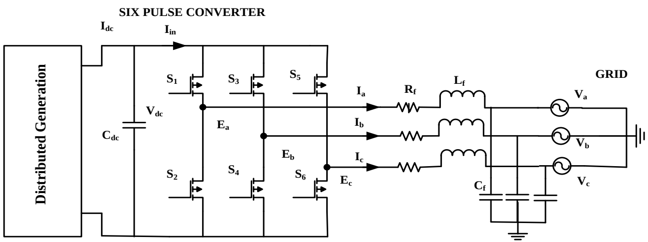



Figure 3.Schematic circuit of Three-phase grid-connected inverter

In the *abc* reference frame, the state space equations of the system equivalent circuit are given as

$$\frac{d}{dt}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \frac{R_s}{L_s}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \frac{1}{L_s}\left(\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} - \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}\right) \tag{2}$$

Using Park's transformation, (2) can be expressed in the *dq* reference frame as

$$\frac{d}{dt}\begin{bmatrix} I_p \\ I_q \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_s} & \omega \\ -\omega & -\frac{R_S}{L_s} \end{bmatrix}\begin{bmatrix} I_p \\ I_q \end{bmatrix} + \frac{1}{L_s}\left(\begin{bmatrix} E_d \\ E_q \end{bmatrix} - \begin{bmatrix} V_P \\ V_q \end{bmatrix}\right) \tag{3}$$

where $\omega$ is the coordinate angular frequency, and the Park's transformation can be defined as

$$I_{dqo} = T I_{abc} \tag{4}$$

where, $I_{dqo} = \begin{bmatrix} I_p \\ I_q \\ I_0 \end{bmatrix}$, $I_{abc} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$ , $T = \frac{2}{3}\begin{bmatrix} cos\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin\theta & sin\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$

and $\theta = \omega_s t + \theta_0$ is the synchronous rotating angle, $\theta_0$represents the initial value.

### 3.1. Phase Locked Loop(PLL)

The synchronization algorithm for attaining a controllable power factor must detect the phase angle of the three-phase utility grid voltage with optimal dynamic response and reliability in order to obtain the synchronization of the controlled three-phase inverter current and to ensure the proper behavior of the inverter control strategy. A three-phase PLL structure is shown in Figure 4, consisting of Clark's and Park's transformations (also known as *abc* to *dq* transformation ), the PI regulator as the loop filter, and an integrator as the voltage- controller oscillator(VCO). This PLL structure is also known as Synchronous Reference Frame(SRF) PLL or *dq* PLL. The input variables are three phase utility grid voltages($V_a$, $V_b$, $V_c$)and output variable is the phase angle($\theta$).[16],[17]

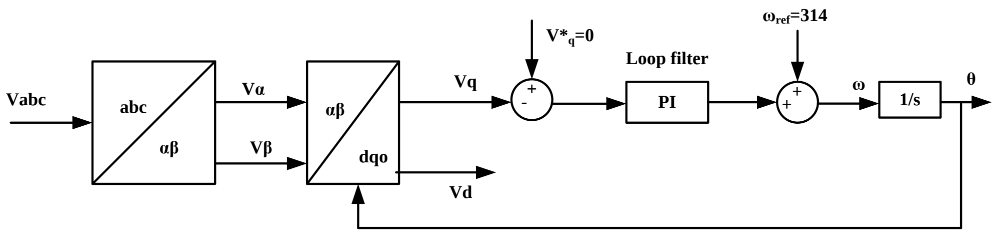



Figure 4. Block diagram of the *dq* PLL synchronization algorithm

### 3.2. VSI control strategies

VSI is needed to interface the DG unit to the grid and provide flexible operation. As shown in Figure 5, the power circuit of the VSI based DG unit is associated with the control structure, so the controlled operation of the DG unit relies on the inverter control mode. For instance, in the grid-connected mode, DG unit operates as a PQ generator and the inverter should follow the PQ control mode, while voltage and frequency regulation are not required because the grid voltage is fixed. However, in the islanded mode, the DG units are expected to meet the load demand with respect to the quality of power supply. In this case, the voltage and frequency are not fixed and the inverter should follow the (*V-f)* control mode taking into account the inverter power rating for sharing power issue [15],[16].

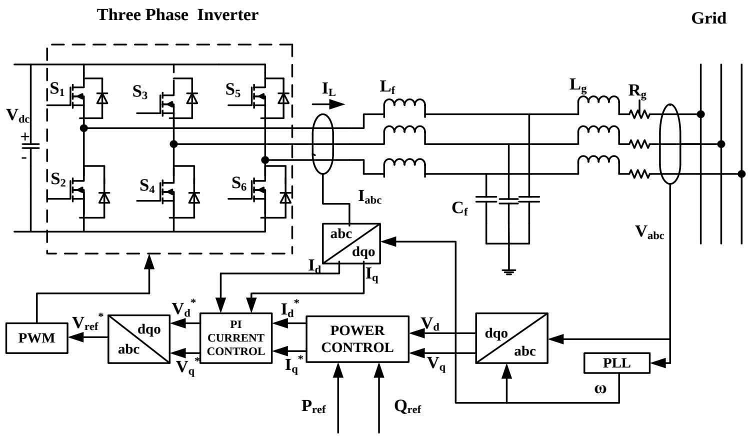



Figure 5. Control Structure of Grid-connected VSI

### 3.3. PQ Control Strategy

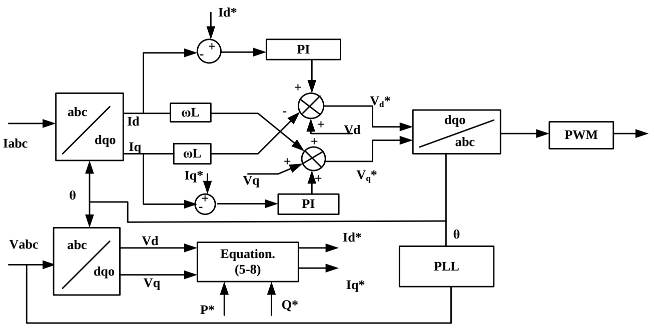



Figure 6. Structure of active and reactive control

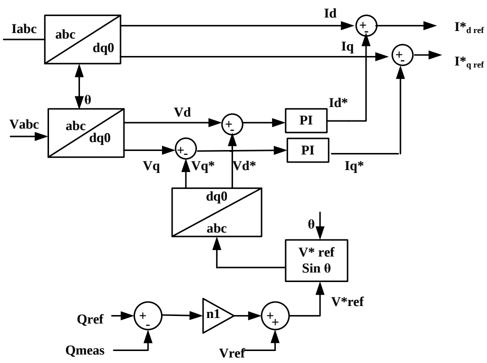



Figure 7. Structure of voltage and frequency control

For both microgrid operation modes, as long as the voltage and frequency are in stable condition, the PQ control mode can be used either to import less power from the utility (Peak Shaving) in grid-connected mode or to inject a stable active and reactive power in a standalone mode. The PQ mode is usually applied to the DG units which supply a constant power. In this case, the amplitude and phase angle of the inverter current is controlled in order to inject the pre-set active and reactive power values which can be defined locally or by the Microgrid Control Centre (MGCC). [18]-[20]. Figure 6 shows the block diagram of the PQ control strategy. The measured values of the active and reactive power can be expressed as

$$P = \frac{3}{2}\left(V_d * I_d + V_q * I_q\right) \tag{5}$$

$$Q = \frac{3}{2}\left(V_q * I_d - V_d * I_q\right) \tag{6}$$

The variation in frequency and voltage are considered to adjust the active and reactive power. The equations (7) and (8) provide the details of droop adjustment in voltage and frequency to control the current loop and voltage loop (see Figure 6)

$$\omega = \omega^* - \left(k_p + \frac{k_i}{s}\right)(P - P^*) \tag{7}$$

$$V = V^* - \left(k_p + \frac{k_i}{s}\right)(Q - Q^*) \tag{8}$$

### 3.4. *V-f* Control strategy

For a reliable operation of the microgrid, it is necessary to ensure the continuous transition between the microgrid modes and keep a stable operation during the islanding mode in terms of regulating the microgrid voltage and frequency with respect to the load demand. In this case, the DG units must follow the load demand and maintain the voltage and frequency within threshold limits, so that *V-f* control mode has to be adopted by one or more DG units in order to satisfy the above requirements [9]. The block diagram of the application is shown in Figure 7. Since the reference voltage and frequency values can be defined locally, the frequency can be measured by the PLL as

$$V_d^* = I_d^* - \omega I_d + V_d \tag{9}$$

$$V_q^* = I_q^* - \omega I_q + V_q \tag{10}$$

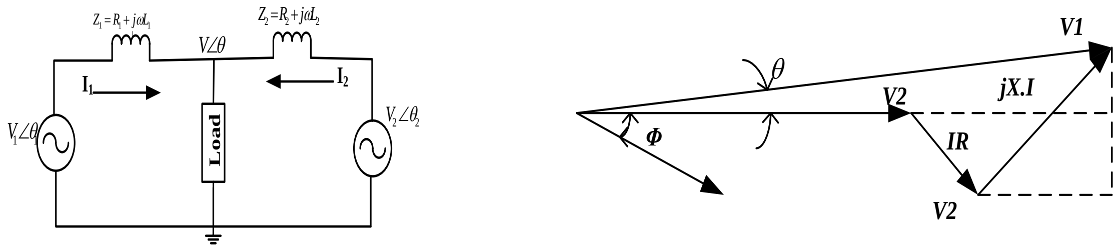
The system turns in to grid-connected mode when there is drop in frequency and voltage, the reason behind is the change in impedance value and the disturbance in the PLL. The measured reactive is compared with reference reactive power to regulate the voltage. The measured difference combined with droop co-efficient produces direct axis and quadrature axis voltage. The *d* and *q* voltages are compared and regulated through PI controller in order to obtain the new *d* and *q* current reference values. The changes of d and q axis currents are represented by (11) and (12) respectively.

$$I_d^* = (k_p + k_i/s)(V_d^* - V_d) \tag{11}$$

$$I_q^* = (k_p + k_i/s)(V_q^* - V_q \tag{12}$$

## 4. POWER SHARING FOR PARALLEL CONNECTED CONVERTER OPERATIONS

The droop technique has been widely used as a power sharing scheme in conventional power system with multiple generators. In this method, the generators share the system load by drooping with the frequency of each generator with the real power *(P)* delivered by the generator. This allows each generator to share the changes in total load in a manner determined by its frequency droop characteristic and essentially utilizes the system frequency as a communication link between the generator control systems. Similarly, a drop in the voltage amplitude with reactive power (*Q*) is used to ensure reactive power sharing.




(a) (b)

Figure 8. (a) Single Phase equivalent circuit (b) its respective phasor diagram

Since this load sharing technique is based on the power flow theory in an AC system, which states that the flow of the active power *(P)* and reactive power *(Q)* between two sources can be controlled by adjusting the power angle and the voltage magnitude of each system. The active power flow (*P*) is mainly controlled by the power angle, while the reactive power (*Q*) is mainly controlled by the voltages magnitude, indicates critical variables for load-sharing control of paralleled power converters as given in Figure.8 (a -b). As it shows, the supply from inverted source *(V1)* and supply from grid side *(V2)* represented by two voltage sources are connected to a load through line impedance *Z* represented by pure inductances *L1*and *L2* for simplified analysis purpose. Note that $Z = R + jX$; $X = \omega L$ and $\omega = 2\pi f$.In general, the complex power at the load due to the inverter measured at any network is given by

$$S_i = P_i + jQ_i = V.I_i^* \tag{13}$$

where, *i* : 1, 2. $I_i^*$ is the complex conjugate of the inverter current and it can be expressed as

$$I_i^* = \left[\frac{V_i cos\,\theta + jV_i sin\theta - V}{R + j\omega L_i}\right]^* \tag{14}$$

$$S = V_2 \left[\frac{V_1 cos\,\theta + jV_2 sin\,\theta - V_2}{R + j\omega L}\right]^* \tag{15}$$

Based on the single phase equivalent circuit of the network (Figure 8(a)) and the current and complex power equations (14) and (15), the phasor diagram is obtained as given in Figure 8 (b). Further, considered the power converter as an ideal voltage source connected to the main grid through a given line impedance, the active and reactive powers is delivered to the grid as given by

$$P_1 = \frac{V_1}{R^2 + X^2}[R(V_1 - V_2 cos\theta) + XV_2 sin\theta] \tag{16}$$

$$Q_1 = \frac{V_1}{R^2 + X^2}[-RV_2 sin\theta + X(V_1 - V_2 cos\theta)] \quad (17)$$

where $P_1$ and $Q_1$ are the active and reactive powers respectively flowing from the source 1 (power converter) to the source 2 (grid), $V1$ and $V2$ are the voltage values of these sources, $\theta$ corresponds to the phase-angle difference between the two voltages and $\emptyset$ is the impedance angle.

Assuming sin $\theta \approx \theta$ and cos $\theta \approx 1$, (16) and (17) can be rewritten as,

$$P_1 = \frac{V_1}{\omega L}(V_2 sin\theta) \quad \Rightarrow \theta = \frac{\omega L P_1}{V_1 V_2} \quad (18)$$

$$Q_1 = \frac{V_1}{\omega L}(V_1 - V_2 cos\theta) \quad \Rightarrow \quad V_1 - V_2 = \frac{\omega L Q_1}{V_1} \quad (19)$$

The direct relationship between the power angle $\theta$ and the active power $P$ as well as the voltage difference $V1 - V2$ and the reactive power $Q$ can be observed from equations (18) and (19). These relationships permit regulating the grid frequency and voltage at the point of connection of the power converter, by controlling the value of the active and reactive powers delivered to the grid. Hence, the droop control expressions can be given for inductive lines as

$$f = f_o + m_i(P - P^*) \quad (20)$$

$$V = V_o + n_i\left(Q - Q^*\right) \quad (21)$$

where $f$ is grid supply frequency, $fo$ is nominal frequency, $V$ is grid voltage and $Vo$ is nominal voltage. It is noted that $(f\text{-}fo)$ and $(V\text{-}V_O)$ represent the grid frequency and the voltage deviations, respectively from their rated values and ($P$- $P^*$) and ($Q$- $Q^*$ ) are the variations in the active and reactive powers delivered by the power converter to compensate such deviations. These relationships can be graphically represented by the droop characteristics as shown in Figure 9.

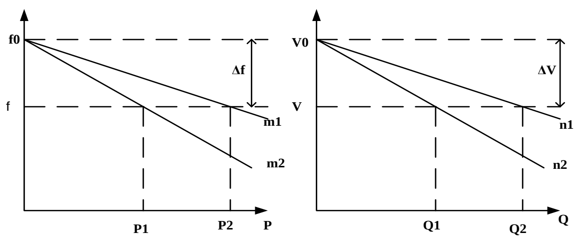



Figure 9. Droop characteristics of voltage and frequency

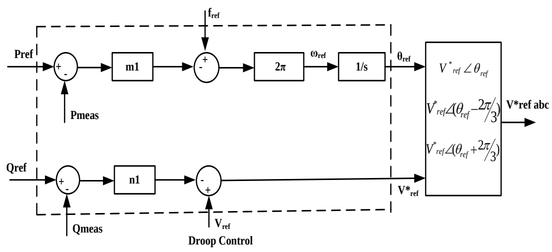



Figure 10. Reference voltage and frequency of Droop characteristics

As stated in (20) and (21), the gain of the control action in each case, i.e., the slope of the frequency and voltage droop characteristic, is set by $V$ and $f$ parameters respectively. Therefore, as depicted in Figure 9, each of the grid-supporting power converters operating in the microgrid will adjust its active and reactive power references according to its $P$-$f$ and $Q$-$V$ droop characteristic to contribute in the regulation of the microgrid frequency and voltage, respectively.[14-16].In case of multiple inverters, the proportion of the load shared by each inverter can be adjusted by choosing the droop coefficient, depending on its apparent power rating as $m_1.S_1 = m_2.S_2 = \cdots = m_n.S_n$ and $n_1.S_1 = n_2.S_2 = \cdots = n_n.S_n$.

s Figure 8(a) shows, two inverters share the real and reactive loads proportionally based on the chosen droop coefficients. Figure 10 shows the block diagram of reference voltage by droop method. This is the reference signal generated with phase angle ($\theta_{ref}$) by the real power ($P$) and amplitude ($Vref$) by the reactive power ($Q$), and this is used for the reference voltage of each power converter. The complete block diagram of the control structure developed is given in Figure 11 and the system parameters are given in Table 1.

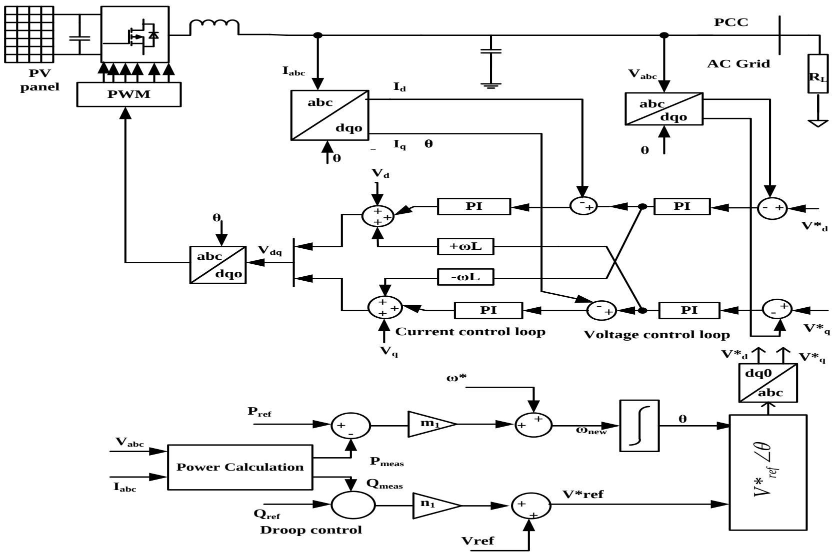


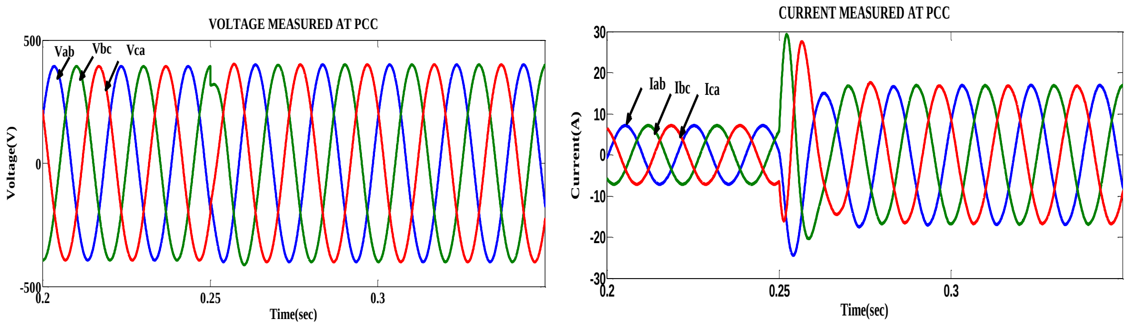

Figure 11. Block diagram of Complete Control structure of the study

Table 1. Simulation parameters

| Parameter | Value | Description |
|---|---|---|
| *Vg* | 400*V(rms)* | Grid voltage(rms) |
| *Vdc* | 750 *V* | DC voltage |
| *Cdc* | 800*uF* | DC link capacitor |
| *DG power* | 10*Kw* | PV Arrays |
| *Fs* | 10*KHz* | Switching Frequency |
| *Lf* | 45*mH* | Filter inductor |
| *Cf* | 500*uF* | Filter capacitor |
| *L1* | 4*uF* | Link inductor |
| *f* | 50*Hz* | Grid supply frequency |

## 5. SIMULATION RESULTS

To verify the effectiveness of the active and reactive power and droop control, the controller testing is conducted in two different modes, grid-connected mode and island mode. The complete control structure discussed in the study is tested with different active and reactive load conditions. The transition from islanded mode to grid-connected mode using proposed schemes have been analyzed. The test has been conducted for the time duration of 0.5sec.




(a) (b)

Figure 12. Simulation results of voltage and current measured at PCC

The following sequence of occurrences is observed. Initially, the system starts to operate in an islanded mode at t=0sec, the system transits to grid-connected mode at t=0.25sec.

*Initial operating conditions:* At t =0sec, the real and reactive power set points of DG is set to 3.5 kW and 2.2kVar (*Pf* 0.85).

*Occurrence (i):* At t = 0.25 sec, the real and reactive power set points of DG are changed from 3.5kW and 2.2kVar to 10 kW and 0.5kVar (upf), the system transits to grid-connected mode.
*Occurrence (ii):* During t=0.25sec to t= 0.28sec, change of phase angle and drop in voltage are observed. In view of the change, a decrease in frequency value and change in active power is observed. Due to the drop in voltage the reactive power decreases gradually. The increase in current values (see Figure 12(b)) shows; the VSI supports the main grid when it is connected to grid -connected mode of operation.
*Occurrence (iii):* At t = 0.28sec, the power remains unchanged. The settling time of 0.03sec is achieved as per the design. The voltage measured at PCC shows, the voltage values are nearer to the grid set voltage.

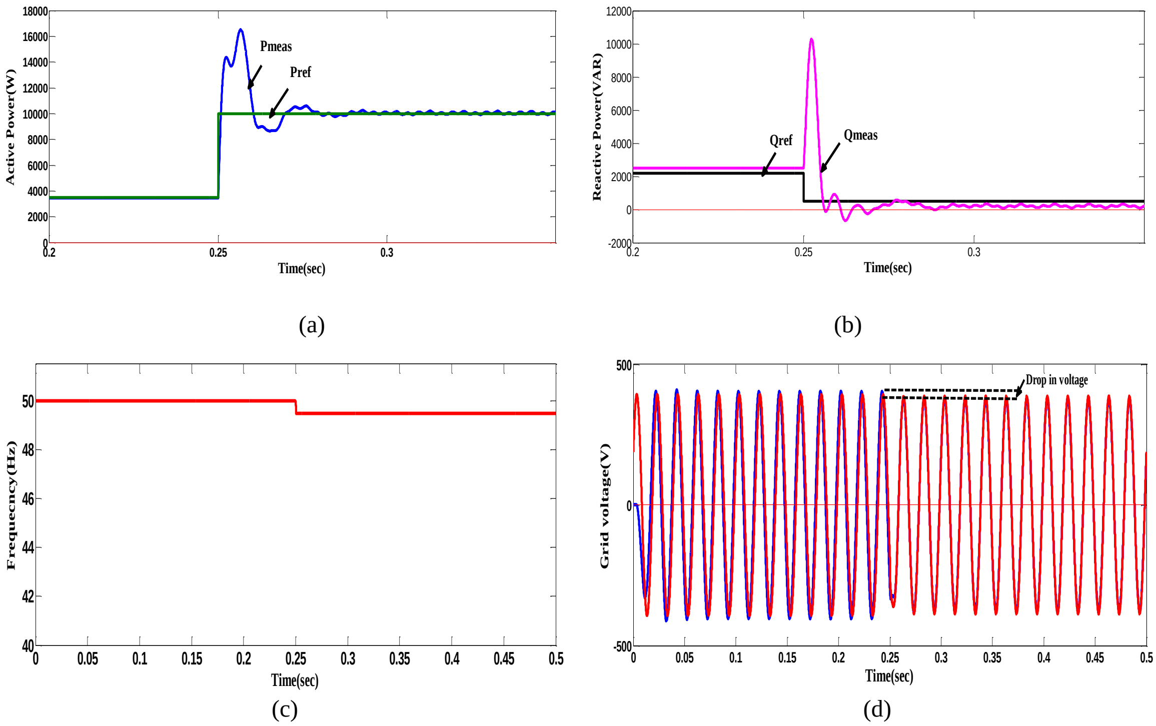
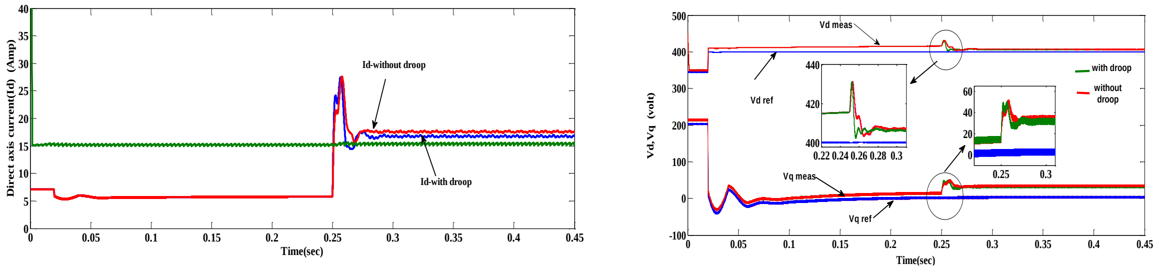



Figure 13. Simulation results of power sharing (a) Active power (b) Reactive power (c) Frequency (d) Drop in Voltage

The performance of active synchronizing control scheme is evaluated in the micro grid as shown in the figure 13. The current controller, voltage controller, and droop controller are collectively engaged to validate the control loops of active and reactive power so as to support the grid-connected DG operation. The active power controller test is performed with support unit step signal. During grid synchronizing or dynamic operation, there is a drop in frequency which is managed with support of direct axis current in addition to the droop co-efficient. The predetermined power values show,(see Figure.13(a), (c)) with the efficient smooth tracking of set values, the load sharing in the grid, manage the frequency drop during the sudden change in loads. The reactive power controller effort is based on the reactive power difference between Qref and Q measured and grid voltage drop. The variance in voltage is controlled by voltage and frequency control loop. The droop controller controls the variance in reactive power through PI controller and droop co-efficient provided in the droop control loop.

Figure 14 shows the comparison of the variations in the current and voltage during the islanded and grid connected modes of operation between the proposed model and conventional method. During the transition, DG injects the active power to grid which increases the grid current (see figure 14(a)). The droop is implemented during the transition for the system stabilization. Droop control maintains the smoother operation of current controller and reduces the settling time. The variation in the voltage during the transition controlled through *V-f* controller and droop control and nature of *d*- axis and *q*-axis voltage is represented in figure 14(b).




(a) (b)

Figure 14. Simulation results of direct axis quadrature axis values of
a) direct current b) direct and quadrature voltage

## 6. CONCLUSION

The proposed method dynamically coordinates between frequency/active power and voltage/ reactive power generation and consumption to keep the PCC point frequency and voltage close to their nominal values. The use of PQ control ensures that DGs can generate certain power in accordance with real and reactive power references. Droop controller is implemented to ensure the quick dynamic frequency response and proper power sharing between DGs when a forced islanding occurs or load changes. Compared to pure *V-f* control and master-slave control, the proposed control strategies have the ability to operate without any online signal communication between DGs and make the system fast responding to load changes. The simulation results obtained show that when compared to existing method; the proposed controller is effective in performing real and reactive power tracking, voltage control and power-sharing during both grid-connected mode and islanded mode, makes the system more resilient, fast and adaptive under frequent load shedding and restore rapidly. This method is suitable for small and medium-sized micro grids and is not recommended for very large microgrids unless simplification can be made to the system model.

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