International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-8 Issue-11, September 2019

Strategy for Flawless Transfer of Islanded and Grid Connected Modes with Modifed Droop Controller

A.Sheela, S.Revathi, S.Ragul,

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Abstract: *Technical advances in power electronics and generation capabilities have made the possibility of Distributed Generation (DG) systems. A microgrid is an effective division of a distributed generation system which is analysed by its capability of its operation both as a grid connected and isolated condition. All independent sources operate separately when the main grid is capable of supporting voltage. In case of islanded mode, dynamics is greatly influenced by the connected sources and on the power handling ability. Control of power interfaced converters is of major concern in both the modes of operation. In grid connected mode of operation, the current of the voltage developed needs to be controlled whereas, in Isolated condition, building of voltage is required.In the islanded mode of operation, all the resources in a microgrid should be controlled in coordination with each other so that a stable and a balanced three-phase sinusoidal voltage is obtained. Conventional droop controller is modified for accurate sharing among power converters even when the measured voltage and frequency of the inverters are not the same. Droop coefficients are estimated so that power sharing is more accurate for the respective changes in the power values. They also enable the flawless transfer of the operation mode from islanded to grid connected or vice versa.*

Key words:*Microgrid, grid connected mode, Islanded mode, droop coefficients*

I. INTRODUCTION

Normally, grid connected mode is carried by the microgrids, but it is also anticipated that it may need to operate in islanded mode at any time. It is expected from the microgrid that it has to provide the necessary generation ,and control at least to part of the load during islanded mode because load would be disconnected from the main grid. In grid connection, almost all the system behavior depends on the main grid and the microgrid has less significance during this mode because of its lower capacity. During this mode, good quality of active and reactive power is transported by controlling active and reactive components of current. So, the interfaced converter acts as current source in this mode of operation. Main grid balances the power mismatch instantly thereby maintaining system frequency and voltage.

n contrast, during the islanded mode, the interface converter acts as a voltage source since the voltage has to be built by the converters. Change of controller is required when there is transition from one mode to another.

Manuscript published on 30 September 2019.
***Correspondence Author(s)**
Dr.A.Sheela, Department of EEE,Kongu Engineering College Erode, India,sheelagerard@gmail.com
Ms.S.Revathi, Kongu nadu college of Engineeringand technology, Trichy. revathis.1990@gmail.com
Mr.S.Ragul, Kongu nadu college of Engineeringand technology, Trichy.

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It is more important to have a flawless transfer of controller from one mode to another. Another important aspect is the active and reactive power flow control and regulation of voltage and frequency. All the coordinated systems work with Active and Reactive power (PQ) control strategy because the reference power is available. DGs supply constant power in this mode of operation. Islanded mode of operation would cause large power mismatches creating problems. So, in islanded mode of operation, microgrid operates in V/f or droop control for compensating power and for controlling voltage and frequency. This mode of microgrid depends highly on the integration of DGs and on the controller of the interface converters. Droop control shares reactive and active power without proper communication. Total Harmonic Distortion (THD) is a major problem in microgrids. THD values within the grid has to be maintained low as per standards. H^∞ repetitive controller is used to design the voltage and current loops for obtaining low THD[1]. Obtaining low THD values in any one mode is not a difficult task. Simultaneous control for obtaining low THD to attain flawless transfer by varying the base values to the controller is proposed. An Estimated Droop Controller (EDC) is proposed, in which the coefficients are estimated depending on the demanded power and output power of the inverter. Improvement in power quality indices like voltage and frequency magnitude maintained within nominal values and reduction in THD are also targeted. H^∞ repetitive controller is used for voltage and current loop design. Figure 1 shows the overall block diagram of the proposed method. Based on the operating mode signal, a proper control technique has to be chosen. System is assumed to be in grid mode when the switch is in closed condition and act as a constant source. During this mode it injects required power. The system is in isolated mode when the switch is in open condition. During fault all renewable sources are to be disconnected for supplying reliable power. The major issue is the power control and the voltage control.

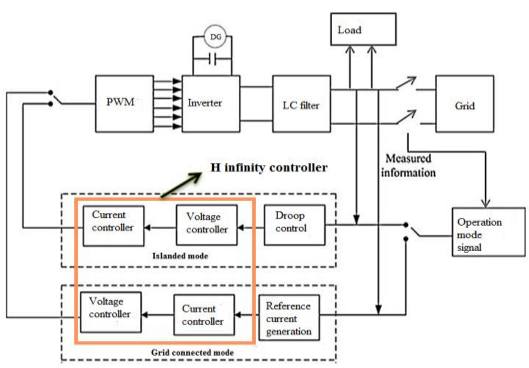

Fig. 1

II. CONTROL STRATEGY FOR GRID CONNECTED MODE

In grid connected mode, microgrid operates in PQ control strategy wherein the direct axis and quadrature axis currents are proportional to power. Therefore by proper control of these components, power can be controlled. Figure 2 shows the diagram of interface converters in the grid connected mode. DGs can supply power only if the electrical parameters at the point of common coupling are within specified limits. Under normal condition, microgrid works in grid mode and the power can be matched simulataneously. System voltage and frequency are supported in this way.

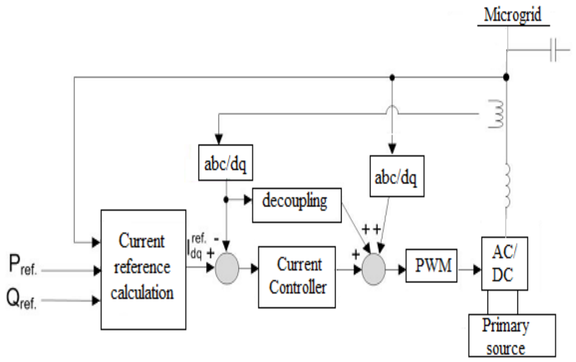

Figure 2 Control structure of grid connected mode (Green et al. 2007)

Figure 3 shows the block diagram of the processes involved in the control of the grid connected mode.

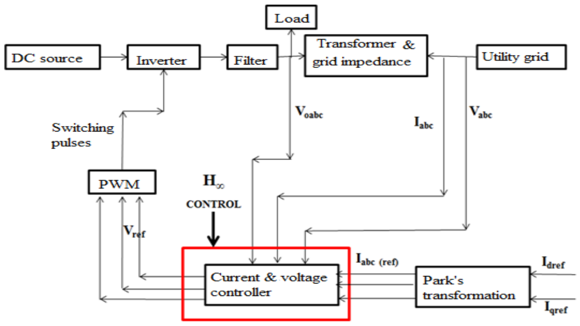

Figure 3 Block diagram of grid connected mode

For controlling PQ of the inverter, as shown in the above figure, Park's transformation converts all the voltage and currents at the main grid into rotating frame. The current components are generated from the reference real and reactive power. By controlling those components, powers through an inverter can be controlled. The reference currents for predetermined power settings P_{ref} and Q_{ref} are given by

$$i_{dref} = \frac{P_{ref}}{V_d} \tag{1}$$

$$i_{qref} = \frac{-Q_{ref}}{V_d} \tag{2}$$

The reference current is converted into three phase quantity using Clarke's transformation. The output reference voltage obtained by the voltage and current loop is given to the PWM inverter which provides switching pulses to the inverter.

III. CONTROL STRATEGY FOR ISLANDED MODE

The objective of islanded mode is to establish the required voltage while that of the grid connected mode is to control the current. When a disturbance occurs in the main grid, sometimes intentionally, the switch opens ,and the microgrid operates in islanding mode. In islanding operation mode, due to the inqdequate supply from the main grid, the power mismatch has to be meet out by the DGs to supply loads, and to maintain power quality. The frequency is changed and it is determined by the droop coefficients of DGs when mode transition occurs. For maintaining frequency within nominal values, determination of droop coefficients should be properly done. DGs are made to operate in V/f control for maintaining voltage and frequency at nominal values. In isolated mode, the sources with PQ strategy the voltage and frequency references are not developed which would be present if it is under grid connected mode. PQ control strategy changes to VF strategy. The power mismatch is compensated through the main grid before islanding.Figure 4 reveals the diagram for the total processes.

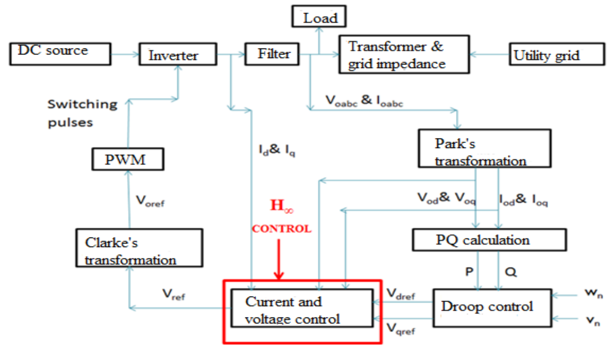

Figure 4 Block Diagram of the islanded mode control

DGs share power by the droop. Power values are calculated from instantaneous voltage and current.

IV. DROOP CONTROL FOR ACTIVE AND REACTIVE POWER SHARING

The theory which lies behind droop theory is the speed governor of synchronous generator. Load increase is affected by frequency reduction. Reactive power is proportional to the voltage. Same thing is followed in droop characteristics. Equivalent circuit is shown in Figure 5.

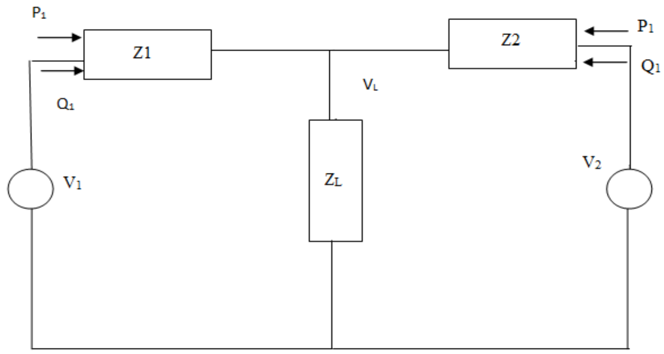

Figure 5 Equivalent circuit of parallel inverters

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The effect of power sharing between two inverters connected in parallel can be expressed by the following equations. The same expressions can be extended for any number of parallel inverters.

$$p_i = \frac{V_L V_i \cos(\theta_i - \theta_{zi})}{Z_i} - \frac{V_L{}^2 \cos(\theta_{Z_i})}{Z_i} \quad (3)$$

$$q_i = \frac{V_L V_i \sin(\theta_i - \theta_{zi})}{Z_i} - \frac{V_L{}^2 \sin(\theta_{Z_i})}{Z_i} \quad (4)$$

where z and θ are the magnitude and phase of line impedance and V_L and V_i are the load voltage and inverter voltages with the phase angle difference between them. Considering impedance is purely inductive and so

$$\theta_{zi} = 90° \quad (5)$$

The real and reactive power equations become

$$p_i = \frac{V_L V_i \theta_i}{X_i}$$

$$q_i = \frac{V_L V_i \theta_i}{X_i} - \frac{V_L{}^2}{X_i} \quad (6)$$

The above relations show that the active power is mostly affected by the angle θ_i while the reactive power is affected by the difference in voltages. Phase angle vigorously depends on the frequency and thus as per Equation 6, active power depends on the control of frequency. Similarly, reactive power is controlled by controlling voltage magnitudes. Thus, by controlling frequency and voltage, active and reactive power can be controlled. Control incorporating this strategy can be implemented as P-f and Q-V droop control. RMS voltage set points of the inverters are E_{r1} and E_{r2}. Both the inverters share the same load voltage.

$$v_L = E_{r1} - Z_1 i_1 = E_{r2} - Z_2 i_2 \quad (7)$$

From Equation 7, it is obvious that when the load increases, the load voltage drops which is called load effect. To share accurate power, load voltage shared by all the inverters should be the same. Measurement of load voltage at the terminals of the inverter should also be the same. To prevent any erroneous measure of voltage at inverter terminals, an additional effort has to be incorporated. To measure the same load voltage, inverter terminal, which is not connected internally, also has to be provided. This terminal is connected to the load with an additional wire for measuring the voltage. For power sharing among inverters, conventional P-f and Q-V droop control exist as per Equations (8) and (9) and the phenomenon is explained by Soultanis et al. (2007)

$$\omega_i = \omega_0 - m_i p_i \quad (8)$$

$$v_i = v_0 - n_i q_i \quad (9)$$

In the equations, m_i and n_i are the droop coefficients of the droop characteristic curves while ω_0 and v_0 are the no load values of angular frequency and voltage respectively as shown in Figure 6.

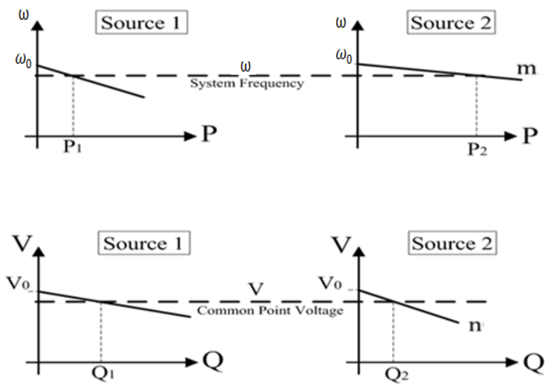

Figure 6 Droop characteristic curves

Figure 6 shows the droop characteristic curves for active and reactive power sharing based on the droop coefficients. For sharing the active and reactive power among two inverters, the droop coefficients should be inversely related to their power rating.

$$m_1 S_1{}^* = m_2 S_2{}^* \quad (10)$$

$$n_1 S_1{}^* = n_2 S_2{}^* \quad (11)$$

Additionally, droop coefficients should satisfy the following relation.

$$\frac{m_1}{n_1} = \frac{m_2}{n_2} \quad (12)$$

Conventionally, droop coefficients are defined as in Equation (13) and (14)

$$m = \frac{\Delta\omega}{P_{\max}} \quad (13)$$

$$n = \frac{\Delta v}{Q_{\max}} \quad (14)$$

where $\Delta\omega$ and Δv are maximum allowable deviations of frequency and voltage while $P_{\max}$ and $Q_{\max}$ are maximum active and reactive powers. The reference values are obtained by the droop control. The conventional droop control scheme is shown in Figure 7. From the figure, it is seen that the reference voltage and frequency are generated for an ith inverter. The droop coefficients are calculated using Equation (13) and (14).

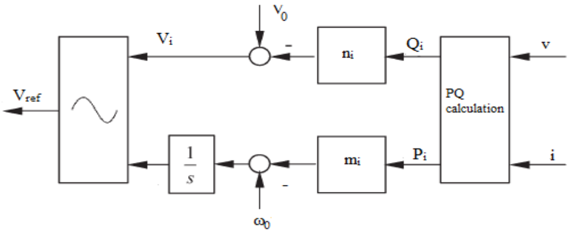

Figure 7 Conventional droop control scheme (Qing et al. 2013)

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The sources of microgrid would modify their active or reactive power output when the frequency or voltage of the inverters changes from the nominal values. Voltage and frequency reference values are set by the droop controller for the parallel operation of inverter for power sharing and for regulating voltage and frequency.

4.1 Real Power Sharing

In steady state condition, parallel inverters have the same frequency , and so it is obvious that the accuracy of real power sharing with inductive output impedance is maintained accurately as indicated by Li et al. (2009). From Equation (10), the relation is

$$m_1 P_1 = m_2 P_2 \tag{15}$$

Frequency droop coefficients should satisfy Equation (10) & Equation (15) and so real power sharing proportional to its power rating is achieved.

$$\frac{P_1}{S_1^*} = \frac{P_2}{S_2^*} \tag{16}$$

From Equation (6) the relation

$$m_1 \frac{V_L V_1 \theta_1}{X_1} = m_2 \frac{V_L V_2 \theta_2}{X_2} \tag{17}$$

If $\theta_1 = \theta_2$ and $V_1 = V_2$ exist, then the following relation exists.

$$\frac{m_1}{X_1} = \frac{m_2}{X_2} \tag{18}$$

If the frequency set points are different for the inverters, then the error in power sharing among parallel unit occurs. Real power deviation due to the deviation of frequency set points $\Delta\omega_i$ by Equation (8) is

$$\Delta P_i = -\frac{1}{m_i}\Delta\omega_i \tag{19}$$

When two inverters are connected in parallel with $P_1 + P_2 = P_{r1} + P_{r2}$, the relative power sharing error which may exist due to the measurement of frequency $\Delta\omega = \Delta\omega_1 - \Delta\omega_2$ is

$$P_e\% = \frac{P_1}{P_{r1}} - \frac{P_2}{P_{r2}} = \frac{\Delta P_1}{P_{r1}} - \frac{\Delta P_2}{P_{r2}} = -\frac{\omega_0}{m_i P_{ri}}\frac{\Delta\omega}{\omega_0} \tag{20}$$

where $m_i P_{ri} / \omega_0$ is the frequency droop ratio at the rated real power. If this ratio is smaller, real power sharing error is bigger. For example the frequency boost ratio of 10% and the frequency set point deviation $\Delta\omega / \Delta\omega_0$ of 10% which may occur for any probable reasons, the real power sharing error is 100%. The accuracy is much reduced.

4.2 Reactive Power Sharing

For real power sharing relation between real power and frequency droop coefficients exist as per Equation (15). Similarly, to achieve reactive power sharing

$$n_1 Q_1 = n_2 Q_2 \tag{21}$$

and

$$\frac{Q_1}{S_1^*} = \frac{Q_2}{S_2^*} \tag{22}$$

the voltage deviation should be zero as of Equation (3.9). Voltage deviation cannot be maintained at zero because of disturbances, errors, system parameter variations and so on.

The relation exists for reactive power from Equation (6) for $V_1 = V_2$ is,

$$\frac{n_1}{X_1} = \frac{n_2}{X_2} \tag{23}$$

where n_1 and n_2 are selected proportional to their output reactance. The per unit impedance of the inverter is given by

$$\gamma_i = \frac{X_i}{V_L / I_i} = \frac{X_i S_i^*}{V_L^2} \tag{24}$$

Equation (24) is equivalent to

$$\gamma_1 = \gamma_2 \tag{25}$$

The output impedances of the parallel inverters should be the same for proportional reactive power sharing. Based on this criteria, virtual output impedance method is used for power sharing by Guerrero (2006). If this condition is not satisfied, then the voltage set points are not the same for the inverters and reactive power sharing error occurs.

By Equation (9), reactive power deviation due to variation in voltage set point of the inverter ΔV_i is

$$\Delta Q_i = -\frac{1}{n_i}\Delta v_i \tag{26}$$

When two inverters are connected in parallel with $Q_1 + Q_2 = Q_{r1} + Q_{r2}$, the relative power sharing error which may exist due to the measurement of voltage $\Delta v = \Delta v_1 - \Delta v_2$ is

$$Q_e\% = \frac{Q_1}{Q_{r1}} - \frac{Q_2}{Q_{r2}} = \frac{\Delta Q_1}{Q_{r1}} - \frac{\Delta Q_2}{Q_{r2}} = -\frac{v_0}{n_i Q_{ri}}\frac{\Delta v}{v_0} \tag{27}$$

where $n_i Q_{ri} / v_0$ is the voltage droop ratio at the rated reactive power. If this ratio is smaller, reactive power sharing error is bigger. For example, frequency boost ratio of 10% and voltage set point deviation $\Delta v / \Delta v_0$ of 10% which may occur for any probable reason, the reactive power sharing error is 100%.

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The accuracy is much reduced.

If the system is stable for parallel inverters with inductive output, then the following conditions prevail.

$$C_1 = \begin{Bmatrix} \omega_1 = \omega_2 \\ \dfrac{m_1}{X_1} = \dfrac{m_2}{X_2} \end{Bmatrix} \quad (28)$$

and

$$C_2 = \begin{Bmatrix} v_1 = v_2 \\ \dfrac{n_1}{X_1} = \dfrac{n_2}{X_2} \end{Bmatrix} \quad (29)$$

An additional condition of the above equations is that m_i and n_i should be proportional to each other. If C_1 is satisfied for real power sharing, the reactive power sharing is also achieved. If C_2 is satisfied for reactive power sharing, then real power sharing is also achieved. However, this is not possible in reality to meet $\omega_1 = \omega_2$ or $v_1 = v_2$ because of practical difficulties. It is also not possible to maintain $\Upsilon_1 = \Upsilon_2$ due to the difference in the impedances and mismatches in the components. Moreover, the droop coefficients are fixed in conventional droop control. There is a possibility that all the inverters may start operating with a lower value of frequency and magnitude of the voltage which are different from the set point frequency and voltage.

V. LIMITATIONS OF CONVENTIONAL DROOP CONTROL

There exist a few problems with the existing droop characteristics as listed below.

1. To share the load in proportion, all the parallel connected inverters have to measure the same load voltage and frequency (i.e) line impedances should be the same.
2. Due to fixed droop coefficients, all inverters may start operating with a new lower frequency and voltage comparatively different from the set point values.
3. The droop coefficients must be smaller for lesser reduction in load voltage. The response is sluggish for smaller droop coefficients which should be chosen bigger for a fast response. So, there is a contradiction in selecting the droop coefficients.

5.1 MODIFIED DROOP CONTROLLER

The conventional droop controller is modified to share the load equally among the inverters when the above mentioned uncertainties occur. The voltage and frequency drop due to droop control as in Equation (8) and (9). From the droop equations, it is clear that

$$\Delta\omega_i = \omega_i - \omega_0 = -m_i p_i \quad (30)$$

$$\Delta v_i = v_i - v_0 = -n_i q_i \quad (31)$$

Change in voltage is integrated and is implemented in the loop proposed by Marwali et al. (2004), Li et al .(2004) and Marwali et al.(2008)

$$v_i = \int_0^t \Delta v_i dt \quad (32)$$

But the controller works only for grid connected mode, and not for islanded mode of operation. Load voltage drops due to load effect and droops effect. For smaller values of n_i and m_i the voltage and frequency drop would be lesser, but the smaller value would slow down the response. For maintaining the voltage with limited range, the voltage drop $(v_0 - v_L)$ has to be fed back through an amplifier gain. Similarly for maintaining frequency within limited range, frequency difference $(\omega_0 - \omega_L)$ has to be fed back through amplifier gain. Due to this modification load voltage drop and frequency drop are considered along with droop effect, and so the performance gets improved. Proportional load sharing is maintained accurately among inverters even when the voltages and frequencies are not the same.

The modified droop controller is shown in Figure 8.

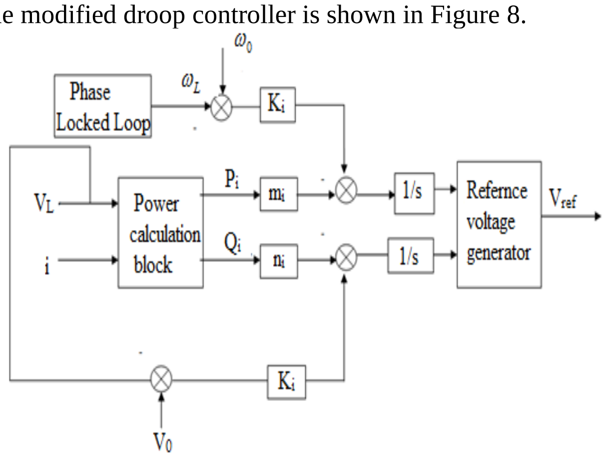

Figure 8 Modified droop controller

Under steady state condition, the input of the integrator should be zero. So, the following conditions prevail instead of Equations (8) and (9)

$$m_i P_i = K_i(\omega_0 - \omega_L) \quad (33)$$

$$n_1 Q_i = K_i(v_0 - v_L) \quad (34)$$

For constant K_i value, $m_i P_i$ is always the same which assures equal real power sharing for all the parallel inverters. Similarly, $n_1 Q_i$ is always the same which assures equal reactive power sharing for all the parallel inverters. Real and reactive power is shared accurately without having the same frequency and voltage i.e ω_i and v_i . The possibility of deviation in real and reactive power sharing may be due to the measurement of the load voltage and frequency. The possible real and reactive power sharing error is given by the following equations.

$$\Delta P_i = \frac{K_i}{m_i} \Delta\omega \quad (35)$$

$$\Delta Q_i = \frac{K_i}{n_i} \Delta v \quad (36)$$

From Equation (33) & (34) the following relation exists.

$$\omega_L = \omega_0 - \frac{m_i P_i}{K_i \omega_0} \omega_0 \quad (37)$$

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$$v_L = v_0 - \frac{n_i Q_i}{K_i v_0} v_0 \qquad (38)$$

In the above equation, voltage drop ratio $n_i Q_i / K_i v_0$ considers the voltage drop due to load effect and droop effect. Conventional droop controller by Sao (2005) considers only drop due to droop effect. The strategy in conventional literature compensates drop due to load effect, but not due to droop effect whereas the proposed controller improves voltage regulation by compensating voltage drop due to load effect and droop effect. The droop equation is not decided by the output impedance as given in Equation (7), but by the parameters in voltage drop ratio. Voltage drop can be reduced if K_i value is very large because it is proportional to the ratio n_i / K_i, but the sharing error as per Equation (36) is proportional to the ratio K_i / n_i. So, a contradiction exists between voltage drop and power sharing error. Voltage drop and sharing error can be reduced by properly choosing K_i value.

5.2 Droop Calculation Block

In conventional method, the droop values are fixed and calculated as per Equation (8) and (9). The coefficients depend on the maximum power and do not change if any change in the output power of the inverter exists. If any major variation occurs, these fixed coefficients would make the system unstable. With this proposed method, new droop coefficients are adopted for any major deviation from normal situations that occur. Robustness and reliability increase by using these estimated coefficients. The following equations are used to generate tracking signals for the control loops.

$$\hat{m}P_i = K_i(\omega_0 - \omega_L) \qquad (39)$$

$$\hat{n}Q_i = K_i(v_0 - v_L) \qquad (40)$$

VI. SIMULATION OF MICROGRID WITH MODIFIED AND ESTIMATED DROOP CONTROLLER

For verifying the proposed method for sharing active and reactive power among the inverters, a sample microgrid with two sources along with constant and switched loads is considered.

6.1 Simulation of Parallel Inverters

To analyze the performance of the proposed controller two different cases are considered for simulation.

Case 1: Two parallel inverters with the same line impedance for K_i value as 2

Case 2: Two parallel inverters with the same line impedance for K_i value as 2

6.1 Simulation of Parallel Inverters

To analyze the performance of the proposed controller two different cases are considered for simulation.

Case 1: Two parallel inverters with the same line impedance for K_i value as 2

Case 2: Two parallel inverters with the same line impedance for K_i value as 2

6.2 Case 1: Two Parallel Inverters with Same Line Impedance

The performance of the system is analyzed for the system with same line impedance. Initially, inverter 1 is connected to the load and inverter 2 is connected at 0.5 seconds. The system responds to the change quickly and the inverters get synchronised. Figure 9 shows that the voltage of both the inverter remains the same and the slight deviation is not visible due to the overlapping of two signals. Parallel inverters share equal voltages as well as the equal current which can be seen from Figure 10 . The output current of inverter 2 before 0.5 second is 0A which is then equally shared between two inverters. The load is varied at 1 and then at 1.5 seconds. At all these variations,the response of the system is faster and it stabilises at a quicker rate. Frequency is maintained at nominal value for both the inverters which can be seen from Figure 11.

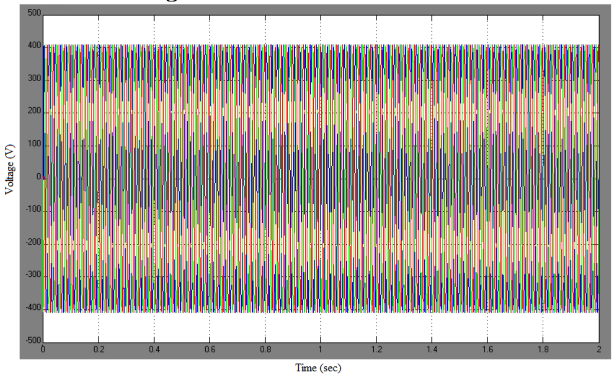

Figure 9 Output Voltage of parallel inverters with same line impedance

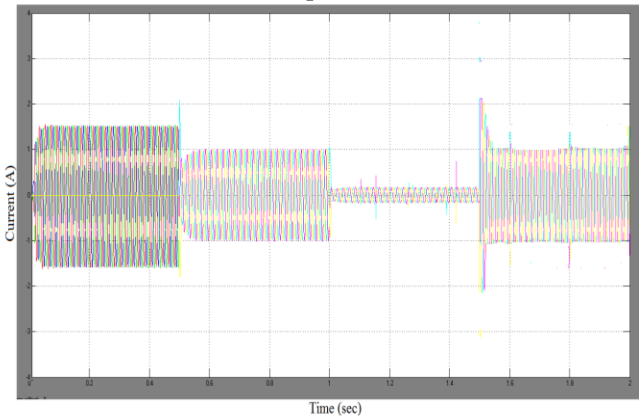

Figure 10 Output current of parallel inverters with same line impedance

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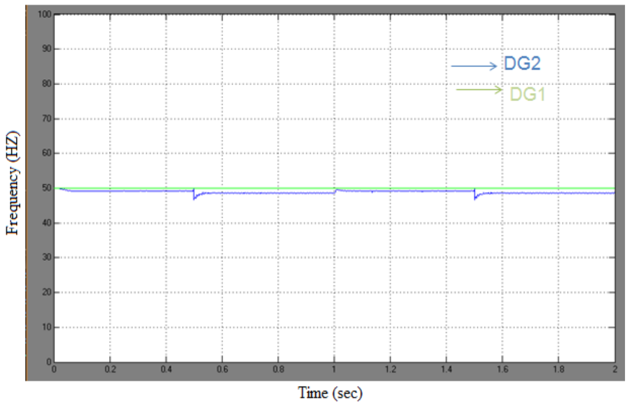

Figure 11 Frequency of parallel inverters with same line impedance

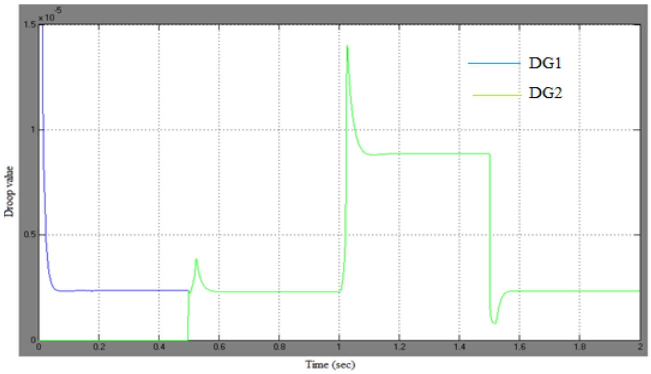

Figure 12 Estimated frequency droop of inverters with same line impedance

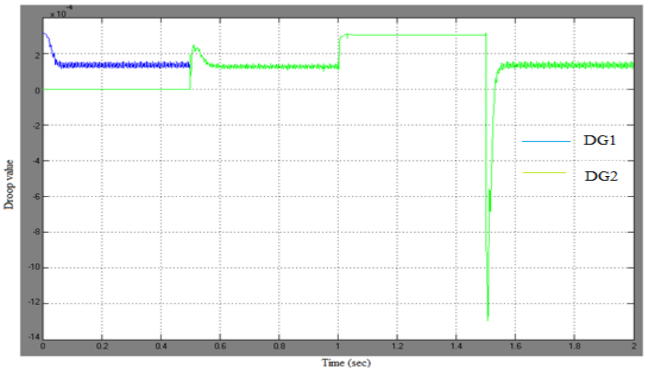

Figure 13 Estimated voltage droop of inverters with same line impedance

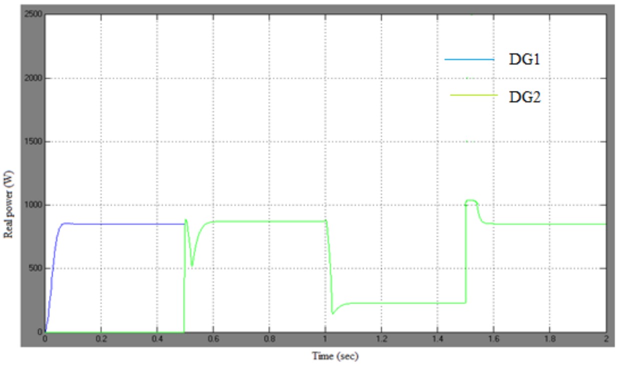

Figure 14 Real powers of two inverters with same line impedance

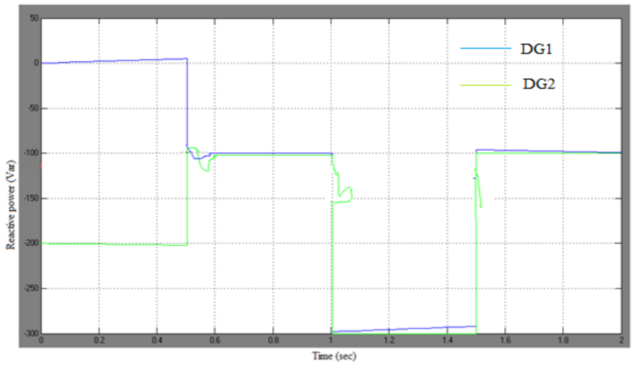

Figure 15 Reactive power of two inverters with same line impedance

Curves for estimated frequency droop coefficients of the inverters are shown in Figure 12. The values are automatically estimated after 0.5 seconds for inverter 2 and it remains same for both the inverters. This is the different feature compared with the conventional controller where drrop coefficients are fixed initially. Similarly, plots for voltage droop coefficients for the parallel inverters are shown in Figure 13. The same droop value ensures equal power sharing among parallel inverters . Equal power sharing is shown in Figures 14 and 15.

6.3 Case 2: Two Parallel Inverters with Different Line Impedance

Performance is analyzed for parallel inverters with different line impedances. With conventional droop strategy system will become unstable due to high flow of voltage and current due to the problem of synchronisation. Figure 16 shows the output voltage of the inverters which remain almost the same during load variations. Due to the different line impedance output current of the inverters are different. The load shared by the inverters will be different when the impedance is different among the inverters. Both inverters are expected to inject different value of current into the load. Figure 17 shows the injected current values of the inverters. For clear understanding, the current is shown for one phase only. It is visible that the inverter currents are different and the phase angle difference is evident. Even then the inverters are synchronised and system is stable . It is observed that the phase difference is almost 90 degree which does not affect the phase difference between voltages. It is observed from the literature that with conventional droop strategy the phase difference is 180 degree when line impedances are different. If the phase difference is 180 degree, it would create phase difference between voltage which would disturb the synchronisation process. In the proposed droop controller the phase difference between the currents does not exceed 90 degree which assures stability even with different line impedances. Secondly, the frequency of the whole system is maintained at a normal value and it is observed from Figure 18.

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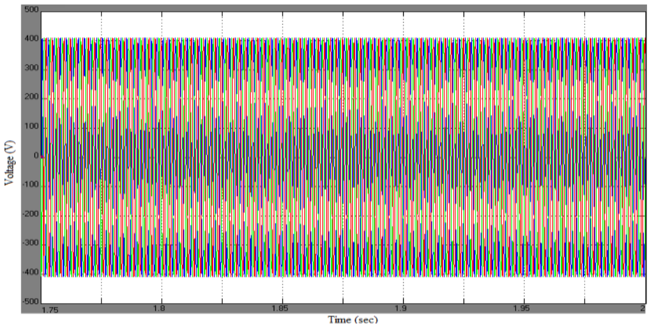

Figure 16 Output voltage of two inverters with different line impedance

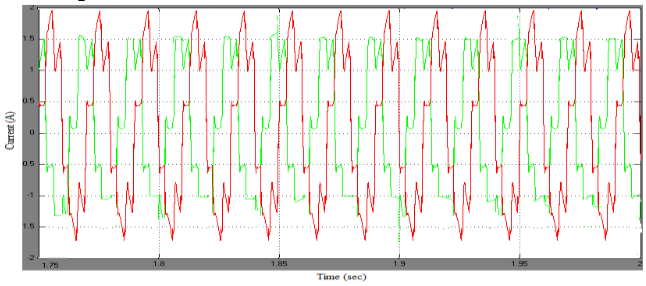

Figure 17 Output current of two inverters with different line impedance

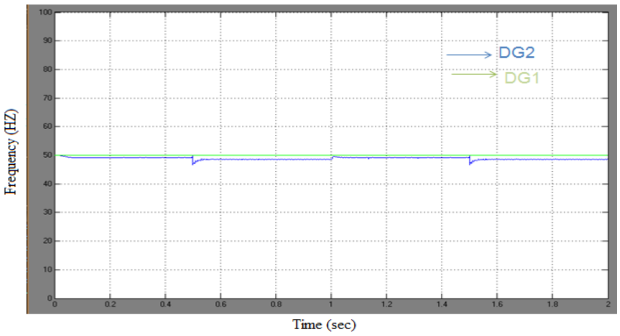

Figure 18 Frequency of two inverters with different line impedance

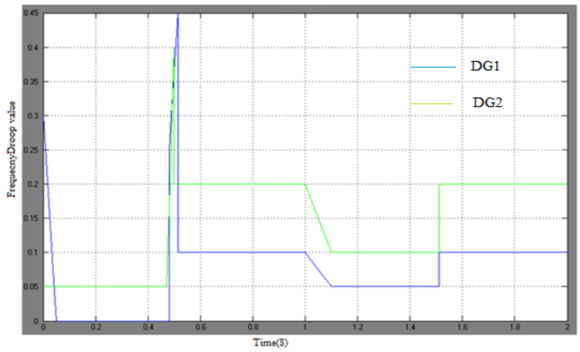

Figure 19 Estimated frequency droop of inverters with different line impedance

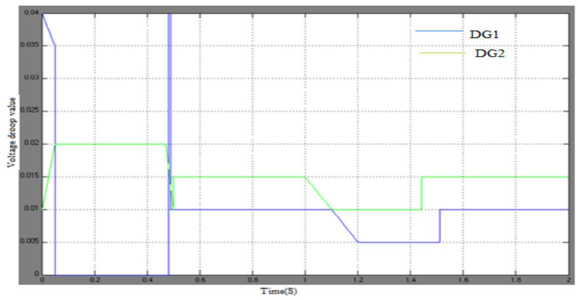

Figure 20 Estimated voltage droop of inverters with different line impedance

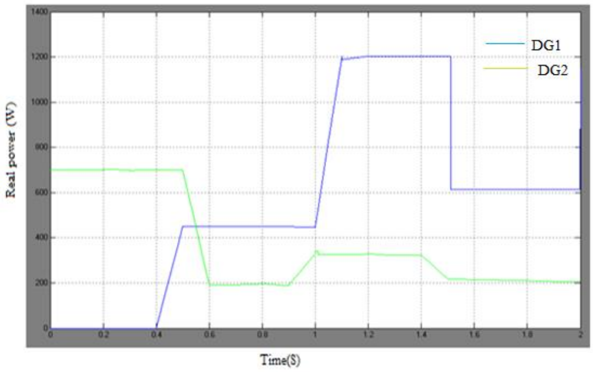

Figure 21 Real powers of two inverters with different line impedance

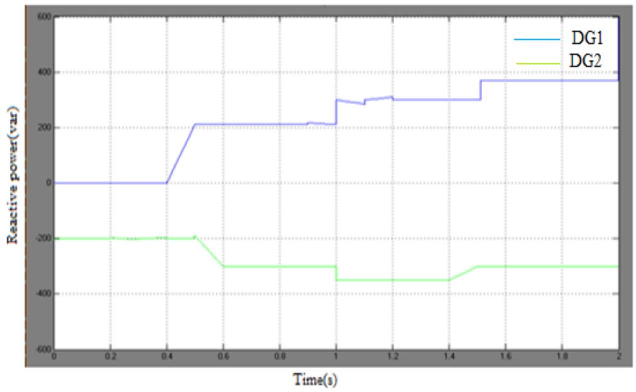

Figure 22 Reactive power of two inverters with different line impedance

Parallel inverters estimate their droop coefficients based on the impedance and power output. This can be seen in Figures 19 and 20. Real and reactive power of the inverters is shown in Figures 21 and 22. Parallel inverters are delivering different values of real and reactive power to the load.

VII. CONCLUSION

In this paper, real and reactive power sharing is improved by incorporating modifications in the conventional droop loop. Droop coefficients are estimated for the operating condition which is different from the conventional method where the coefficients are fixed. Drop due to load effect and droop effect are considered and compensated for improving voltage regulation. The droop equation is not decided by the output impedance, so the power sharing is proper for both same and for different line impedances. Simulation results show that the proposed approach is able to share both real and reactive power among inverters independently according to changes in load demand. The performance of the system is analyzed for the system with same line impedance. Initially, inverter 1 is connected to the load and inverter 2 is connected at 0.5 seconds. The system responds to the change quickly and the inverters get synchronised. Figure 9 shows that the voltage of both the inverter remains the same and the slight deviation is not visible due to the overlapping of two signals. Parallel inverters share equal voltages as well as the equal current which can be seen from Figure 10 . The output current of inverter 2 before 0.5 second is 0A which is then equally shared between two inverters.

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The load is varied at 1 and then at 1.5 seconds. At all these variations,the response of the system is faster and it stabilises at a quicker rate. Frequency is maintained at nominal value for both the inverters which can be seen from Figure 11.

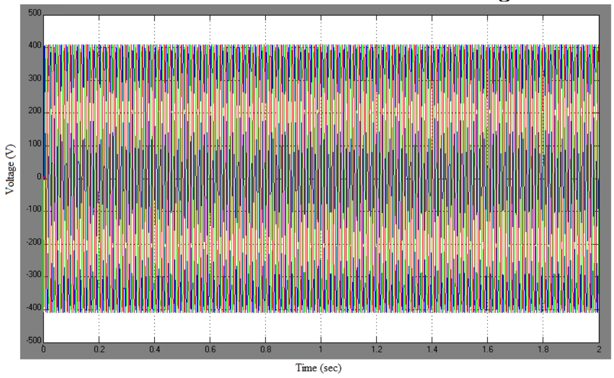

Figure 9 Output Voltage of parallel inverters with same line impedance

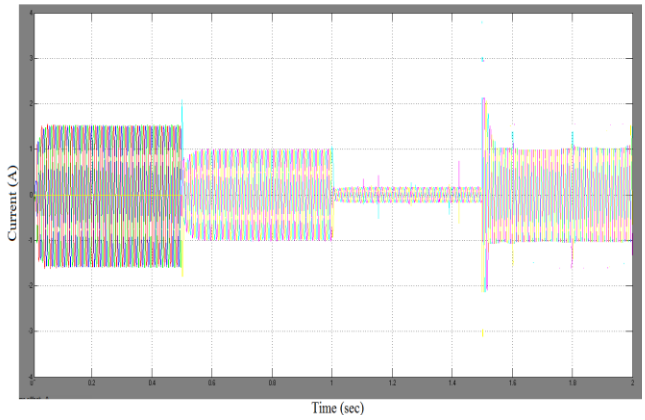

Figure 10 Output current of parallel inverters with same line impedance

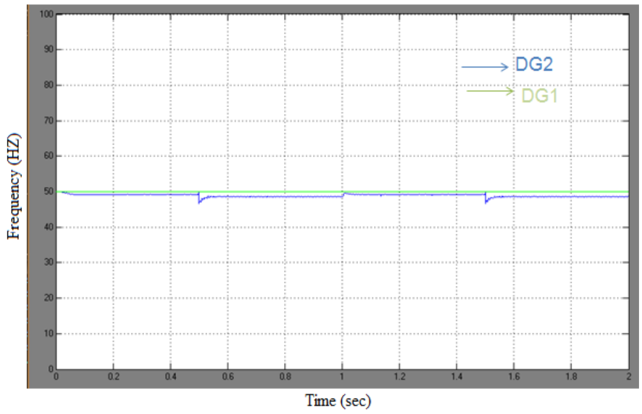

Figure 11 Frequency of parallel inverters with same line impedance

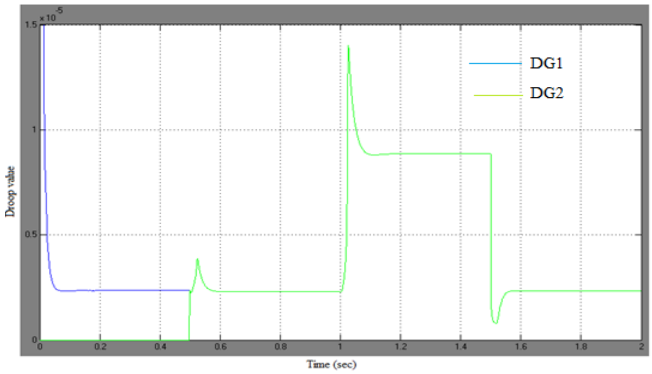

Figure 12 Estimated frequency droop of inverters with same line impedance

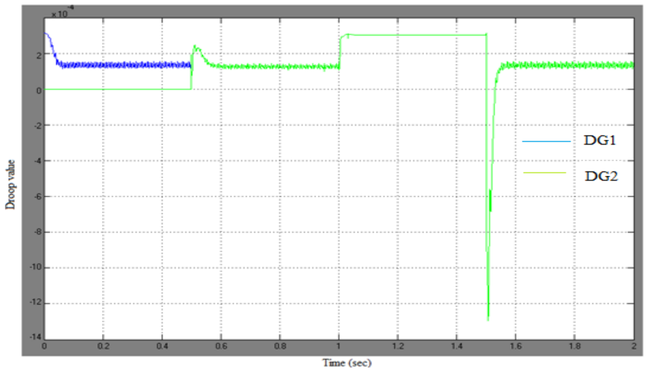

Figure 13 Estimated voltage droop of inverters with same line impedance

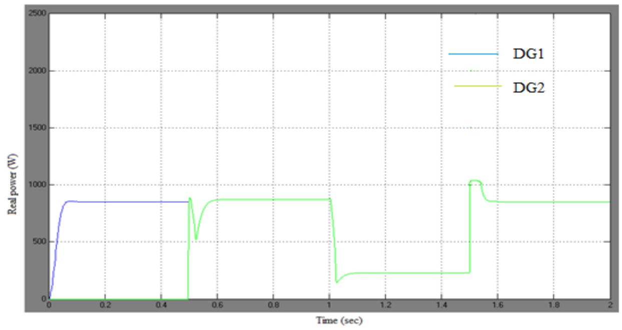

Figure 14 Real powers of two inverters with same line impedance

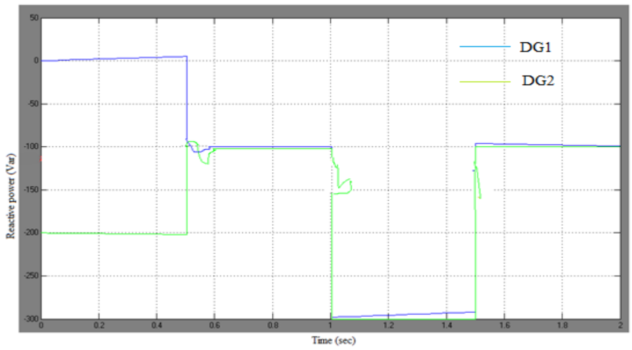

Figure 15 Reactive power of two inverters with same line impedance

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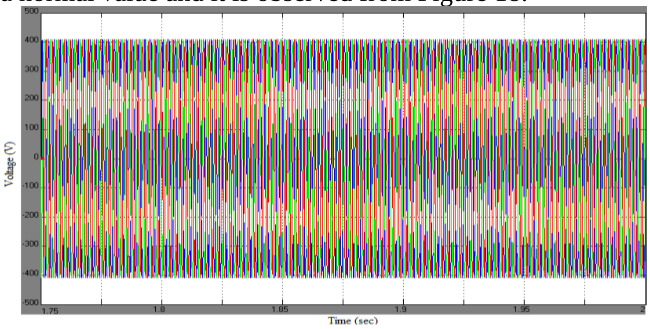

Figure 16 Output voltage of two inverters with different line impedance

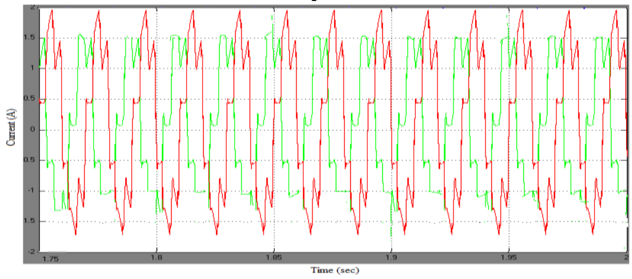

Figure 17 Output current of two inverters with different line impedance

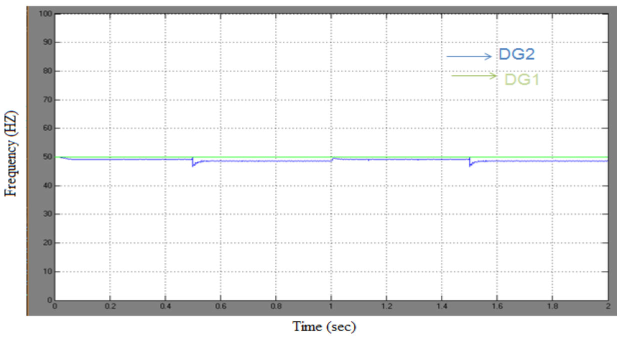

Figure 18 Frequency of two inverters with different line impedance

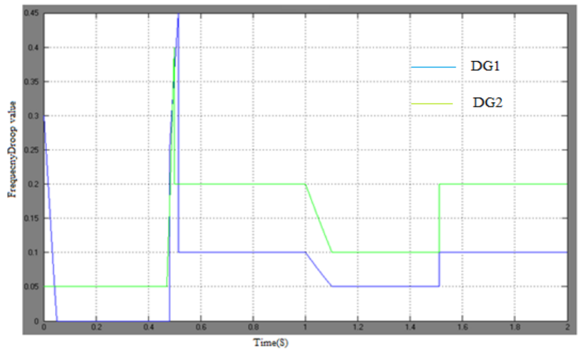

Figure 19 Estimated frequency droop of inverters with different line impedance

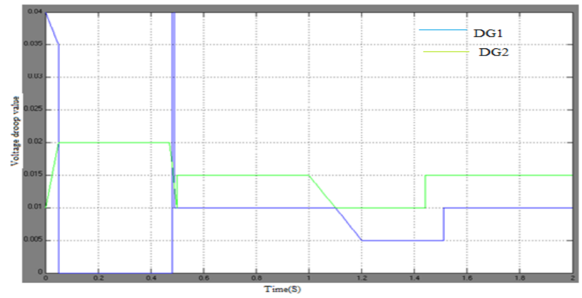

Figure 20 Estimated voltage droop of inverters with different line impedance

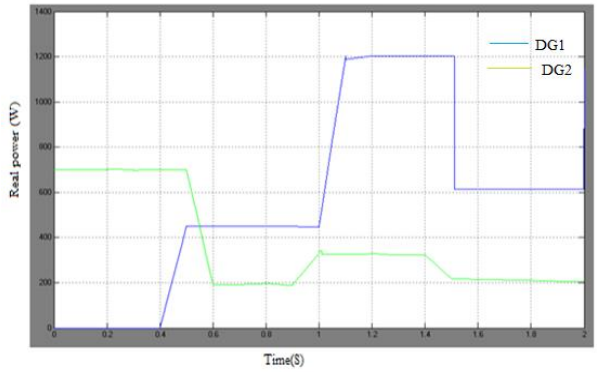

Figure 21 Real powers of two inverters with different line impedance

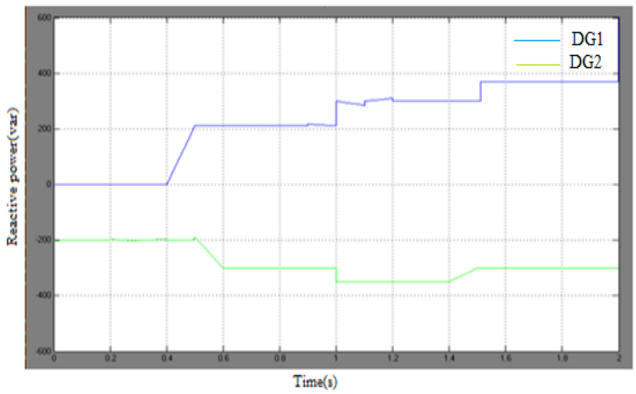

Figure 22 Reactive power of two inverters with different line impedance

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AUTHORS PROFILE

Dr.A.Sheela received her undergraduate degree in Electrical & Electronics Engineering in 2001, Master of Engineering in Power Systems in 2004 and subsequently her Ph.D. in Electrical Engineering in 2016. She has published around 35 papers in various international conferences and journals to his credit. She has received funding from IIT-Madras for pursuing research. Her research interests include smart grid, soft computing and cybersecurity.

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