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Review of Different Droop Control Method

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***Abstract* - in transmission line, there are large quantities of distributed generators in micro-grid, which are all connected with PCC (Point of Common Coupling) through inverters. The droop control method is widely used to distribute active and reactive power among parallel inverters because its properties of low cost, high stability and no need of communication channel. In a micro-grid, the inductance values of transmission lines connecting to respective inverters are different due to the low density of distributed generators. In addition the settling time of the traditional droop control is high. In that situation, the reactive power cannot be equally shared even if all the inverters are using the same droop control method. With regards to this problem, a modification, called virtual impedance loop, is put forward for the droop control strategy to share reactive power equally in this paper. To improve the system response and settling time the arctan function also implement in power-frequency droop control strategy. The feasibility of the design is validated by simulation**.

***Index Terms* - Droop control, Virtual impedance loop, Arctan function, Reactive power sharing**

I. INTRODUCTION

Parallel connection is an important way of power distribution. The control methods for parallel inverters can be divided into parallel connections with signal interconnecting lines and without signal interconnecting lines. In the parallel connection with communication lines, the control methods of main current include master slave mode, central type, average type, chain type [1]–[4]. Their advantage lies in the rapid power sharing speed but disadvantages also exist. Not only the cost of system manufacture is high due to the signal interconnection lines, but also it is easily interfered by high frequency signal for the signal interconnecting lines are quite long in the application of distributed power generation. The control method without signal interconnecting lines refers to the droop control method, in which because the output voltage references are produced by the inverters themselves, signal interconnecting lines are not necessary. That not only reduces the cost of system manufacture, but also eliminates the interference in signal interconnecting lines [5]. Because of those properties, the droop control method is widely used in microgrid, which contains a lot of distributed generations.

Due to the low density of distributed generations in microgrid, the distance between inverters and load has become varied. Thus, the characteristic of transmission lines has to be taken into account, which also brings new problems to the droop control method [7]. A possible solution to the line impedance problem consists of adding an inductor in series with the inverter output, in order to fix the output impedance [6]. Nevertheless, this inductor is heavy and bulky, increasing the size and the cost of the equipment. With the objective of physically avoiding this inductor, several fast control loops emulating the desired output impedance have been proposed [8]–[13].

The aim of this paper is to overcome the aforementioned drawbacks and to modify the control strategies without communication wires, which could be appropriate to high-performance paralleled UPS inverters. The control method here considered consists of three main implements: an inner loop that regulates the output voltage with no steady-state errors, an intermediate loop to program virtual output impedance, and an arctan function implemented [6] for achieve better response and settling time and to function the system with in the pre-set boundaries.

This paper begins by introducing the existing theory on power - frequency and reactive power - voltage droop. Later in this paper the limitations of the conventional droop control method, virtual impedance concept are discussed. Then, the arctan function which is used in power-frequency droop to improve the response time and remove the oscillation is discussed. Lastly, the extensive case studies of above methods are performed to validate the developed control strategies in MATLAB Simulink. Finally, the comparison between conventional droop control and modified droop control is studied.

II. CONVENTIONAL DROOP CONTROL METHOD

Fig. 1 shows the equivalent circuit of an inverter connected to an ac bus or load by considering line impedance is inductive. The complex power drawn to the bus can be expressed as

$$S_i = P_i + Q_i$$

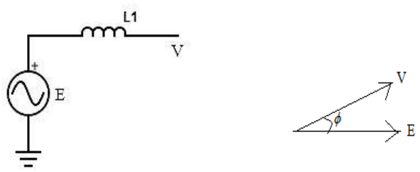

Figure-1 The source with inductive output impedance.

$$P = \frac{EV}{X}\sin\phi \text{.........(1)}$$

$$Q = -\frac{EV\cos\phi - V^2}{X} \text{.........(2)}$$

Where X is the output reactance of an inverter, ϕ is the phase angle between the output voltage of the inverter and the voltage of the common bus, and E and V are the amplitude of the output voltage of the inverter and the common bus, respectively.

From (1) and (2), it is found that the active power is predominately dependent on the power angle, while the reactive power mostly depends on the output-voltage amplitude E. Stated differently, if the real power can be controlled so can the power angle, and if the reactive power can be regulated so can the voltage E will be controllable. In the droop method, each unit uses the frequency, instead of the power angle or phase angle, to control the active power flow since the units do not know the initial phase values of the other units in the stand-alone system. By regulating the real and reactive power flows through a power system, the voltage and frequency can be determined.

$$\omega = \omega^* - m(P_{0i} - P_i) \text{……(3)}$$

$$E = E^* - n(Q_{0i} - Q_i) \text{……(4)}$$

Consequently, most of the wireless-control of paralleled-inverters uses the conventional droop method, where ω is the operating frequency of the inverter, ω* is the frequency set point, m is the frequency droop coefficient, Pi is the real power of the inverter, P0i is the real power set point, E is the output voltage of the inverter, E* is the voltage set point, n is the voltage droop coefficient, Qi is the reactive power of the inverter, and Q0i is the reactive power set point. Similarly if the output impedances of inverter is highly resistive or the microgrid operate at low voltage then, the reactive power control is dependent on the power angle, while the active power mostly depends on the output-voltage amplitude E.

Consequently, a control scheme based on the P–f and Q–V droops should be used for inductive impedance, while for resistive impedance we should use Q–f and P–V droops. For this reason, it is important to design the output impedance properly in order to improve decoupling between active and reactive power and to avoid the line impedance impact over the power sharing.

III. Limitation of Conventional Droop Control Method

To understand the limitation take two inverters with inductive output impedances connected in parallel are shown in figure 2. Here, the line impedance considered is inductive due to the large filter inductance and long transmission line. The reference voltages of the two inverters are, respectively,

$$v_{r1} = \sqrt{2}E_1\sin(\omega_1 t + \delta_1)$$

$$v_{r2} = \sqrt{2}E_2\sin(\omega_2 t + \delta_2)$$

Here, E1 and E2 are the voltage set-points for the inverters. The power ratings of the inverters are S1* =E* I1* and S2* =E* I2*.They share the same output voltage V0.

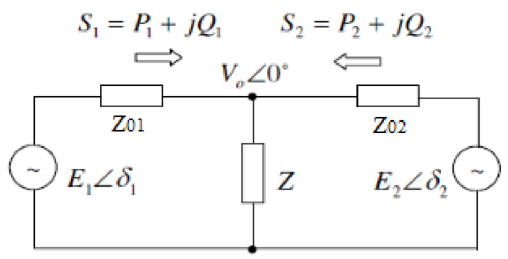

Figure-2 Two inverters with inductive output impedances

Q − E and P − ω droops are used because of the inductive impedances. Otherwise, the Q − ω and P − E droops are used when the output impedances are resistive. The drooping coefficients n and m are normally determined by the desired voltage and frequency drops respectively, at the rated active power and reactive power. The frequency ω is integrated to form the phase of the voltage reference.

In order for the inverters to share the load in proportional to their power ratings, the droop coefficients of the inverters should be in inverse proportional to their power ratings [14], i.e., ni and mi should be chosen to satisfy

$$n_1 S_1^* = n_2 S_2^* \text{……(5)}$$

$$m_1 S_1^* = m_2 S_2^* \text{……(6)}$$

It is easy to see that n_i and m_i also satisfy

$$\frac{n_1}{m_1} = \frac{n_2}{m_2} \text{…… (7)}$$

Active Power Sharing

According to the conventional droop control method, for proportional active load sharing in the steady state, two inverters should work with a same frequency, i.e., ω1 = ω2. For the inductive output impedances, the active power accuracy depends on the (6). (Or the accuracy of reactive power sharing for inverters with resistive output impedances) Indeed, from (3), we get

$$m_1 P_1 = m_2 P_2 \text{......(8)}$$

Since the coefficients *mi* are chosen to satisfy (6), active power sharing proportional to their power ratings is (always) achieved, i.e.,

$$\frac{P_1}{S_1^*} = \frac{P_2}{S_2^*} \text{......(9)}$$

Alternatively, according to (1), there is

$$m_1 \frac{E_1 V_o}{Z_{o1}} \sin\delta_1 = m_2 \frac{E_2 V_o}{Z_{o2}} \sin\delta_2 \text{......(10)}$$

If $\delta 1 = \delta 2$ and $E1 = E2$, then

$$\frac{m_1}{Z_{o1}} = \frac{m_2}{Z_{o2}} \text{......(11)}$$

Reactive Power Sharing

The Reactive power of the two inverters can be obtained by substitute (4) into (2),

$$Q_i = \frac{E^* \cos\delta_i - V_0}{n_i \cos\delta_i + Z_{oi}/V_o} \text{......(12)}$$

Substituting (12) into (4), the voltage amplitude deviation of the two inverters is

$$\Delta E = E_2 - E_1 = \frac{E^* \cos\delta_i - V_0}{\cos\delta_1 + Z_{oi}/n_1 V_o} - \frac{E^* \cos\delta_i - V_0}{\cos\delta_2 + Z_{oi}/n_2 V_o} \text{......(13)}$$

It is known from [14] that the voltage deviation of the two units leads to considerable errors in load sharing. Indeed, in order for

$$n_1 Q_1 = n_2 Q_2 \quad \text{Or} \quad \frac{Q_1}{S_1^*} = \frac{Q_2}{S_2^*} \text{......(14)}$$

To hold, the voltage deviation Δ*E* should be zero according to (13). This is a very strict condition because there are always numerical computational errors, disturbances, parameter drifts and component mismatches. This condition is satisfied if

$$\frac{n_1}{Z_{o1}} = \frac{n_2}{Z_{o2}} \text{...(15)}$$

$$\delta_1 = \delta_2$$

In other words, n_i should be chosen to be proportional to its output impedance Z_{oi} or Z_{oi} should be design to satisfy (15). Taking (15) into account, in order to achieve accurate sharing of reactive power, the (inductive) output impedance should be designed to satisfy

$$Z_{o1} S_1^* = Z_{o2} S_2^* \text{......(16)}$$

Since the per-unit output impedance of Inverter *i* is

$$\gamma_i = \frac{Z_{oi}}{E^*/I_i^*} = \frac{Z_{oi} S_i^*}{(E^*)^2} \text{......(17)}$$

Substitute (17) into (16), the condition is equivalent to

$$\gamma_1 = \gamma_2 \text{......(18)}$$

From (18) it is suggest that for satisfy the condition (15) and (11), the per-unit output impedances of all inverters operated in parallel should be the same in order to achieve accurate proportional power sharing for the conventional droop control scheme [7]. This is the basis for the virtual output impedance approach [13] to work properly. If this is not met, then the voltage set-points Ei are not the same and errors appear in the reactive power sharing. However, this is almost impossible in reality. It is difficult to maintain E1 = E2 or δ1 = δ2 because of the presence of numerical computational errors, disturbances and noises. It is also difficult to maintain γ1 = γ2 because of different feeder impedances, parameter drifts and component mismatches. The reality is that none of these conditions would be met although the reactive power sharing is accurate. A mechanism is needed to achieve an accurate proportional load sharing when such uncertain factors exist.

IV. VIRTUAL IMPEDANCE LOOP

Micro grids where the per unit impedances are not same, voltage source inverters which are droop controlled using P vs.*ω* approach may not behave properly as concluded previously. Therefore, the virtual impedance loop adds virtually impedance in series with the real line impedance as shown in fig.-3, for the purpose of same per unit output impedance.

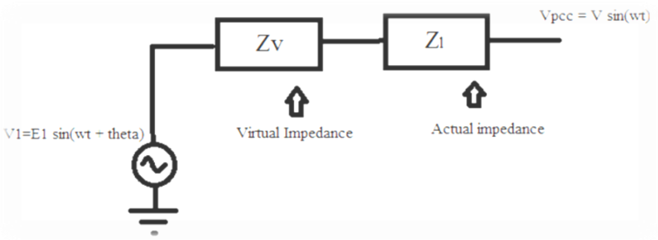

Figure-3 Adding virtual impedance in conventional system

The virtual impedance creates a "voltage drop" without generating real active and/or reactive power losses. According to [10] and [11], fig.-4 shows how the virtual impedance loop should be implemented in the case where local loads are directly connected to the Inverters. The virtual voltage drop is calculated using the inverters' output current. Hence, in this case, the virtual impedance is expected to be added between the inverter and the local load. This allows varying the inverter's output impedance virtually.

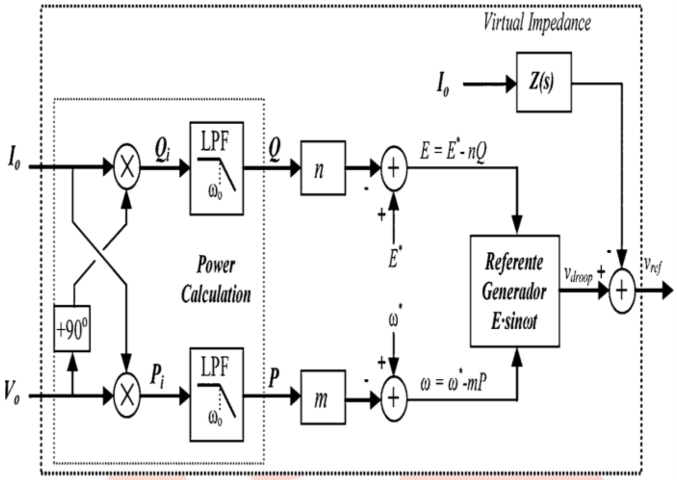

Figure-4 Implementation of virtual impedance loop

In order to increase the stability of the system, reduce the impact of circulating currents, and to share linear and nonlinear loads, some approaches introduce a virtual impedance into the system by an additional control loop [10], [11], [12], of the form

Vref = Vdroop − Zv(s)*Io…… (19)

Where V_{droop} is the voltage reference delivered by the droop method and Zv(s) is the virtual output impedance. The calculation and design of virtual impedances was presented by Guerrero *et al*. in 2005.

V. ARCTAN FUNCTION POWER-FREQUENCY DROOP CONTROL

It is possible to control the real power sharing by controlling the relative droop gradients and the power set point (Po) for each inverter. Equation (3) describes the relationship between calculated power and operating frequency.

$$\omega = \omega^* - m(P_{oi} - P_i)$$

Proper care should be taken that the frequency is operating within the limits. But it is often seen that any excursions in power may cause a rapid change in frequency which causes the DG unit to operate outside the allowed frequency margins. And according to [15], it is seen than higher the m or n gradient, faster is the response. So according to the above discussion it can be concluded that changing of gradient with the load is required to overcome both the operation.

In paper [6], arctan based algorithm is applied to remove the constant frequency droop slope. By implementing the arctan base function it is possible to operate the frequency always within pre-set bounds. In the literature [16] and [17], Dynamic droop adjustments are performed to gain better control whilst implementing frequency and voltage bounding. These systems basically limit the gradient near the frequency bounds whilst utilising a fixed gradient. In a power electronic dominated microgrid it is possible to implement the droop profile, where the control throughout the microgrid is homogeneous. The conventional power frequency droop profile is inherently limited to have a fixed concavity of zero. In arctan function base droop control it is try to allowing variance in both gradient and concavity of the power profile for achieve natural frequency bounding independently from the overall system controller as shown in fig.-5.

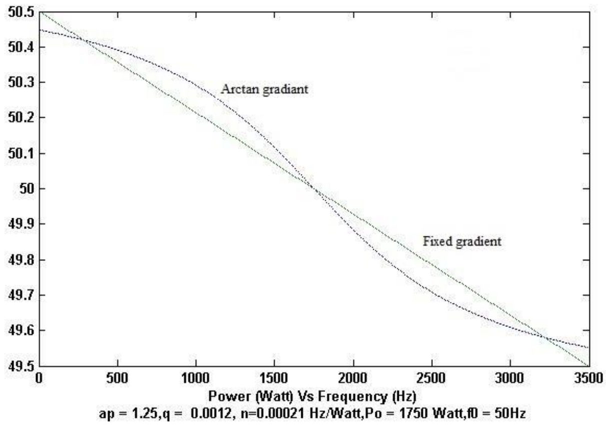

Figure-5 Effect of arctan function on fixed gradient droop

For modification of the power profile it requires a monotonically increasing function for the pre-set boundary. Due to the difficulty achieved in creating a horizontal asymptote, a cubic function is not implemented which complex and time is consuming.

All the limitations are eliminated by the arctan function because it has adequate control over the gradient of droop about the power set point, desirable horizontal asymptotes and existing function libraries in most coding languages. The new frequency droop equation is characterised as shown in (20).

$$f = f_0 - \frac{a_p}{\pi}(\arctan(\rho(P - P_0))) \dots \dots (20)$$

Or equivalently

$$\omega = \omega_0 - 2a_p(\arctan(\rho(P - P_0)))$$

Where f is the operating frequency of the inverter, fo is the frequency set point, ap is the arctan bounding multiplier, and ρ is the arctan droop coefficient. All other terms have been previously defined.

By characterising the function it is possible to bind it within the pre-set boundaries. Like if the ap = 1 the frequency is naturally bounded from (fo + 0.5) Hz to (fo - 0.5) Hz. By changing ρ the gradient or like concavity is controlled. It is worthy of note that under the application of the small angle criteria, the arctan algorithm reduces to the direct $\delta \propto P$ relationship as the general form of droop given in above equation. The implementation of the arctan function based droop control is shown in fig.-6.

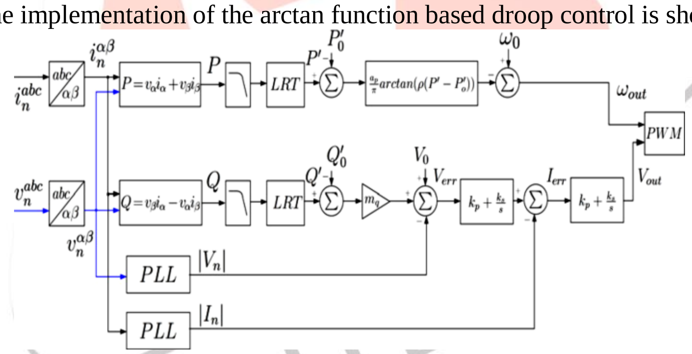

Figure-6 Implementation of arctan function based droop control

VI. Modelling & Simulation

To demonstrate the effectiveness of the proposed control strategy, the system of fig.-2 has been simulated in the MATLAB Simulink software environment. Both DG units are equipped with the proposed power management strategy. Moreover, the virtual inductive impedance loop is employed to improve the steady-state and transient response of the power sharing control unit. The loads are considered as a combination of constant impedance and a constant power load. Several load switching are carried out to verify the steady-state as well as dynamic performances of the proposed control strategy.

Moreover, the simulation case studies are performed for the conventional droop strategy to highlight the main advantages of the proposed method.

The inverters are connected to the ac bus via a circuit breaker CB and the load is assumed to be connected to the ac bus and microgrid work as islanded mode. The frequency of the system is 50 Hz. The rated voltage is 230 V RMS. Inverter 1 and 2 ratings are 4+j2 and 8+j4 KVA respectively. The droop coefficients are: n1 = 10 and n2 = 5 V/KVAR; m1 = 0.5 and m2 = 0.25 Hz/KW. Hence, it is expected that P2 = 2P1 and Q2 = 2Q1.In the case study, up to t=3 s, a RL load of (13.84+ j 9.23) Ω connected to the PCC. After t=3 s, additional (10+ j 10) Ω RL load is connect to the PCC.

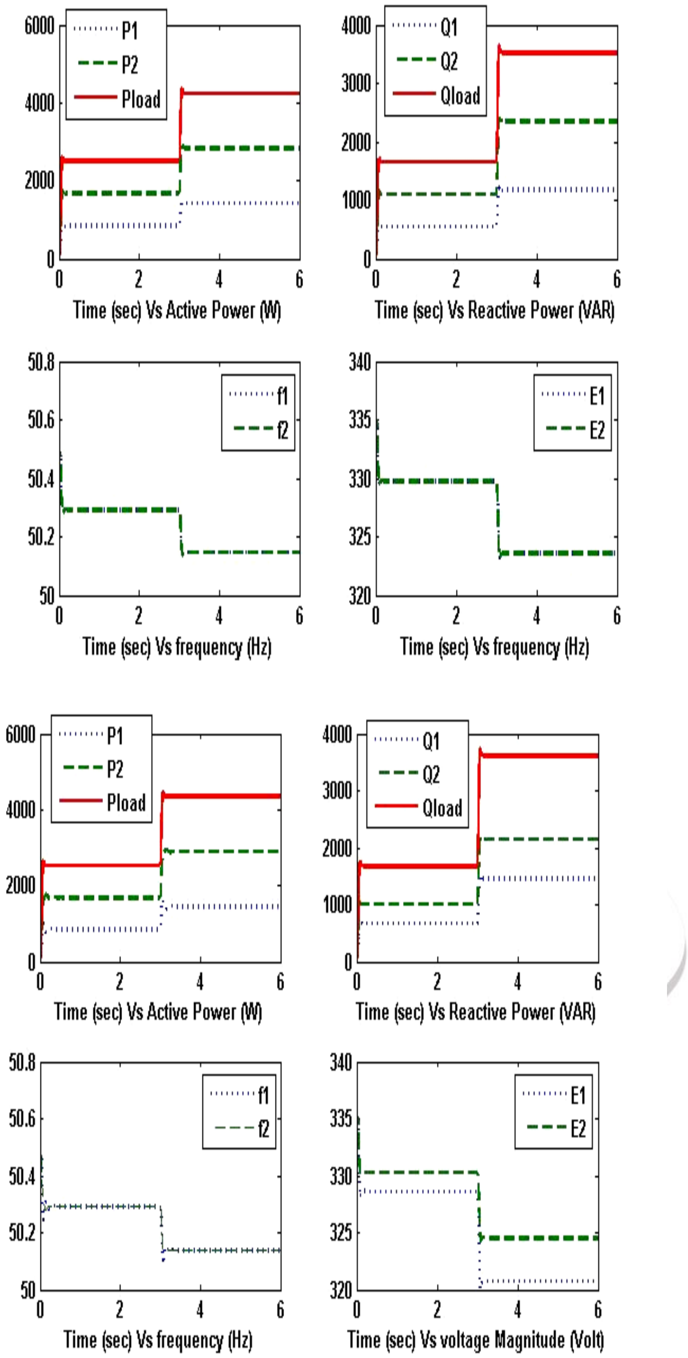

Figure-7 Simulation results for the Case: conventional droop control to achieve 2: 1 power sharing a) with intentionally same per unit impedance and b) without same per unit impedance.

The instantaneous real and reactive powers of the feeders during the load changes are measure and to verify the droop effects the voltage and frequency change also measure and shown for different case study.

Case-I conventional droop control load sharing with same per unit impedances

As the main contribution of the paper is to understand the concept of virtual impedance loop and arctan function controller and to analyse the error in power sharing, the attention is not paid to the design of the inner-loop controller. To understand the output impedance effect, the conventional droop control method is simulating with intentionally the same per unit impedance and the results shown in fig.-7(a). Here, the feeder impedances are Z01= j3.768Ω and Z02 =j1.884 Ω.

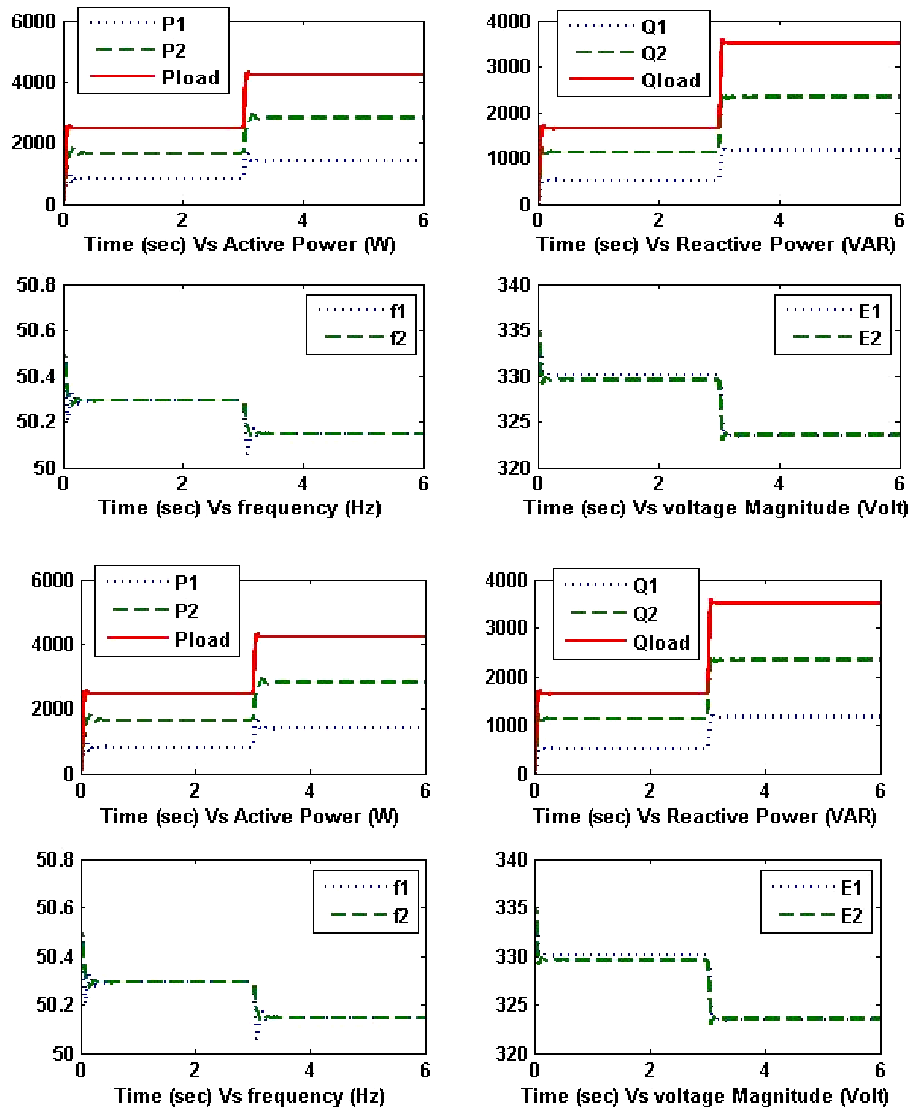

Figure-8 Simulation results for the Case: conventional droop control with to achieve 2: 1 power sharing a) with virtual impedance loop adding b) With Virtual impedance loop and arctan function implementing.

Case-II conventional droop control load sharing with mismatched per unit impedances

In this case study the per unit impedances mismatches and the feeder impedances are Z01= j2.512Ω and Z02 =j1.884 Ω.

The effects of mismatched per unit impedances are shown in fig.-7(b). From the two cases using the conventional droop controller, the trade-off between the sharing accuracy and the voltage drop can be clearly seen. The active power sharing is proportional but there are the errors in the reactive power sharing. The reactive power is not accurately shared in 1:2 ratios.

Case-III conventional droop control load sharing with Virtual impedance loop

In this case study, the inverters per unit impedances are mismatched and to minimize the mismatched effects the impedance is added virtually. So the feeder impedances are Z01= j2.512Ω and Z02 =j1.884 Ω and ZV=j1.2 Ω. Where ZV is the virtual impedance.

From the fig.-8(a) and 9(a) results it is shown that the effects of mismatched impedances are minimized but the response is oscillatory for starting or transient time, and the settling time is high.

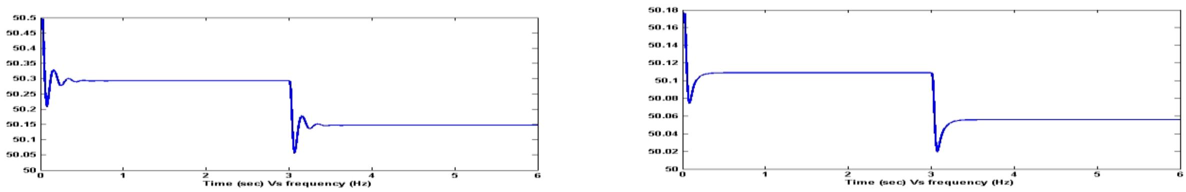

Figure-9 Frequency response of the (a)Virtual impedance loop implemented conentional droop control. (b)Arctan function implemented conventional droop control.

Case-IV conventional droop control load sharing with Arctan function implementation and Virtual loop adding

In this case the arctan function is implemented and the system is simulated for the same feeder impedances of case-III. From the fig.-8(b) and 9(b), it is shown that the sharing is accurate and the response time and settling time are improved.

VII. CONCLUSION

For the conventional droop control method, to ensure equal load sharing and to avoid circulating currents, voltage set points and the output impedances in per unit of all inverters in the microgrid must be same. To achieve a fast & better response, the droop for inverter values (i.e. frequency and voltages) should be higher for rated values and operating boundaries. And for stable operation the droop gradient near the boundaries was low. In other words, the droop gradient should change as changes happen in load frequency and voltage magnitude. This feature is not seen in conventional droop method. It also has several intrinsic problems related to its limited transient response. The limitation of the conventional droop method is overcome by the arctan function implementation and adding virtual impedance loop. The only limitation is droop ratio of all inverter should be same. $\frac{n_1}{m_1} = \frac{n_2}{m_2}$.

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