Dynamic Response of Distributed Generators in a Hybrid Microgrid

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***Abstract*— A microgrid may be supplied from inertial (rotating type) and non-inertial (converter-interfaced) distributed generators (DGs). However the dynamic response of these two types of DGs is different. Inertial DGs have a slower response due to their governor characteristics while non-inertial DGs have the ability to respond very quickly. The focus of this paper is to propose better controls to improve the dynamic interaction between different DG types in an autonomous microgrid. The transient behavior of DGs and microgrid is investigated during the DG synchronization and load changes. Power sharing strategies based on frequency and voltage droop are considered. Control strategies are proposed for DGs to improve the smooth synchronization and real power sharing minimizing transient oscillations in the microgrid. Simulation studies are carried out on PSCAD for validation.**

***Index Terms*— Microgrid, Distributed power generation, Droop control, Power sharing, Synchronization**

I. Introduction

A Microgrid can supply power to small/medium sized urban housing communities or to large rural areas. It can be an economical, environment friendly and reliable way to supply power at distribution levels. The sources in a microgrid can be mainly classified as dispatchable or nondispatchable in terms of power flow control [1, 2]. The output power of dispatchable sources such as microturbines, fuel cells and biodiesel generators can be controlled to maintain the desired system frequency and voltage in an isolated microgrid. However, nondispatchable sources such as wind and PV, in which the output power depends on the environmental conditions, are expected to be mainly controlled on the basis of maximum power point tracking.

Furthermore, the sources in a microgrid can also be classified as inertial and non-inertial depending on the way they are connected to the system. For example, a diesel generator and a hydro generator are inertial sources while the sources connected through converters such as PV, fuel cell and batteries are non-inertial. A microgrid can operate either in grid connected or islanded mode. The available power of all DG units should meet the total load demand for islanded operation; otherwise load shedding need to be implemented. The control of real and reactive power output of the sources is essential to maintain a stable operation in a microgrid, especially when it operates in the islanded mode. The frequency and voltage in an islanded microgrid should be maintained within defined standards. The frequency variations are very small in strong grids; however, large variations can occur in autonomous grids [3]. Thus power management strategies are vital for an autonomous microgrid in the presence of few small DG units, where no single dominant energy source is present to supply the energy requirement [4]. Also, fast and flexible power control strategies are necessary to damp out transient power oscillations in an autonomous microgrid where no infinite source available [5].

Many researchers have addressed the operational, control and protection issues in microgrids [2, 6-9]. The real and reactive power output of a generator can be independently controlled by changing the voltage angle (based on frequency) and the magnitude respectively [10, 11]. Therefore, frequency and voltage droop controls are the most common methods used to share the real and reactive load power in a microgrid. However, the reactive power sharing among the DGs will not be precise as expected from the droop due to microgrid cable impedances [12].

Different droop controls and converter control strategies have been proposed. The control strategies required for converter connected islanded microgird system is analyzed in [12]. A droop control based on the active and reactive current control is presented for parallel converters [10]. The control of parallel converters in a standalone ac power supply without the need of communication is presented in [13]. The response of microgrid in the presence of a diesel generator and a converter interfaced DG has been investigated in [14]. The system stability in the presence of high converter interfaced DG penetration levels has been investigated [15]. In [16], droop based on angle is proposed to share the real power in a converter connected microgrid.

The literature survey reveals that the most researchers have only considered the control of converter connected microgrids. Little attention has been given so far to the control and operational aspects of hybrid microgrids, which consist both inertial and non-inertial sources. The purpose of this paper is to analyze the interaction of different types of sources in an autonomous microgrid to propose better control strategies. Decentralized control of DGs, DG synchronization and load power sharing using frequency and voltage droop controllers are considered in this paper. It has been assumed that no explicit communication system is present. Investigations are performed to improve the plug and play approach for different

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types of microgrid sources to minimize any transient oscillation.

II. Real and Reactive Power Sharing in a Microgrid

Both inertial and non-inertial sources can be present in a hybrid microgrid. These different types of sources can connect or disconnect to the network at any time. However, the dynamic behavior of inertial and non-inertial sources is different. The DGs connected through converters can respond very quickly by changing its output parameters. On the other hand, the response of a synchronous machine DG will be slower compared to the DGs connected through converters. Therefore the investigation of transient behavior of these two different sources during generator synchronization and load changes will help to design and implement a stable operation in a microgrid.

In a conventional frequency droop control method, each DG in the system uses the frequency at its point of connection (PC) to inject the required amount of real power. Thus, the system frequency will act as the communication signal amongst the DGs to share the real power appropriately. The conventional frequency droop characteristic can be expressed as [10, 13, 17]

$$f^* = f_r + m \times (0.5P_r - P^*) \qquad (1)$$

where f^* is the instantaneous frequency setting for a generator considered, f_r is the rated frequency of the system, P_r is the rated real power output of the generator and P^* is the measured actual real power output of the DG. The droop coefficient is donated by m. The frequency droop characteristic given in (1) is shown in Fig. 1. In this figure, isochronous frequency range is denoted using the allowable minimum and maximum system frequency (i.e. f_{min} and f_{max} respectively). When a generator operates in frequency droop control mode, the system frequency can change between f_{min} and f_{max} depending on the value of real power output. A slower outer control loop can be used to shift the droop line vertically by changing the rated frequency to restore the steady state frequency to a standard value (i.e., load frequency control).

The droop coefficient m can be calculated using defined values of minimum and maximum frequency and the rated real power output of the generator. When few generators with different capacities are operating in frequency droop control, each generator may have a unique value for the droop coefficient, m. The different droop coefficients allow sharing the total load power requirement among the generators according to a predefined ratio. For example, the total load power requirement of a microgrid can be shared proportionally to rated real power output of each generator.

The output voltage magnitude of a generator can be controlled to change the reactive power supplied to the system. However in the presence of few generators, maintaining a voltage to a pre-defined value can cause the reactive power circulation amongst the sources. This aspect is crucial especially when a microgrid contains short line segments. The best solution to this problem is to implement voltage droop control in generators. Also the voltage droop control results in reactive load power sharing in the microgrid. The conventional voltage droop control characteristic can be given by [10, 13]

$$V^* = V_r + n \times (0.5Q_r - Q^*) \qquad (2)$$

where V^* is the instantaneous voltage magnitude setting, V_r is the rated voltage of the microgrid system, Q_r is the rated reactive power output of the generator and Q^* is the measured actual reactive power output. The voltage droop coefficient is denoted by n. The voltage droop characteristic given in (2) is shown in Fig. 2. In this figure, the minimum and maximum allowable voltages in the system are represented by V_{min} and V_{max} respectively. The voltage droop coefficient can be calculated using the generator rated reactive power output and minimum and maximum voltage levels.

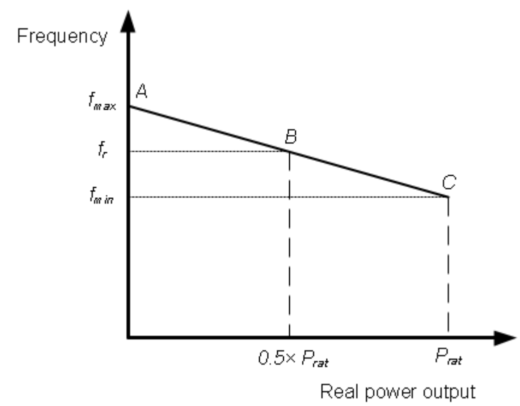

Fig. 1. Frequency droop characteristic of a generator.

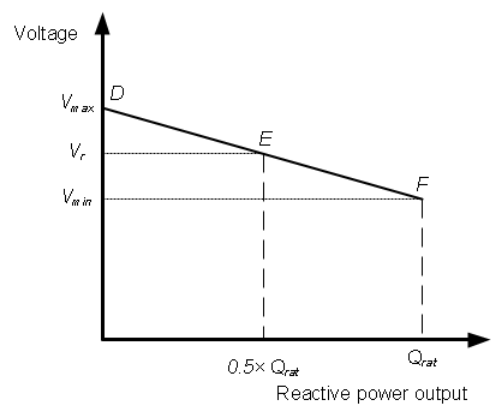

Fig. 2. Voltage droop characteristic of a generator.

The frequency and voltage droop controls in (1) and (2) can be employed in each dispatchable generator to maintain the microgrid frequency and voltage within the specified standards. However, the nondispatchable generators in the microgrid are operated in maximum power tracking mode to enhance the benefits of renewable energy sources.

In this paper, the interaction between different types of DGs in an autonomous microgrid is investigated considering transient response and power sharing ability. It is assumed that a microgrid can consist of only inertial sources or only non-inertial sources or both. The synchronization of DGs into the microgrid is also considered in the analysis.

III. Microgrid Operation Studies

Consider the microgrid system shown in Fig. 3. Two DGs, DG1 and DG2 are connected at BUS-1 and BUS-3 respectively. The real and reactive power output of DG1 and DG2 are denoted by P_1, Q_1 and P_2, Q_2 respectively. The DG circuit breakers are used for synchronization and isolation purposes. Two loads, *load1* and *load2* are connected at BUS-2 and BUS-4. The system parameters are given in Table 1. It is to be noted that each DG and load in the microgrid are connected through a short line segment. The microgrid is modeled in PSCAD for simulation.

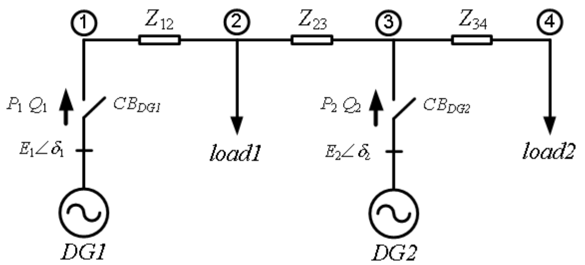

Fig. 3. Schematic diagram of two DGs sharing loads.

TABLE 1 System Parameters

System data	Value
System frequency	50 Hz
System voltage	0.415 kV rms (L-L)
DG1 power rating	(12 + j 8) kVA
DG2 power rating	(15 + j 10) kVA
Feeder impedance (Z12=Z23)	(0.025+ j 1.2566) Ω
load1 impedance	(15+ j 11.781) Ω
load2 impedance	(20+ j 15.708) Ω
Frequency droop coefficient (Hz/kW)	m1=33.33, m2= 41.67
Voltage droop coefficient (V/kVAR)	n1=1.2, n2=1.5

Two types of DGs: inertial and non-inertial are considered in the microgrid simulation. The frequency and voltage droops are employed to control and share the real and reactive power output of each DG in the microgrid. Depending on the loading condition, the droop controller will calculate the operating frequency for each DG. The droop coefficients for each DG are selected to control the frequency within isochronous frequency range (here it is selected as ± 0.25 Hz) and voltage within the ± 6% of nominal value while sharing the real and reactive power amongst loads proportional to the DG capacity. It is to be noted that the primary aim is to study the transient behavior of sources in a microgrid. Therefore no attempt has been made to restore the frequency to the nominal value by shifting droop line vertically using a slower control loop.

Three different cases are considered to analyze the interaction between abovementioned two types of DGs. A diesel generator is selected to represent the inertial DG while a three phase converter supplied by ideal DC voltage source is selected to represent the non-inertial source. In the first case, the behavior of microgrid is analyzed under inertial DGs. The response of microgrid with non-inertial DGs is presented next. Finally, both inertial and non-inertial DGs are considered to analyze the microgrid dynamics. The interaction between DGs during synchronization and load changes is shown. The simulation results for the three cases mentioned above are presented below.

A. Microgrid Response with Inertial DGs

In this study, it is assumed that DG1 and DG2 are inertial sources based on diesel generators. Each generator consists of an internal combustion (IC) engine coupled to a synchronous generator. The IC engine is integrated with a governor for controlling the output speed of the engine shaft by adjusting the amount of fuel supplied to the engine. Once the frequency droop of the diesel generator is activated, the IC engine maintains the required output shaft speed to a value requested by the droop. Also the diesel generator is incorporated with an exciter and a voltage regulator to control the output terminal voltage. The required value for the regulated voltage can be set based on the voltage droop. The parameters of the first diesel generator (i.e. DG1) is given in Appendix-A.

Real and reactive load power sharing amongst diesel generators and synchronization of generators are investigated. To analyze the generator synchronization, it is assumed that DG1 is connected to the system supplying both *load1* and *load2*, while the microgrid is operating in autonomous mode. DG2 is then synchronized to the microgrid using the circuit breaker CB_{DG2}. During the synchronization, the voltage magnitude of incoming generator (i.e. DG2) is adjusted to the value equal to the PC. Then the phase angle of DG2 and the frequency are adjusted to match the values at PC. Next, CB_{DG2} is closed at the point of voltage zero crossing. In the simulation, DG2 is connected to the microgrid at 26.593s once the synchronization conditions are satisfied. After the DG2 connection, both DGs operate in frequency and voltage droop sharing the load power in the microgrid.

The real and reactive power sharing before and after the connection of DG2 is shown in Fig. 4. It can be seen that DG2 starts supplying the real and reactive power after the connection. The variation of DG frequency setting based on droop (i.e. the frequency calculated from the droop equation) is shown in Fig. 5. Just before the synchronization, DG1 maintains the microgrid frequency in droop control and the frequency of DG2 is adjusted to the PC frequency (i.e. equal to DG1 droop frequency) for synchronization purpose. However, once the DG2 is connected, its frequency changes to no load frequency since real power output is zero at the moment of connection. DG2 then starts to inject real power causing droop frequency to decrease gradually. On the other hand, real power output of DG1 gradually decreases as DG2 is injecting power to the microgrid. Finally the system comes to the steady state after about 12 seconds. The droop coefficients, given in Table 1, are selected to supply the load power proportional to the DG capacity. In the steady state, the ratio of real power output between two DGs is 1.25. This is in accordance with the ratio of real power ratings of these two DGs given in Table 1. The output currents of DG1 and DG2 during and after the synchronization are shown in Fig. 6.

From Figs. 4 and 5, transient oscillations can be seen in frequency and real power waveforms after DG2 is connected to the microgrid. The system oscillations are further demonstrated by the DG output currents shown in Fig. 6. These DGs inject currents at slightly different frequencies until the steady

state droop point is achieved. The main reason for these oscillations is the slower governor response of these inertial generators. The output speed/frequency of each generator cannot be changed instantly according to the value requested from the frequency droop.

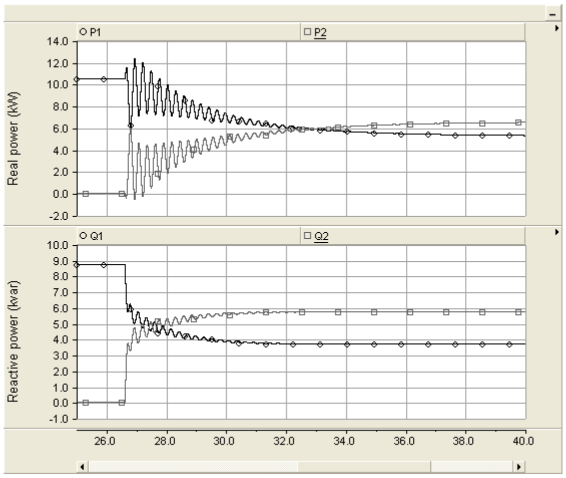

Fig. 4. Real and reactive power sharing amongst inertial DGs.

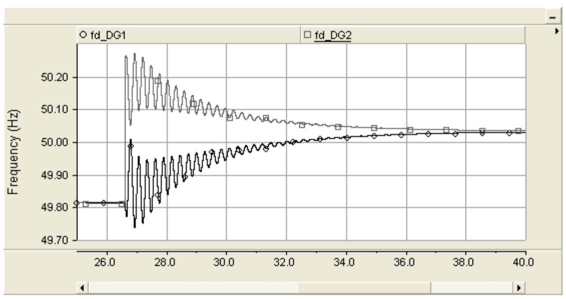

Fig. 5. The variation of DG droop frequencies of inertial DGs.

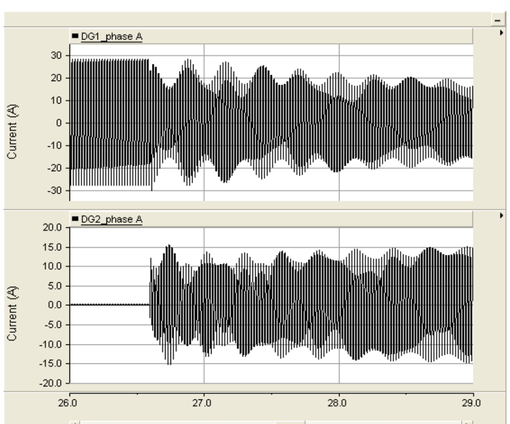

Fig. 6. The variation of DG output currents in phase A.

Also, the absence of a single strong source (such as utility grid) in an islanded microgrid, these frequency oscillations manifest more vigorously. In this microgrid configuration, the two diesel generators are separated by a small line segment, which further limits the damping oscillations. However, it is worthwhile to damp out these transient oscillations as quickly as possible from the view point of stability and power quality issues. Therefore, a method is proposed to achieve a smooth droop transfer characteristic for the incoming diesel generator (i.e. for DG2). This is obtained by slowly changing the frequency setting of incoming generator from the PC frequency to the droop frequency. The characteristic for smooth droop transfer can be implemented by modifying (1) as

$$f_d = f^* + (f^* - f_{pc}) \times \sqrt{\left(1 - \frac{t^2}{T_p^2}\right)} \times \left[u_s(t) - u_s(t - T_p)\right] \quad (3)$$

where f_d is the droop frequency of the incoming DG, f_{pc} is the measured frequency at PC and T_p is the time constant chosen to reach the droop frequency from the PC frequency. The time t is measured after the DG circuit breaker is closed. $u_s(t)$ is the unit time step function. The term inside the square brackets will be zero after the time T_p elapses, forcing the last term of (3) to be zero. Therefore the frequency of the incoming DG will be equal to droop frequency calculated from (1). The value of T_p can be selected according to the diesel generator dynamics. According to (3), an ellipsoidal shape is selected to reach the droop frequency from the PC frequency. This shape is selected because the rate of frequency increase towards droop becomes higher with the elapsed time. However, this will only be active for a defined time period (T_p) after the DG connection.

The simulation study performed before is repeated while applying the modification in the droop control given in (3) to the incoming DG2. Fig. 7 shows the response of real and reactive power output of DG1 and DG2. It can be seen that DG2 increases its output power gradually minimizing the power fluctuations. The variation of DG frequency during and after the synchronization is shown in Fig. 8. It shows the DG2 frequency increases gradually until it reaches the droop frequency. This results in smooth connection of incoming diesel generator minimizing frequency and power fluctuations in the autonomous microgrid.

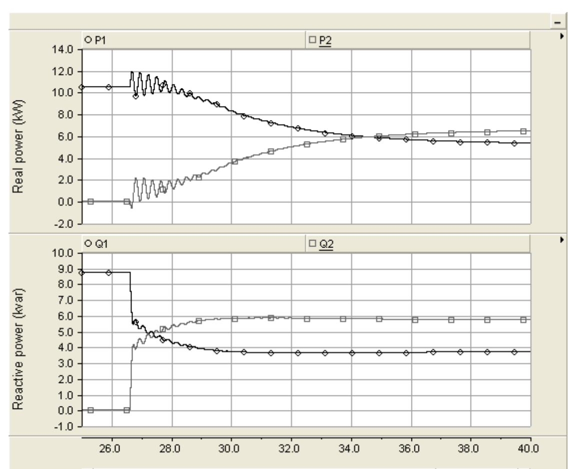

Fig. 7. Real and reactive power sharing amongst inertial DGs.

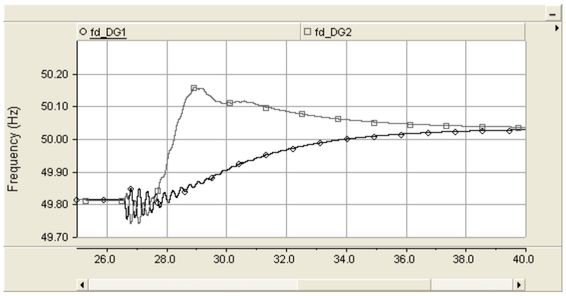

Fig. 8. The variation of DG droop frequency of inertial DGs.

B. Microgrid Response with Non-Inertial DGs

The same microgrid structure shown in Fig. 3 is also considered in this case, except that both DG1 and DG2 are now non-inertial sources connected through converters. Furthermore, the DG capacities and feeder impedances also remain the same. Initially, DG1 supplies *load1* operating in frequency and voltage droop according to (1) and (2) respectively. DG2 is connected at 5.262 s once synchronizing conditions are satisfied. Subsequently, *load2* is connected to the microgrid at 7.0 s.

The real and reactive load power sharing of DGs are shown in Fig. 9. DG2 starts to inject real power soon after the connection to the microgrid. DG2 further increases the output power once *load2* is connected. However, it can be seen that the system attains steady state within 0.2 s after either DG2 synchronization or the load change. Also, the DGs share the real power more precisely according to the generator ratings (i.e. 1.25).

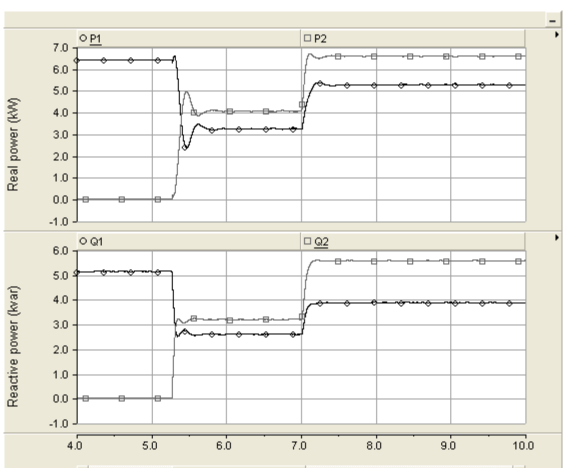

Fig. 9. The real and reactive power sharing with non-inertial DGs.

The variation of DG frequencies is shown in Fig. 10. After DG2 synchronization, DG2 frequency changes to no load frequency as calculated by the droop and then it reaches to steady state system frequency within one second. However, no frequency and real power fluctuations can be observed unlike the case of two diesel generators. The interaction between these two non-inertial DGs during synchronization and load change is smooth. Since converters can respond quickly, they have the ability to reach the steady state rapidly.

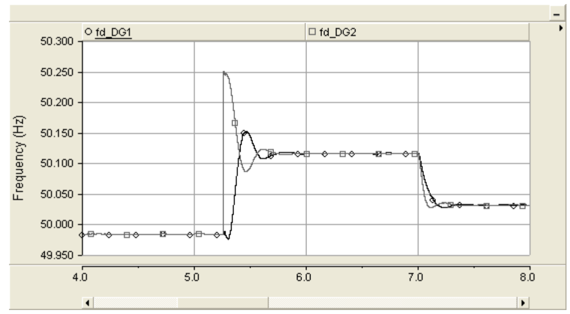

Fig. 10. The variation of droop frequency of non-inertial DGs.

It can thus be concluded that if the microgrid only contains converter connected DGs, conventional frequency and voltage droop given in (1) and (2) can be used to share the real and reactive power without any appreciable transient oscillations.

C. Microgrid Response with Inertial and Non-Inertial DGs

In this case, the interaction amongst inertial and non-inertial DGs in the microgrid is investigated. The same microgrid structure, as shown in Fig. 3, is considered. It is assumed that DG1 is an inertial DG, while DG2 is non-inertial. In the simulation, *load2* is assumed to be equal to *load1*. Furthermore, it is assumed that DG1 is connected to the microgrid supplying *load1* operating in frequency and voltage droops. DG2 is synchronized to the microgrid at 3.5 s. Subsequently, *load2* is connected to the microgrid at 6 s.

The real and reactive load power sharing amongst DG1 and DG2 is shown in Fig. 11. DG2 starts to inject real power after its connection. However, it cannot increase the real power output quickly since DG1 responds slowly. Thus, the system takes 2-3 seconds to come to the steady state. The variation of DG frequencies is shown in Fig. 12.

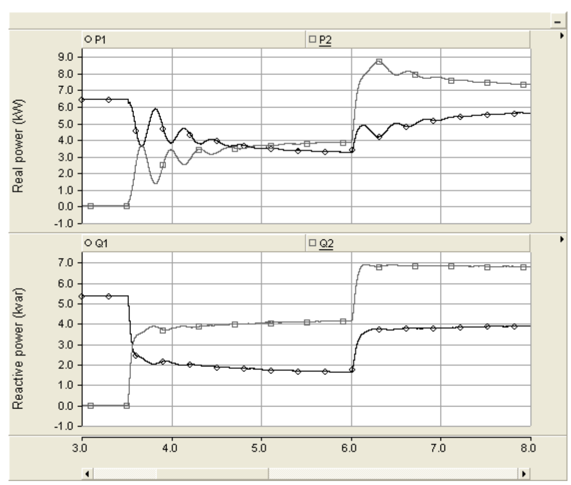

Fig. 11. Real and reactive power sharing with inertial and non-inertial DGs.

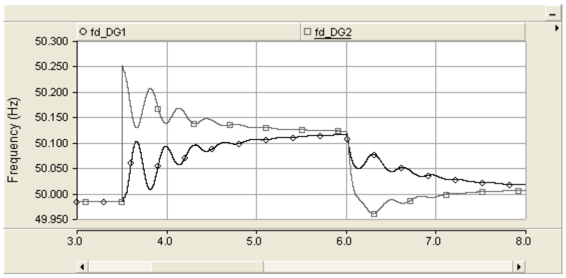

Fig. 12. The variation of DG droop frequency settings

These results show that there are frequency and real power fluctuations when either DG2 or *load2* is connected. However, the magnitude of these fluctuations is low compared to the case where both inertial DGs are present. In this case of mixed generation sources, the inertial generator cannot change its output frequency/power instantly unlike the converter interfaced DGs. Therefore, the slower response of diesel generator can initiate frequency and real power fluctuations in the autonomous microgrid.

To minimize the transient oscillations in the presence of both inertial and non-inertial sources, a method is proposed, which takes into cognizance that a converter can change its output voltage angle instantaneously. Therefore, instead of droop frequency, a corresponding angle is set for the converter output voltage. This angle calculation corresponding to the droop frequency is explained in Appendix-B. As explained in this appendix, the angle for the converter output voltage can be calculated using

$$\phi = 2\pi\left[\frac{f^* - f_r}{f^*}\right] \tag{4}$$

where f_r is the rated frequency and f^* is the droop frequency.

A phase lock loop (PLL) is used at PC to set the frequency for each DG converter voltage. The voltage reference for the converter is selected based on the PC frequency and calculated angle from (4). For example, the reference voltage setting for phase A can be given as

$$V_a = V_m Sin(2\pi f_{pc} t + \phi) \tag{5}$$

where V_m is the voltage magnitude calculated from the voltage droop in (2), f_{pc} is the measured frequency at PC using the PLL and ϕ is the angle calculated from (4). It is to be noted that the proposed method is only applicable if there is at least one inertial DG already connected to the microgrid. Since the microgrid frequency is mainly controlled by the inertial sources, the reference frequency of the non-inertial DG is basically controlled by them. Therefore, to avoid any transient oscillation, the PC frequency is used for reference voltage calculations.

The real and reactive power sharing amongst DG1 and DG2 is shown Fig. 13 after setting the DG2 angle according to (5). It is evident that there are no frequency and power oscillations during the synchronization and load change. However, it can be noticed that the accuracy of power sharing between the inertial DG and non-inertial DG is not as precise as that obtained from the conventional frequency droop.

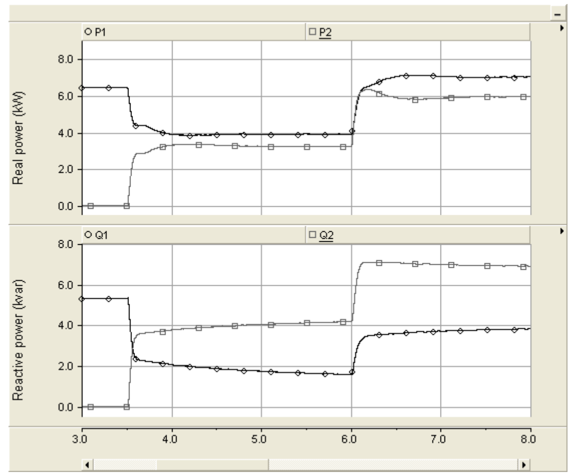

Fig. 13. Power sharing with modified droop based on angle.

To improve the real power sharing amongst these DGs, the frequency droop controller is further improved by introducing an integration process to reach the steady state droop point in the system. In the proposed modification, the error between calculated droop frequency in (1) and measured frequency at PC is passed through the integrator to force the frequency to reach the steady state droop point. This is given by

$$f_d = f^* + \int (f^* - f_{pc})\, dt \tag{6}$$

where f_d is the modified droop frequency setting for the DG, f^* is droop given in (1) and f_{pc} is the measured frequency at PC. The angle (ϕ) corresponding to modified droop frequency f_d in (6) is calculated using (4). The time constant of the integrator is selected according to the inertial DG dynamics. The power sharing of DGs after deploying the proposed frequency droop in (6) and angle setting in (5) is shown in Fig. 14. According to this, the accuracy of power sharing has improved and the transient oscillations are avoided.

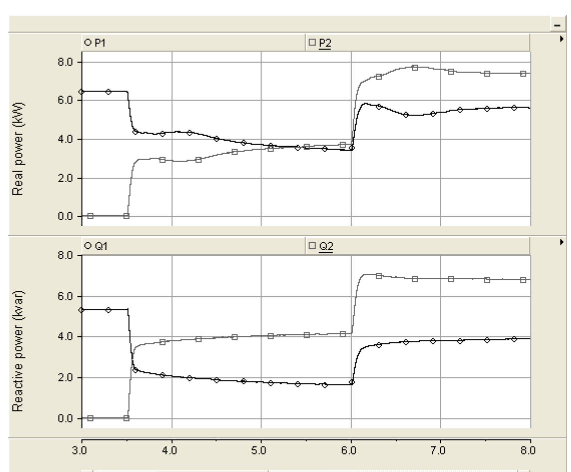

Fig. 14. Real and reactive power sharing with integral droop.

It can therefore be concluded that in the presence of both inertial and non-inertial sources in a microgrid, conventional frequency droop can initiate frequency and real power oscillations during the synchronization and load changes. However these oscillations can be avoided if angle corresponding to the droop frequency is set in the converter voltage reference generation. It is shown that an integration process is required to improve the real power sharing amongst these inertial and non-inertial sources.

IV. Conclusions

In this paper, the dynamic interaction amongst different types of DGs is analyzed in an autonomous microgrid during DG synchronization and load changes. The study is carried out to propose better controls to improve the dynamic response of the microgrid. The microgrid has been assumed to contain both inertial and non-inertial sources. In the case of inertial sources, a method has been proposed for incoming generator to smoothly reach the droop frequency after synchronization, thereby damping out the frequency and real power oscillations.

In the presence of both inertial and non-inertial sources, it is proposed to set the angle based on the frequency obtained from droop for non-inertial source to minimize the transient oscillations during synchronization and load changes. However to implement this method there should be at least one inertial source already connected to the microgrid. Moreover, an integral process towards system steady state frequency droop line is introduced for non-inertial DG to improve the real power sharing accuracy in a mixed DG microgrid.

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VI. Appendix-A: Diesel generator parameters

Rated voltage	415V
Rated power	12kW, 14.4kVA
Rated frequency	50Hz
Rated speed	1500rpm
Reactance	**Value (per unit)**
X_d	2.26
X'_d	0.15
X''_d	0.060
X_q	0.13
X''_q	0.107
X_2	0.91
X_0	0.005
Time constants	**Value (ms)**
t'_d	25
t''	25
t'_{d0}	368
t_a	4

VII. Appendix-B: DG Voltage Angle Calculation

Let the rated frequency of the system be denoted by f_r while the calculated droop frequency for a DG using frequency droop be denoted by f^*. The droop frequency, f^* represents the amount of frequency deviation from its rated value. The variation of angular frequency vectors related to f_r and f^* is shown in Fig. B.1. It can be seen that angular vector corresponding to f_r reaches 2π at time t_1 while angular vector related to f^* reaches 2π at time t_2. In this figure, it is assumed that $f_r > f^*$.

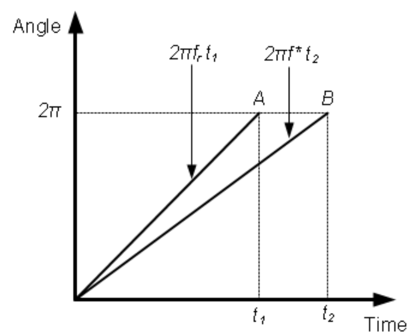

Fig. B.1 The variation of angular vectors

From Fig. B.1 we can write

$$2\pi = 2\pi f_r t_1 = 2\pi f^* t_2 \quad \text{(B.1)}$$

The angular vector related to the droop frequency can be expressed in terms of rated frequency and an angle difference ϕ such that the condition in (B.1) is satisfied. Then it can be written as

$$2\pi f^* t_2 = 2\pi f_r t_2 + \phi \quad \text{(B.2)}$$

Using (B.1) and (B.2), the angle difference can be calculated as

$$\phi = 2\pi\left(\frac{f^* - f_r}{f^*}\right) \quad \text{(B.3)}$$

Therefore the required angle corresponding to the droop frequency can be found using the rated frequency and calculated droop frequency. The reference voltage generation of each phase of the converter is then performed with the aid of angle in (B.3).

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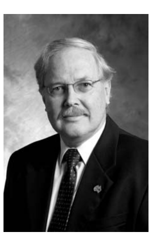

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