



A Control Method for Autonomous Microgrid in High Droop Gains

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Abstract

This paper investigates the effect of boosting droop gain on stability of an autonomous microgrid. Boosting droop gain improves power sharing accuracy while decreasing overall system stability. Therefore, to use a high droop gain, a new controller parallel to conventional one is proposed. Applying this controller, oscillatory response of distributed generation (DG) output power is damped. This control loop includes three gains and three lead-lag compensators. Coordinated design of supplementary control loops for each DG is carried out in MATLAB by using Cuckoo Optimization Algorithm and the microgrid is simulated in PSCAD software. Results show that the proposed strategy maintains system stability even with high droop gains.

Keywords: *Autonomous Microgrid, Droop Gain, Power Control, Load Sharing.*

1. Introduction

Interconnection of loads and small size generation forms a new type of distribution system, the microgrid. The microgrid (MG) concept assumes a cluster of loads and micro-sources operating as a single controllable system that provides both power and heat to its local area [1]. In an autonomous operational, the key control issues include: voltage and frequency control, real/reactive power control, and the load-sharing control [2–5]. Most of the generation units are connected to the MG through voltage source inverters (VSIs) that are controlled by the droop controller. The VSIs should be controlled so as to guarantee equitable active and reactive power sharing between the DGs; conceptually this is called load sharing. Load sharing without communication between converters is a desirable option which could be complex and it could cover a large area. A common approach to that goal is using frequency and voltage droop characteristic to make the parallel converters to locally inject proper active and reactive power to the grid. Active and reactive power sharing could be achieved by using two independent parameters, i.e. voltage and frequency [6–9]. The most important advantage of using the droop control is to maintain system stability while multiple DG units are operating in the system. For example, in a case of two DGs in the microgrid, if the droop controller isn't used, each DG will inject proper reactive power by considering its voltage while it might be difference between their voltage regulation point which will lead to a master DG that injects reactive power and a slave DG absorbing reactive power. Therefore, droop control is used to overcome this problem [10]. In the autonomous operation of the microgrid, there is a voltage difference between DG output voltage and the microgrid voltage which results in reactive power flow between them. This voltage difference is across the reactance between the inverter unit and point of common coupling (PCC point). Therefore, DG output power will exceed its nominal power leading to significant error in load sharing. This error depends on internal connections impedance and droop gain. The effect of load sharing

on system stability is investigated in [11] and [12]. Moreover, effect of droop gain and lines equivalent impedance on the microgrid small signal stability is investigated in [13] and [14]. In [15-20], the dynamic performance and load sharing are considered and the controller is described in detail. In this paper, to improve load sharing and stability enhancement, a high droop gain controller is proposed. This approach uses variation in each DG power steady state point and creates a control loop to droop the control loop. Simulation studies are carried out to evaluate the performance of the proposed strategy in maintaining the stability of the microgrid.

2. Droop control loops

The droop control method which mimics the behavior of a synchronous generator in traditional power system is adopted, which does not need the use of critical communications [21, 22]. Fig.1 shows power flow between a DG and the microgrid. The more active and reactive power the DG injects to the grid, the more magnitude and phase of the voltage will decrease. In conventional droop control, this droop is calculated by using the following equations that relate active power to frequency and reactive power to voltage [23-25].

$$\omega = \omega^* - m \times P \quad (1)$$

$$V = V^* - n \times Q \quad (2)$$

Where P and Q are DG output active and reactive power, respectively. Also, ω^* , V^* indicate the output voltage angular frequency and amplitude at no load, respectively (see Fig. 2). Finally m and n are droop gains of active and reactive power loops. The advantage of this droop mechanism is that no communication infrastructure is required, therefore, only local measurements for the microgrid control in a decentralized structure, and plug-and play operation are used. It must be noted that in the grid-connected mode, all DGs would incorporate in P, Q control while voltage and frequency are imposed by the upstream network. In the island mode, however; at least one DG with V, f control should exist in the microgrid. For droop mechanism, the following equitable load sharing strategy for the DG is proposed in [26] and [27]:

$$m_1 \times P_{1rated} = m_2 \times P_{2rated} = cte \quad (3)$$

$$n_1 \times Q_{1rated} = n_2 \times Q_{2rated} = cte \quad (4)$$

In other words, the higher is the capacity of the DG, the higher is its share in supplying the loads. It has been discussed in [28] that such a load sharing strategy is not justified economically. As it can be seen in [26], dominant eigen values in the island mode are strongly dependent on the droop coefficients and higher droops might lead to the microgrid instability. However, higher droops improve the equitable load sharing between DGS. Instantaneous active and reactive power flows from DG to microgrid could be expressed by the following equations:

$$p = \frac{V \times V_t \sin(\phi)}{x_f} \quad (5)$$

$$q = \frac{V^2 - V \times V_t \cos(\phi)}{x_f} \quad (6)$$

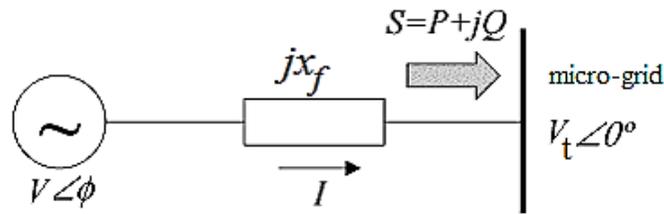


Figure 1: Microgrid-DG connection

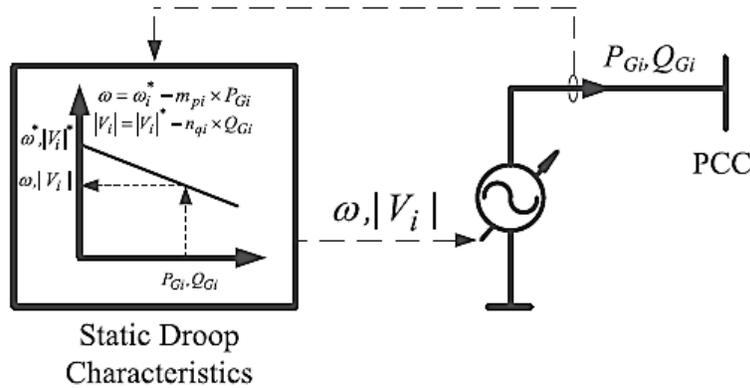


Figure 2: Static droop characteristics

These instantaneous powers pass from the low-pass filters to obtain average powers. It is clear that a DG would not affect the voltage of a strong grid (V_t). Hence, active and reactive power can be controlled by controlling ϕ and V , respectively

3. Power sharing

DGs in an autonomous microgrid should appropriately share the power to avoid circulating current or any damage to the devices. As a result, proper load sharing among the DGs is necessary [29]. Assuming a lossless system, the amount of power that generated by DG.1 (Fig. 3) could be obtained:

$$P_1 = \frac{\lambda_2 + \lambda_{L2} + m_2}{\lambda_2 + \lambda_{L2} + m_2 + \lambda_1 + \lambda_{L1} + m_1} P_L \tag{7}$$

Similarly, the power of DG.2 can be calculated as follows:

$$P_2 = \frac{\lambda_1 + \lambda_{L1} + m_1}{\lambda_2 + \lambda_{L2} + m_2 + \lambda_1 + \lambda_{L1} + m_1} P_L \tag{8}$$

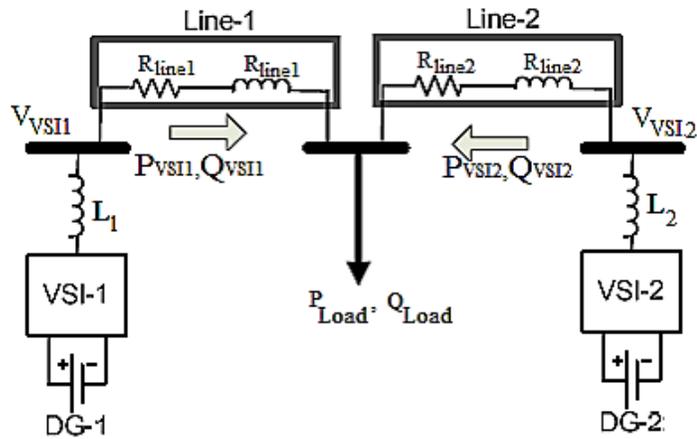


Figure 3: Power sharing with angle droop

where $\lambda_1 = \frac{\omega L_1}{V_t V_1}$, $\lambda_{L1} = \frac{\omega L_{Line1}}{V_t V_1}$, $\lambda_{L2} = \frac{\omega L_{Line2}}{V_t V_2}$ and $\lambda_2 = \frac{\omega L_2}{V_t V_2}$ and λ_2 are negligible in comparison with m_1 and m_2 , in a case of a medium voltage system ex 11KV. Also, microgrid lines are considered mainly resistive with small inductance. Therefore, $m_1 \gg \lambda_1 \gg \lambda_{L1}$ and $m_2 \gg \lambda_2 \gg \lambda_{L2}$. Hence, output power ratio of two DGs is simplifies as:

$$\frac{P_1}{P_2} = \frac{\lambda_2 + \lambda_{L2} + m_2}{\lambda_1 + \lambda_{L1} + m_1} \approx \frac{m_2}{m_1} = \frac{P_{1rated}}{P_{2rated}} \quad (9)$$

In a real system with multiple DGs and loads in different places, line impedance affects the load sharing; however, usually lines inductance is not high. Moreover, high droops have superior effect leading to desirable load sharing with a small deviation.

4. Modeling of microgrid

Equivalent single phase circuit of converter is shown in Fig. 4. In this figure, R_T models switching loss and L_T represents the transformer leakage inductance. C_f represents the filter capacitive section connected to output terminal to bypass switching harmonics and L_f represents DG output filter. By defining state space model of each converter in d-q rotating frame, each converter can be modeled as follows:

$$x_i = [i_{1d} \quad i_{1q} \quad i_{2d} \quad i_{2q} \quad v_{cfd} \quad v_{cfq}] \quad (10)$$

Converter output voltage is equal with filter voltage. As mentioned in section 2, using a low-pass filter, the average active/ reactive power can be obtained from the instantaneous values as follows:

$$P = \frac{\omega_c}{S + \omega_c} p = \frac{\omega_c}{S + \omega_c} (v_{cfd} i_{2d} + v_{cfq} i_{2q}) \quad (11)$$

$$Q = \frac{\omega_c}{S + \omega_c} q = \frac{\omega_c}{S + \omega_c} (v_{cfd} i_{2q} - v_{cfq} i_{2d}) \quad (12)$$

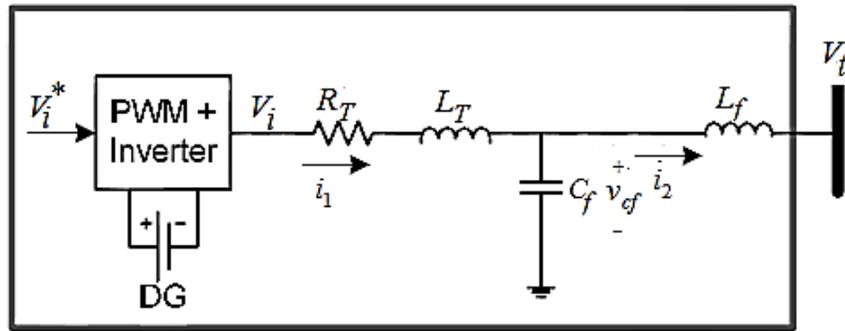


Figure 4: Equivalent circuit of VSC

where ω_c represents cut-off frequency of the capacitive filter. Combining (11), (12) and (10), state space model of converter with droop controller can be represented by the following equations:

$$x_{conv} = [P \quad Q \quad i_{1d} \quad i_{1q} \quad i_{2d} \quad i_{2q} \quad v_{cfd} \quad v_{cfq}] \tag{13}$$

$$\Delta x_{CONV}^o = A \Delta x_{CONV} + B \Delta V_{idq} \tag{14}$$

5. Proposed droop controller

High droop gains negatively affect the system stability. Therefore, a complementary droop control loop is proposed to guarantee desirable stability margin even in a case of high droop gains. The reactive power generated by each DG is used as an input parameter to improve the power sharing as is shown Fig. 5. The proposed controller uses each DG active or reactive power variation near steady state point to make the system stable. Proposed control loop contains a high-pass filter with time constant of 0.05s to damp the oscillatory nature of each DG output reactive power and a lead-lag controller parallel to main the droop controller loop. To ensure system stability, the proposed controller parameters are designed to force the unstable poles to move to stable area.

These parameters can be obtained by solving an optimization problem with stability constraints. Three lead-lag terms with 0.01 and 20 low and high margins are applied to ensure the stability of poles and fast

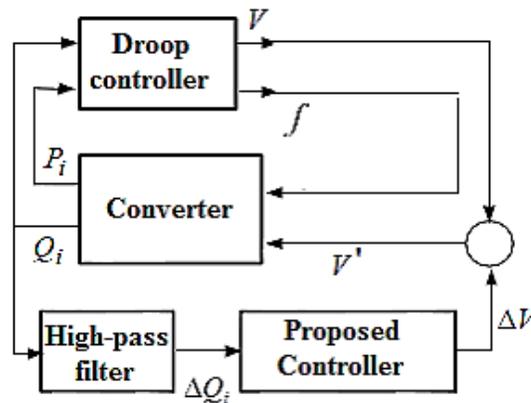


Figure 5: Proposed droop controller configuration using reactive power variation

response of controllers. System stability is the main objective. Therefore, by obtaining transfer function of each converter and analyzing its poles the stability of system can be analyzed. Each converter has 7 parameters to be optimized. Using the proposed control loop and obtaining its parameters via the above mentioned procedure, stability of the system will be guaranteed. By obtaining system state space equations and related transfer function considering ΔQ_i as output, overall system transfer function will be obtained without considering G feedback control. Considering feedback transfer function as:

$$H(s) = \frac{k_i \times (1 + sT1) \times (1 + sT3) \times (1 + sT5)}{(1 + sT2) \times (1 + sT4) \times (1 + sT6)} \quad (15)$$

Overall system transfer function considering feedback path will be as:

$$T = \frac{G}{1 + GH} \quad (16)$$

Having determined the poles which are, in fact, the roots of the system characteristic equation, the stability of system would be analyzed. The best stability condition will exist when all the poles are in the left side of the plane far from $j\omega$ axis. Coordinated design of proposed control loops for each DG is formulated as a parameter optimization problem and solved in MATLAB by using cuckoo optimization algorithm [30]. The flowchart of optimization algorithm is illustrated in Fig. 6. The magnitude of controller gain and time constants obtained by using optimization technique is shown in Table 1.

6. Micro-source controller

The control scheme of the micro-source is shown in Fig. 7. The inputs are either measured values (like the voltages and currents) or set points (for voltage, power and the nominal grid frequency). The outputs are the gate pulses that dictate when and for how long each power electronic device is going to conduct. The voltage droop control block is shown in detail in Fig. 8. The inputs of Q versus voltage droop block are desired voltage at the regulated bus and the current injection of reactive power from the micro-source. The output is new value of voltage request that replaces the one commanded from outside.

This new value is obtained from the linear characteristic of the droop. The inputs of voltage control block are the requested value adjusted from the Q-voltage droop and the measured magnitude of the voltage at the feeder bus. This block is the core of the voltage control: the voltage at the load is regulated by creating an appropriate voltage at the inverter terminals. This block compares the measured and the desired voltage magnitudes. This error is passed through a P-I controller to generate the desired voltage magnitude at the inverter. The control block that realizes the droop is represented in Fig. 9.

There are only two inputs to the block: the measured injected power and the nominal system frequency. The output of this block is the desired angular frequency. The ω_{tCont} is obtained by wrapping the instantaneous quantity $(\omega_0 - \omega)$ around 0 and 2π . This is because the $(\omega_0 - \omega)$ is constantly increasing with a rate nearly equal to ω_0 . Therefore, to avoid overflow of this variable inside the DSP register, the angular frequency is reset to 0 each time it reaches 2π , consequently, ω_{tCont} will have a saw tooth waveform. The reference calculator block is shown in detail in Fig. 10.

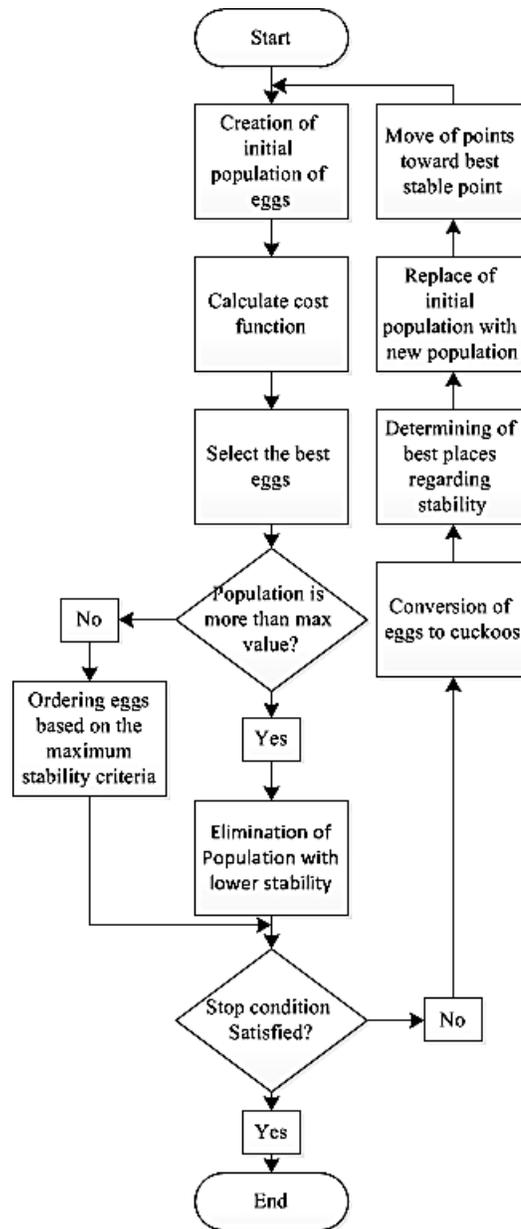


Figure 6: Flowchart of optimization algorithm

TABLE 1: PARAMETERS OF THE PROPOSED DROOP CONTROL LOOP

Parameters	Conv1	Conv2	Conv3
K	-14.64	0.6175	10.2186
T1	11.8940	-14.04	13.9896
T2	3.1550	10.3668	11.7237
T3	12.6817	15.7287	-1.0138
T4	0.3164	0.8223	5.2440
T5	0.7646	7.9252	0.4367
T6	0.9591	0.7229	0.2252

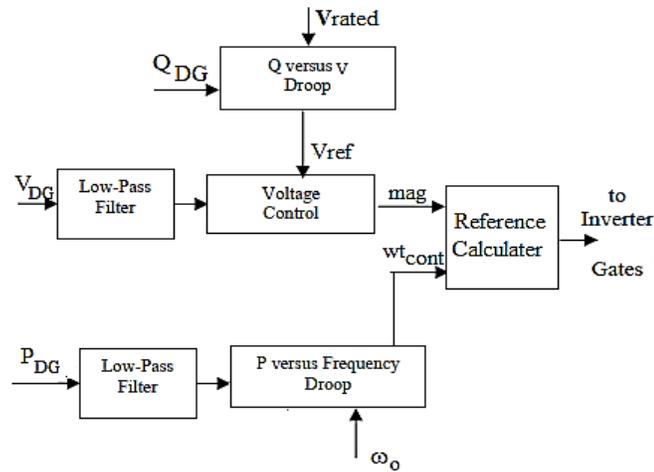


Figure 7: Micro-source control

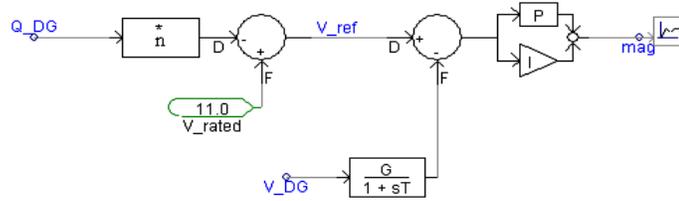


Figure 8: Voltage droop control

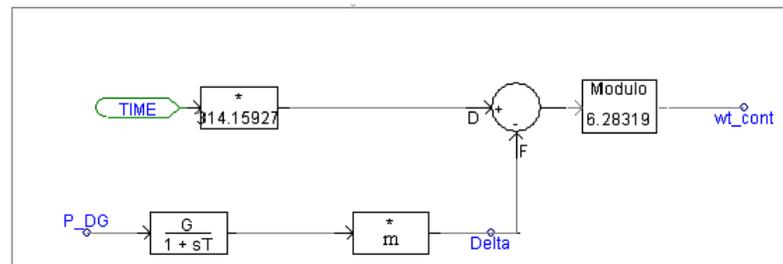


Figure 9: Angular frequency droop control

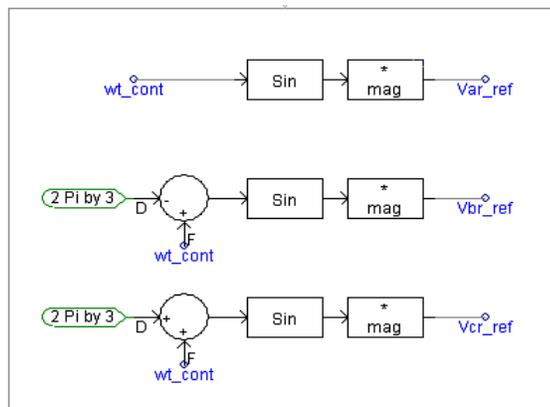


Figure 10: Reference calculator

7. Simulation results

In this section, the microgrid shown in Fig.11 is simulated in PSCAD simulation package. System parameters are shown in Table 2. From the data given in Table 2, it could be inferred that the power sharing ratio of DG1 to DG2 and DG3 are 2 and 1.33, respectively.

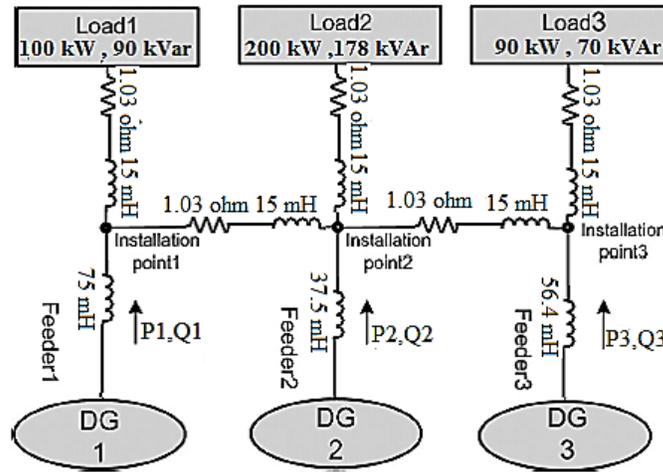


Figure 11: Microgrid system under consideration

TABLE 2: NOMINAL SYSTEM PARAMETERS

Parameters		Values
Microgrid system frequency		50Hz
Error! Bookmark not defined.DGs and VSCs	DG ratings (nominal) DG-1, DG-2, DG-3	100, 200, 150kW
	DC voltages	3.5kV
	VSC losses (R_f)	1Ω
	Filter capacitor (C_f)	10 μF
	Transformer rating	3kV/11kV 0.5 MVA L_f 2.5%
	Hysteresis constant (h)	10^{-5}
Droop coefficients	Power-angle (Higher-Lower Gains)	m1 1-0.1 rad/MW
		m2 0.5-0.05 rad/MW
		m3 0.75-0.075 rad/MW
	Q-Voltage (Higher-Lower Gains)	n1 10-0.04 kV/MVAr
		n2 5-0.02 kV/MVAr
		n3 7.5-0.03 kV/MVAr

7.1. Effect of boosting power-angle droop gain

Here, the system stability in case of high droop gain, when microgrid operates in low droop gains and at $t=1s$ droop gains are boosted is investigated. Fig.12 shows variation of the DG2 angle without the proposed controller. It is clear that with conventional controller, this variation is not acceptable in high droop gains and might result in instability of DGs and the overall system. Fig.13 shows that if each converter output active power is used as input parameter, the proposed controller could overcome this problem.

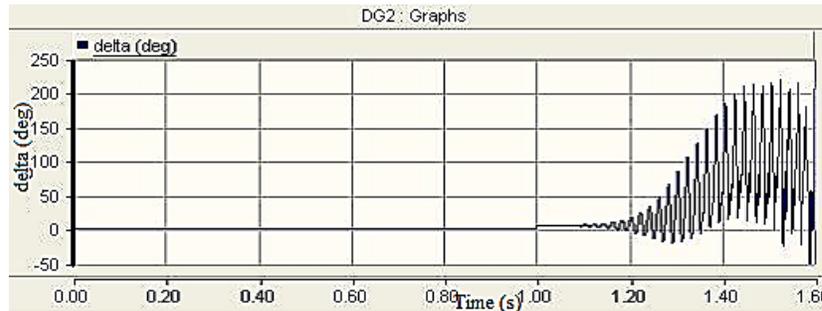


Figure 12: Difference delta with rated delta for DG2 with high droop gain and without the proposed controller

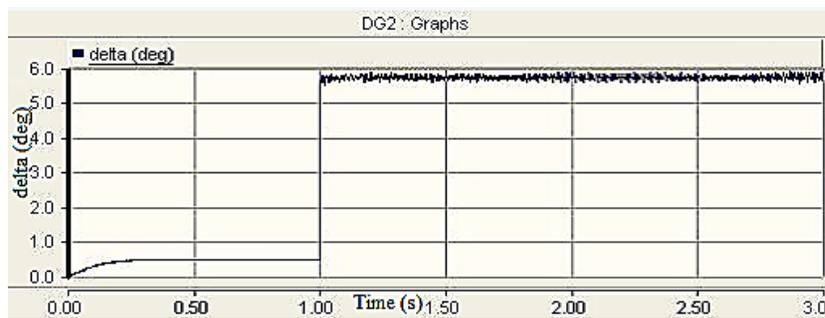


Figure 13: Difference delta with rated delta for DG2 with high droop gain and the proposed controller

7.2. Effect of boosting Q-voltage droop gain

To show the negative effect of high droop gain on stability and its positive effect on load sharing accuracy, the operation of the understudy microgrid in low droops is investigated. At $t=2s$, each converter Q-Voltage droop Gain is boosted to the values given in Table2. Fig. 14 shows variation of DG3 δ with respect to reference δ during the variation of droop without the proposed controller. It is seen that by increasing DG3 droop, $\delta - \delta_{rated}$ will be unacceptable and overall system will lose stability. Fig. 15 shows that by using the proposed controller, $\delta - \delta_{rated}$ will be acceptable and the stability of microgrid will be preserved.

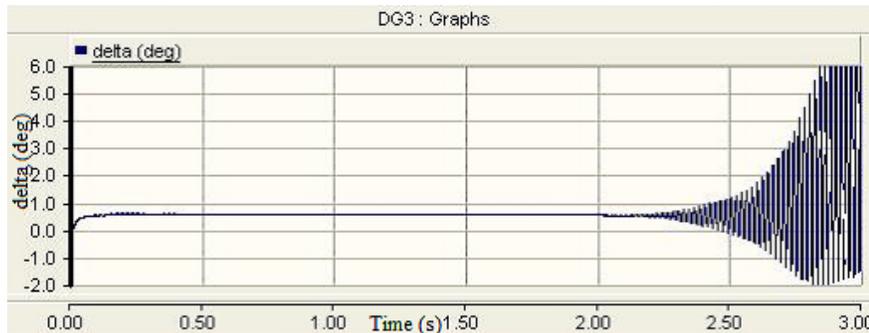


Figure 14: Difference delta with rated delta for DG3 with high droop gain and without the proposed controller

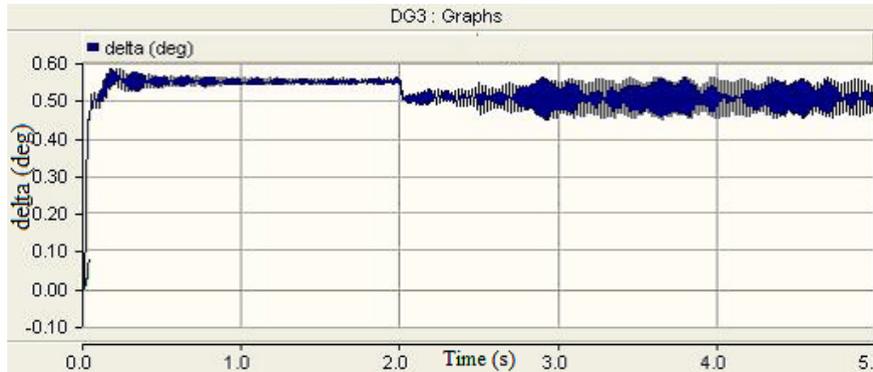


Figure 15: Difference delta with rated delta for DG3 with high droop gain and the proposed controller

7.3. Load sharing without the proposed controller

In this case, it is assumed that all of DGs and loads are connected to the microgrid. Low droop parameters shown in Table 2 are used. When operating in stable mode, load 3 is disconnected from the microgrid at $t=2.25s$. Figures 16 and 17 show active and reactive power sharing, respectively. At steady state point, reactive power sharing ratio of DG1 to DG2 and DG3 in case of disabling the proposed controller is 1.850 and 0.88209, respectively. Therefore, reactive power sharing error is 29.89% in this case. Moreover, active power sharing ratio of DG2 and DG3 to DG1 in the case of disabling proposed controller is 1.964 and 1.458 respectively. Thus active power sharing error in this case is 8.4%.

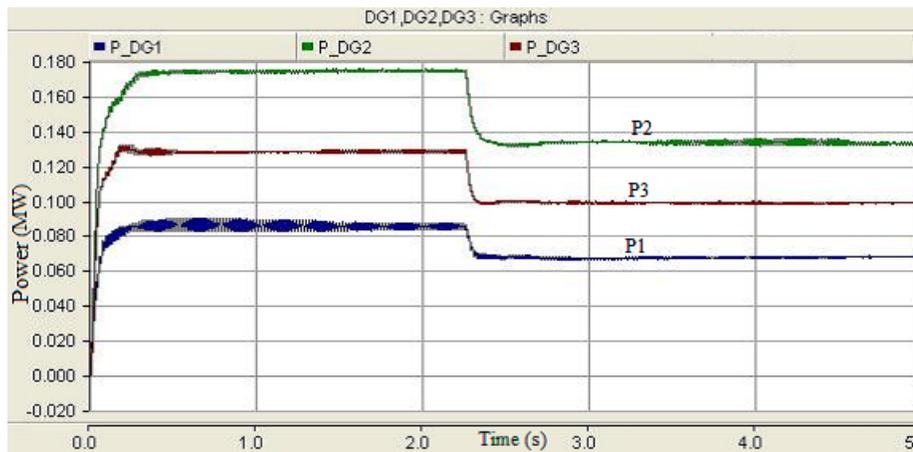


Figure 16: Power sharing with the proposed controller (active power output)

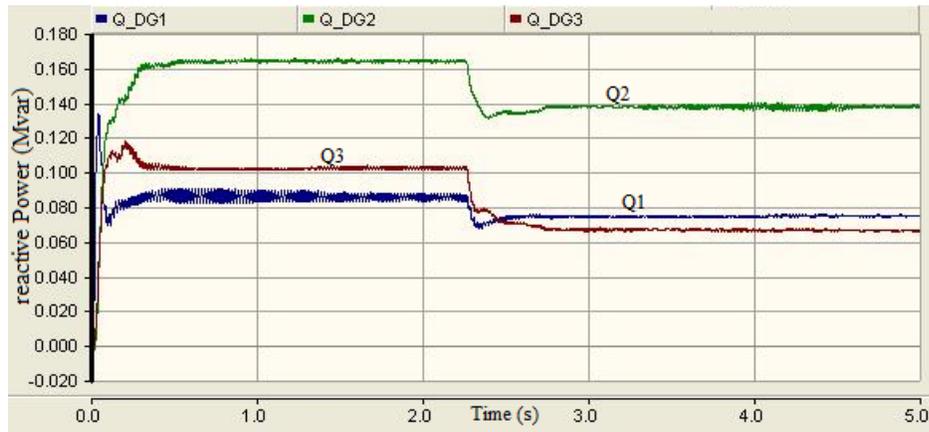


Figure 17: Power sharing with the proposed controller (reactive power output)

7.4. Load sharing with the proposed controller using reactive power variation

In this case, high droop parameters given in Table.2 are used and the proposed controller load sharing capability is investigated. When operating in stable mode, load3 is disconnected from the microgrid at $t=2.25s$. By using the proposed controller, even in case of operation with high Q-V droop gains, the system will be stable. At steady state point, reactive power sharing ratio of DG1 to DG2 and DG3 in the case of using the proposed controller is 2.129 and 1.33, respectively. Therefore, reactive power sharing error is 6.45% in this case. Figures 18 and 19 show active and reactive power sharing, respectively. Numerical values of simulation results in the case that reactive power variation is considered as an input control parameter are shown in Table 3. Average error of load sharing in both cases is also given in that Table 3.

By analyzing these results, it can be found that using the proposed controller and considering reactive power variation as the control input, the accuracy of power sharing is improved in comparison with the conventional droop controller.

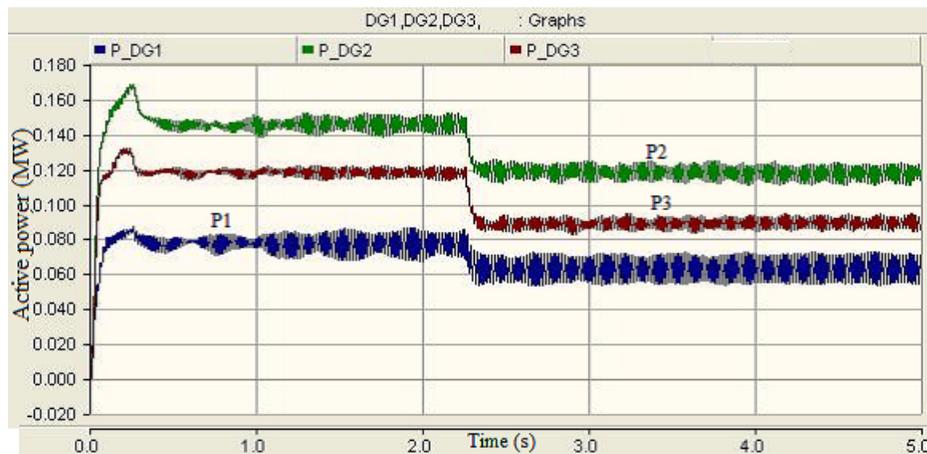


Figure 18: Power sharing with the proposed controller (active power output)

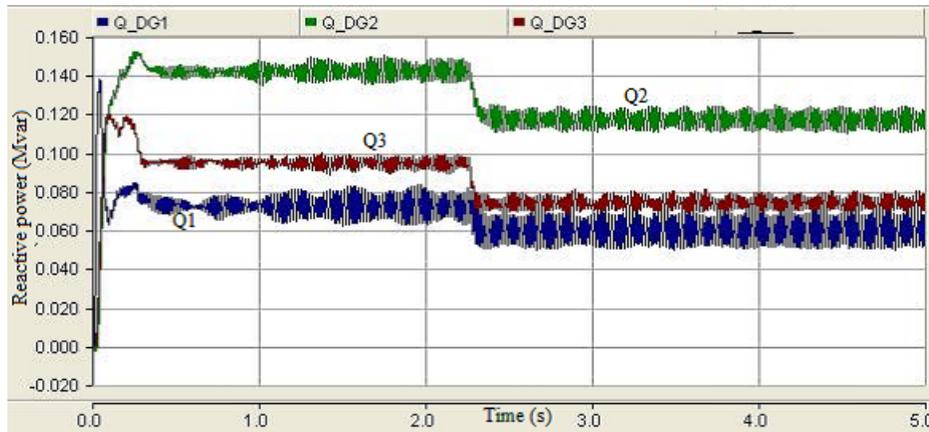


Figure 19: Power sharing with the proposed controller (reactive power output)

TABLE 3: NUMERICAL RESULTS USING REACTIVE POWER VARIATION

Case	Reactive Power	Final Value (MVar) and P.U value based on Q_{DG1}
Power sharing without the proposed controller	Q_{DG1}	0.07425618 (1.0)
	Q_{DG2}	0.13744580 (1.85)
	Q_{DG3}	0.0655008(0.882)
Power sharing with the proposed controller	Q_{DG1}	0.056144305(1.0)
	Q_{DG2}	0.11956912(2.12)
	Q_{DG3}	0.07507195(1.33)
Error in reactive power sharing	Without controller	29.89%
	With controller	6.45%

7.5. Load sharing with the proposed controller using active power variation

In this section, the proposed controller load sharing capability is investigated. All of simulations are carried out with high droop gains. Under stable conditions, load3 is disconnected from microgrid at $t=2.25s$. Fig.20 shows the system response. Sharing ratios of DG2 and DG3 to DG1 without the proposed controller are 2.029 and 1.401. Thus the sharing error in this case is 5.00%. The controller output variation for DG2 is depicted in Fig.21. Variation of DG angles with the proposed controller during a load change is depicted in Fig.22. It is clear that this variation is acceptable by using the proposed method. Numerical results in the case that active power variation is considered as input control parameter are shown in Table 4. From these results it can be found that using the proposed controller and considering active power variation as control input, the accuracy of power sharing is boosted in comparison with the conventional droop controller.

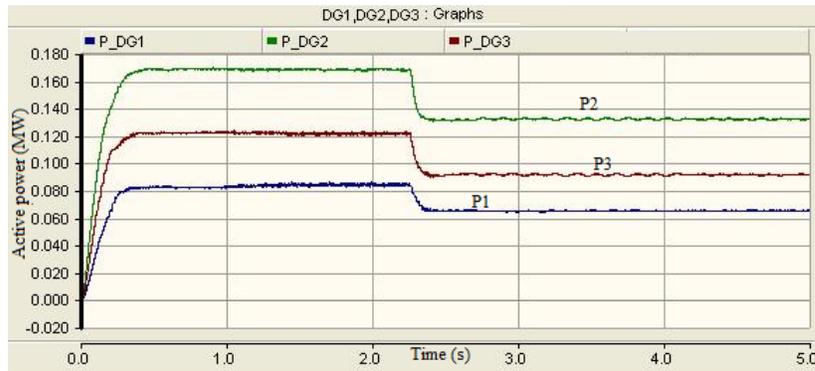


Figure 20: Power sharing with the proposed controller

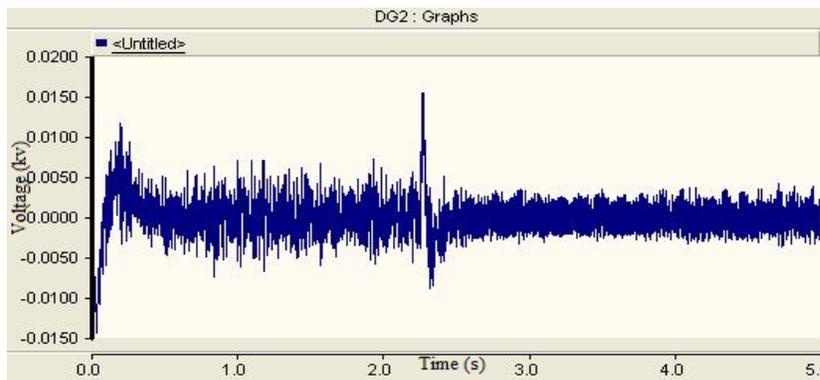


Figure 21: Controller output variation for DG2

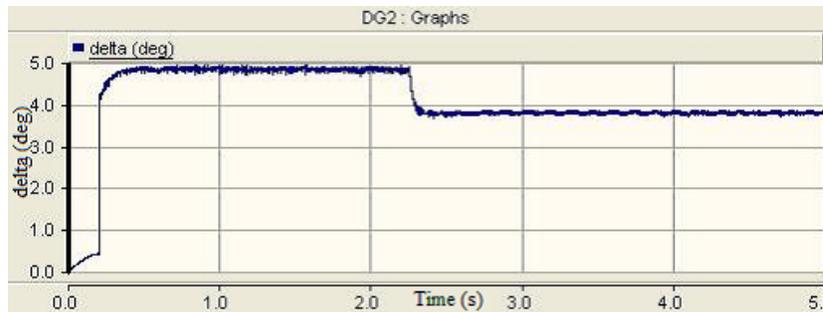


Figure 22: Difference delta with rated delta for DG2 with high droop gain and the proposed controller

TABLE 4: NUMERICAL RESULTS USING ACTIVE POWER VARIATION

Case	Active Power	Final Value (MW) and P.U value based on P_{DG1}
Power sharing without the proposed controller	P_{DG1}	0.06752949 (1.0)
	P_{DG2}	0.13265840(1.96)
	P_{DG3}	0.0984346(1.458)
Power sharing with the proposed controller	P_{DG1}	0.06506014(1.0)
	P_{DG2}	0.13204004(2.02)
	P_{DG3}	0.091185145(1.40)
Error in active power sharing	Without controller	8.4%
	With controller	5.00%.

Conclusion

A new controller is proposed in this paper to improve active and reactive power sharing between DG units in an autonomous microgrid using reactive and active power variation of each converter. This would mitigate the negative effect that increasing droop gain of DG has on system stability. Using the conventional control methods, by boosting DGs droop gain, their stable operation is lost and this might result in the overall system instability. It was proved that using the proposed controller to DGs with high droop gains, not only the stability of the system is preserved, but also the accuracy of power sharing is improved.

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