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Phasor Measurement Unit-Based Power Sharing for Optimal Decentralized Controller Design of Inverter-based Microgrid

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***Abstract*-- Nowadays, a powerful controller is essential for cost and reliability concerns for the future smart grid. In this way, the decentralized inverter control is used extensively in the microgrids. Limited system stability is mainly one of the most important issues that face the decentralized inverter control because of the lack of communications among the different distributed generation (DG) inverters. In this paper, the stability enhancement of the droop based decentralized inverter control in the microgrid is investigated. An optimal control strategy based on power sharing is proposed to incorporate the information provided by phasor measurement units (PMU) to improve the microgrid stability. The traditional droop controller has been modified to improve the stability of the microgrid. An optimal controller design based on the desired power sharing of each DG unit and the acquired information of total generation is proposed. The performance of the proposed control strategy is evaluated based on the nonlinear time domain analysis. The results show satisfactory performance with efficient damping characteristics and confirm the effectiveness of the proposed controller.**

***Index Terms*—Microgrids, PMU, Decentralized control, power sharing, optimal control.**

I. Nomenclature

ω_n : nominal DG angular frequency
V_n : nominal DG voltage magnitude,
P_c : measured real powers after the low-pass filtering,
Q_c: measured reactive powers after the low-pass filtering,
m_p & n_q : droop gains/ slopes of the real and reactive powers,
k_p & k_q : droop gains/ slopes of the real and reactive powers,
F : Feed-forward gain of the voltage controller.

II. Introduction

The impacts of increasing amount of distribution generation (DG) connected to the utility at the distribution level have a great attention because of ever-growing concerns on energy cost, energy security, and environmental issues [1]-[2]. A group of DG units and loads are connected together at a distribution voltage level to perform a microgrid. Microgrid can be used to provide high quality and reliability electric power. Microgrids need control and monitoring to balance supply and demand within the microgrid as well as the utility. It can operate in either a grid-connected mode or an islanded mode. In the autonomous mode, the microgrid is response of support the loads by their active and reactive power demands as well as maintaining the voltage and frequency of the system. To reduce the complexity of DG unit control, localized control is established to control the microgrids. In order to avoid high capital expenditure and low reliability in microgrid operation, decentralized control is indispensable [3]. Establishing an efficient and reliable control over a large number of DG units is one of the primal problems to be solved in the near future. Droop control is the common control method that used to emulate the droop characteristics of the synchronous generators based on local estimates on real and reactive power generation. Based on the droop method, several control techniques have been proposed to achieve good power sharing [4]–[10]. The stability issue of the inverter-based autonomous microgrid is very important due to the lack of inertial generator to provide ride through during transients especially if the power generation by some of the microgrids suddenly reduces such as suddenly cloud covers photovoltaic cells [11]. In networks where the ratio between line resistance and line reactance is high, the coupling between active and reactive power affects badly the stability of the microgrid [12]. The virtual impedance method can be used to decouple the real and reactive power control [6]-[7], especially for the transformer coupled DG units which already have significant output inductance [8]. In order to avoid the complexity in impedance design, the virtual frequency and voltage frame based droop control strategy can be used [9]. The frequency and voltage are transformed to a virtual frame for a completely decoupled relationship between real and reactive power. A Q−V droop control method with V restoration mechanism was presented to improve reactive power sharing [10]. Although most of these control schemes have tried to solve the problems of voltage regulation as well as power sharing, a slow dynamic response, transient oscillations and bad controllability are the main problems face the conventional droop control [13]. Achieving efficient real

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and reactive power sharing while maintaining the microgrid frequency and voltage are the main goal of this paper. The droop based decentralized inverter control is investigated as one of the critical control problems in microgrids.

In this paper, the parameters of the conventional droop control presented in our previous work [14], have been modified to improve the performance of the existing droop control method. A novel scheme to obtain these droop coefficients is proposed to improve the transient response of inverter-based DGs of the autonomous microgrid. The instantaneous active and reactive powers are firstly determined using the output voltage and output current which will be provided by PMU. The problem is formulated as optimization problem where the power controller parameters are obtained using the PSO to achieve the stability of the microgrid. The nonlinear model and control method are explained. In addition, simulation results are presented to validate the effectiveness of the proposed method.

I. MICROGRID MODELING

The microgrid system consists of few DG units, their controllers, some loads, lines and coupling filters as shown in Fig. 1. Three controllers; power, voltage and current controllers are used to control the output active and reactive powers of these DGs while maintain the voltage and frequency of this microgrid. Emulating the droop characteristics of the synchronous generators based on local measured of the real and reactive power generation, the power controller is used to share the power between the DGs units as shown in Fig. 2. The instantaneous active and reactive powers are firstly determined using the output voltage and output current which will be provided by phasor measurement units (PMU). Then the low pass filter is used to obtain the real and reactive powers P_c and Q_c corresponding to the fundamental components. Finally, the frequency ω and the output d-axis voltage magnitude reference v^*_{od} corresponding to these powers can be determined as follows;

$$\omega = \omega_n - m_p P_c \quad , \quad \dot{\theta} = \omega \quad (1)$$

$$v^*_{od} = V_n - n_q Q_c \quad , \quad v^*_{oq} = 0 \quad (2)$$

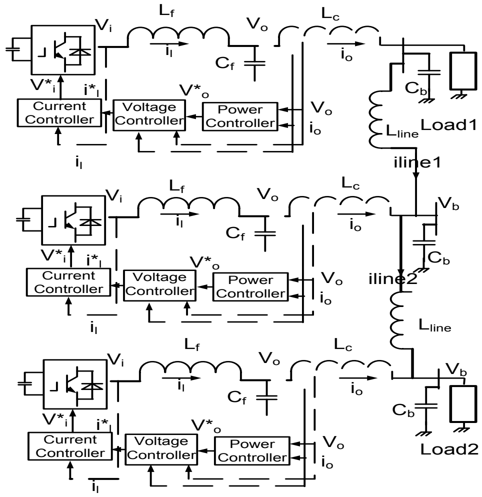

Fig. 1 Autonomous microgrid

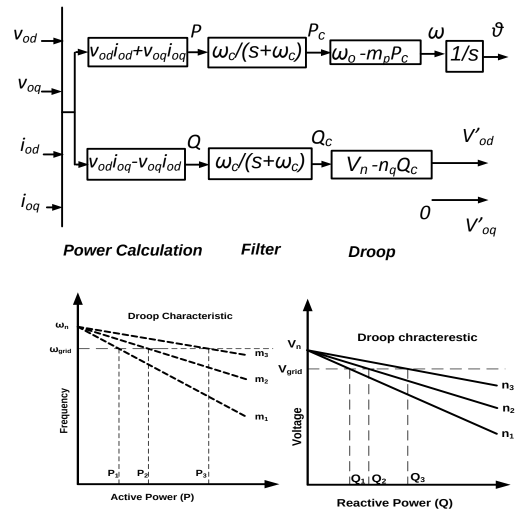

Fig. 2 Power controller and Droop characteristics

The output voltage magnitude reference is aligned to the d-axis of the inverter reference frame while the q-axis reference is set to zero. The output voltage is controlled using a standard PI voltage controller as shown in Fig. 3. The state and the algebraic equations of the output voltage can be written as:

$$\dot{\phi}_d = v^*_{od} - v_{od} \, , \; \dot{\phi}_q = v^*_{oq} - v_{oq} \quad (3)$$

$$\begin{aligned} i^*_{ld} &= F i_{od} - \omega_n C_f v_{oq} + K_{pv}(v^*_{od} - v_{od}) + K_{iv}\phi_d \\ i^*_{lq} &= F i_{oq} + \omega_n C_f v_{od} + K_{pv}(v^*_{oq} - v_{oq}) + K_{iv}\phi_q \end{aligned} \quad (4)$$

A PI current controller shown in Fig. 4 is used to control the output current of the filter inductor. The state and algebraic equations are given as:

$$\dot{\gamma}_d = i^*_{ld} - i_{ld} \quad , \; \dot{\gamma}_q = i^*_{lq} - i_{lq} \quad (5)$$

$$\begin{aligned} v^*_{id} &= -\omega_n L_f i_{lq} + K_{pc}(i^*_{ld} - i_{ld}) + K_{ic}\gamma_d \\ v^*_{iq} &= \omega_n L_f i_{ld} + K_{pc}(i^*_{lq} - i_{lq}) + K_{ic}\gamma_q \end{aligned} \quad (6)$$

The state equations of the *LC* filter and the coupling inductance are given assuming the inverter produces the demanded voltage ($v_i = v^*_i$),

$$\dot{i}_{ld} = -\frac{r_f}{L_f} i_{ld} + \omega i_{lq} + \frac{1}{L_f}(v_{id} - v_{od}) \quad (7)$$

$$\dot{i}_{lq} = -\frac{r_f}{L_f} i_{lq} - \omega i_{ld} + \frac{1}{L_f}(v_{iq} - v_{oq}) \quad (8)$$

$$\dot{v}_{od} = \omega v_{oq} + \frac{1}{C_f}(i_{ld} - i_{od}) \quad (9)$$

$$\dot{v}_{oq} = -\omega v_{od} + \frac{1}{C_f}(i_{lq} - i_{oq}) \quad (10)$$

$$\dot{i}_{od} = -\frac{r_c}{L_c} i_{od} + \omega i_{oq} + \frac{1}{L_c}(v_{od} - v_{bd}) \quad (11)$$

$$\dot{i}_{oq} = -\frac{r_c}{L_c} i_{oq} - \omega i_{od} + \frac{1}{L_c}(v_{oq} - v_{bq}) \quad (12)$$

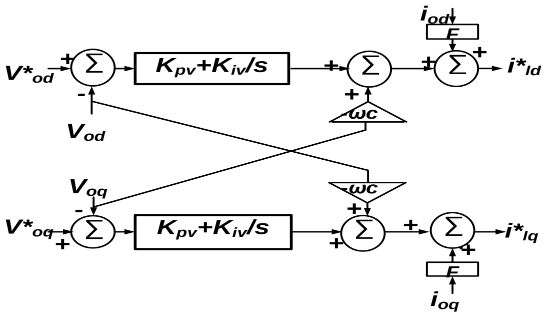

Fig. 3 Voltage controller

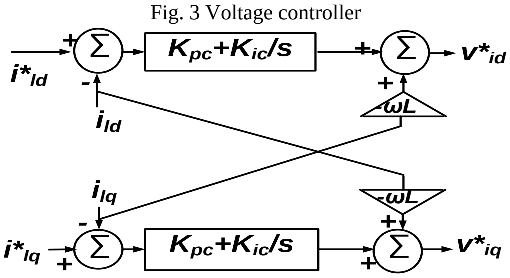

Fig. 4 Current controller

The state equations of line current of i^{th} line connected between nodes j and k can be expressed on a common reference frame as follows:

$$\dot{i}_{lineDi} = -\frac{r_{linei}}{L_{linei}} i_{lineDi} + \omega i_{lineQi} + \frac{1}{L_{linei}} (v_{bDj} - v_{bDk}) \quad (13)$$

$$\dot{i}_{lineQi} = -\frac{r_{linei}}{L_{linei}} i_{lineQi} - \omega i_{lineQi} + \frac{1}{L_{linei}} (v_{bQj} - v_{bQk}) \quad (14)$$

The state equations of the considered RL load connected at i^{th} node are:

$$\dot{i}_{loadDi} = -\frac{R_{loadi}}{L_{loadi}} i_{loadDi} + \omega i_{loadQi} + \frac{1}{L_{loadi}} v_{bDi} \quad (15)$$

$$\dot{i}_{loadQi} = -\frac{R_{loadi}}{L_{loadi}} i_{loadQi} - \omega i_{loadDi} + \frac{1}{L_{loadi}} v_{bQi} \quad (16)$$

$$\dot{v}_{bDi} = \omega v_{bQi} + \frac{1}{C_f} (i_{oDi} - i_{loadDi} \pm i_{lineDi,j}) \quad (17)$$

$$\dot{v}_{bQi} = -\omega v_{bDi} + \frac{1}{C_f} (i_{oQi} - i_{loadQi} \pm i_{lineQi,j}) \quad (18)$$

II. PROPOSED CONTROL TECHNIQUE

In fact, the transient droop parameters have to be selected carefully to guarantee stability and good transient response. It is obvious that the damping of the dominant low frequency mode is highly dependent on the operating condition. Therefore, we extend our previously proposed power sharing based control strategy [14]. The conventional droop controller coefficients have been modified to increase the controllability of the power sharing controller since the power-sharing controllers and the power filters are mainly the dominant low-frequency modes. The modified droop functions are given as follows:

$$\omega = \omega_n - k_p m_p P_c \quad , \qquad \dot{\theta} = \omega \quad (19)$$

$$v_{od}^* = V_n - k_q n_q Q_c \quad , \qquad v_{oq}^* = 0 \quad (20)$$

The proposed control scheme is used to improve the transient response by controlling the power sharing parameters. Specifically, a proportional term is incorporated in the frequency droop control to damp the oscillation in real power sharing without affecting the original droop gain while an integral term is incorporated in the voltage droop control to correct the inaccurate reactive power sharing based on the traditional droop control. To improve the relative stability of the power-sharing dynamics, an optimization-based approach is proposed in this paper. The proposed approach relies on the nonlinear system dynamics to ensure optimized large-signal stability-constrained performance. The design problem is to find the optimum transient droop parameters k_d and k_q that maximize the microgrid stability under different operating conditions.

III. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Eberhart and Kennedy [15] in 1995, inspired by social behavior of bird flocking or fish schooling. PSO technique tries to find the best solution (candidate) inside the population. It is started by random particles inside the population. Then it tries to obtain the optimum values by updating the generations. The particles change their position by following the optimum particles. The algorithm, starting anywhere in the search space, ensures the convergence to the optimal solution. The advantages, basic elements and the steps of PSO technique are briefly stated and defined in [3]. The best position (p_{best}) of this particle will indicate the position that is related to the highest fitness value for that particle. In the minimization problem, at a given position, the highest fitness corresponds to the lowest value of the objective function at that position. The best position of the all particles will be memorized. Then the best value of these values will be the global best position which is denoted by (g_{best}). The new position of each particle at iteration n+1 is calculated as follows:

$$x_{n+1}^i = x_n^i + v_{n+1}^i \quad (21)$$

where x^i_{n+1} is the position of particle i at iteration $n+1$; and v^i_{n+1} is the corresponding velocity vector.

At each time step, the velocity of each particle is modified using its current velocity and its distance from the personal and global best positions as follows:

$$v_{n+1}^i = w v_n^i + c_1 r_1 p_{best} - x_n^i + c_2 r_2 (g_{best} - x_n^i) \quad (22)$$

where w is the inertia weight;

r_1 and r_2 are random numbers between 0 and 1;

p_{best} is the best position found by particle i ;

g_{best} is the best position in the swarm at time n;

and c_1 and c_2 are the "trust" parameters.

The computational flow of the proposed PSO-based tuning algorithm is shown in Fig. 5.

IV. RESULTS AND DISCUSSION

A. System Description

Three inverter-based (10KVA) DG units connected with two load banks are controlled to share the real and reactive powers over the lines 1 and 2 as shown in Fig. 1. One of them is

located at bus 1 and the other is located at bus 3. Each DG unit is represented by a dc voltage source, a VSI, a series LC filter, and coupling inductance L_c. Simulation studies have been carried out in the MATLAB code. System parameters are given in Table I. DG1 and DG2 are located relatively close together compared to DG3. A resistive load of 5.8 kW (25 per phase) at bus 1 and 7.3 kW (20 per phase) at bus 3 is considered as an initial operating point.
The droop sharing coefficients are dictated by optimization so that they optimally share the fundamental power. The objective of this paper is to investigate the stability of the system for the optimized droop gains. A complete model of the test system was obtained using the procedure outlined in Section II. First, initial steady-state conditions of the system are obtained using a general power flow program. Then to verify the system stability, a disturbance by a lot of ways such as step change of real power, load addition and fault disturbance.

B. Simulation with fault occurred at load

The first disturbance was chosen to be a fault occurs at the first load. Figs. 6-9 show the response of state variables of all the three inverters obtained from the model when the fault occurs at the load bus 1. It can be seen from these figures that the system is stabile after getting disturbance. Hence, during fault in the load bus, closely located DGs may be overloaded and can be tripped out due to the limited overload capacity of the inverters.

Table I. Test System Parameters

Inverter parameters (10KVA rating)			
Parameter	Value	Parameter	Value
f_s	*8 kHz*	ω_c	*31.41*
L_f	*1.35 mH*	r_c	*0.03 Ω*
C_f	*50 μF*	L_c	*0.35 mH*
r_f	*0.1 Ω*		

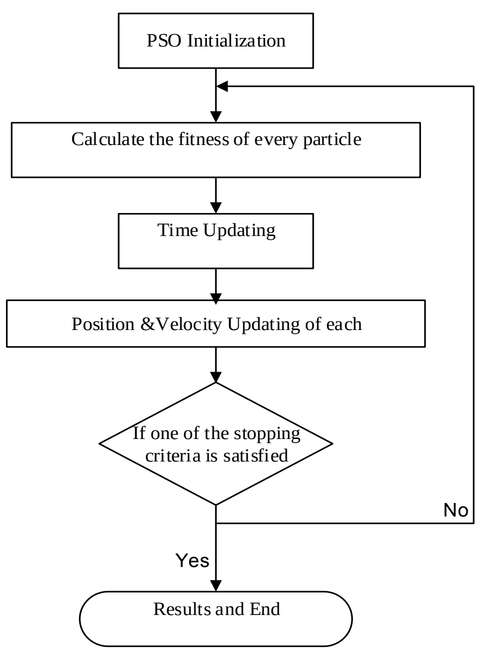

Fig. 5 Computational flow of the proposed PSO

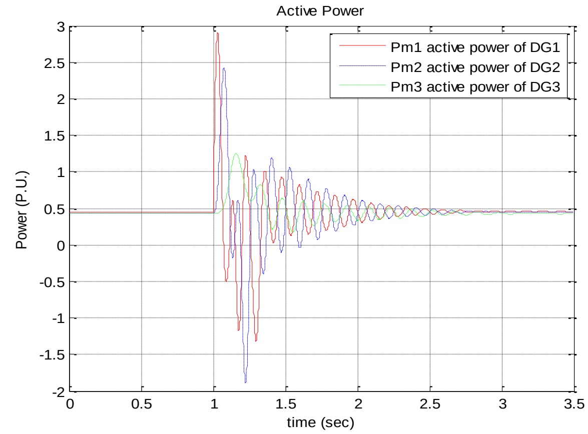

Fig. 6. Output active power response of the microgrids when the fault ocurrs at load1

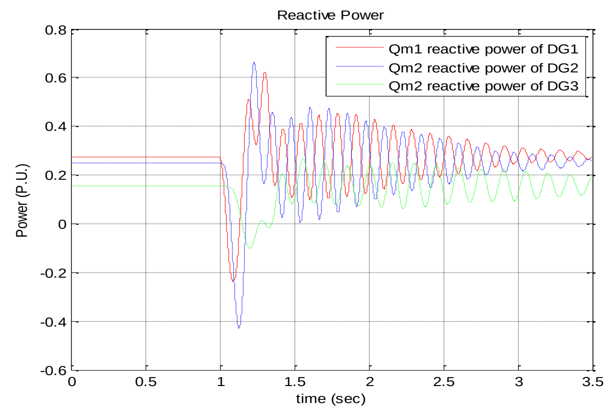

Fig. 7. Output reactive power response of the microgrids

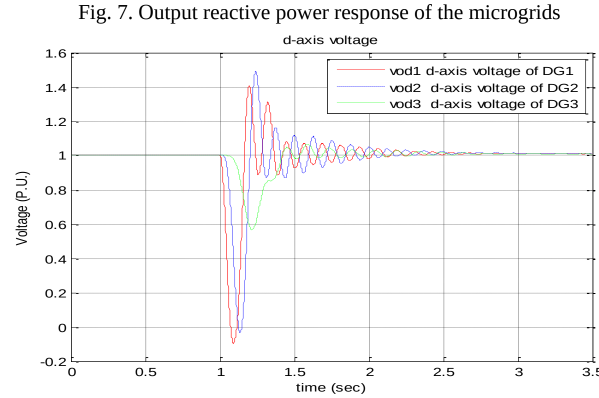

Fig. 8. Output voltage (d-axis) response of the microgrids

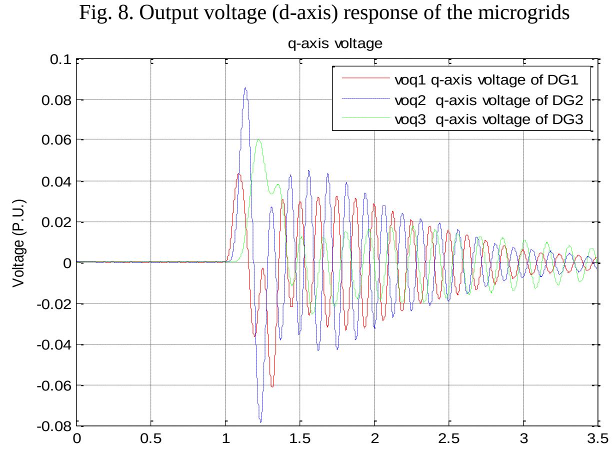

Fig. 9 Output voltage (q-axis) response of the microgrids

C. *Simulation with step change in load*

To investigate the low frequency mode response under severe test load conditions, a test involving a step change of load 1 was conducted. In this test, there was initially no load connected to the system and then a load of 3.8-kW at bus 1 was switched on. Fig. 10-12 shows the DG fundamental output active, reactive power and voltage responses for a 3.8-kW step change in DG1 for the model system. The optimal controller capability has been finally checked out when the first DG has been lost. The optimal parameters obtained before have been used to investigate the controller capability and to assess the system stability. Figs. 13-14 show the system response when the first DG has been lost using the optimal parameters obtained. As shown in results, the system is going to stable mode after getting loss DG disturbance.

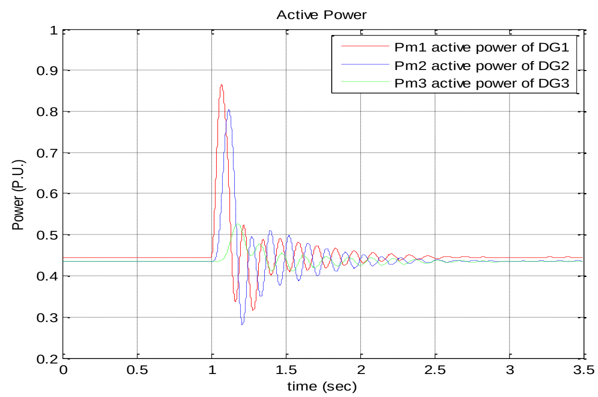

Fig. 10 Output active power response of the microgrids when the step response ocurrs at DG1

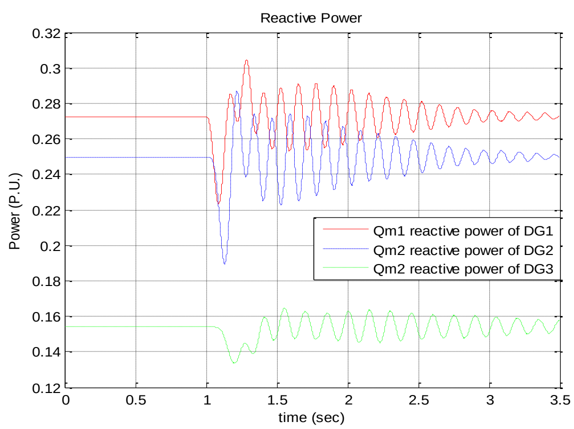

Fig. 11 Output reactive power response of the microgrids

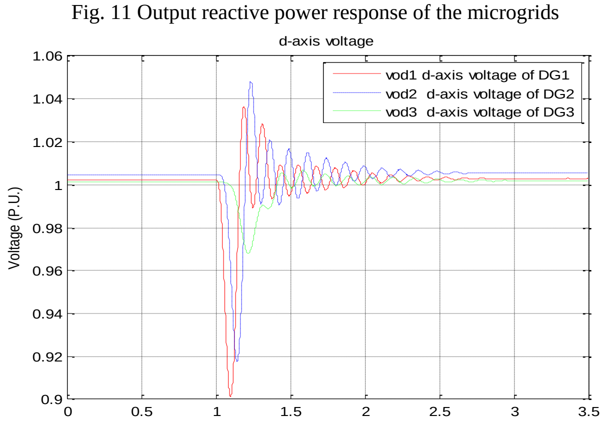

Fig. 12 D-axis output voltage response of the microgrids

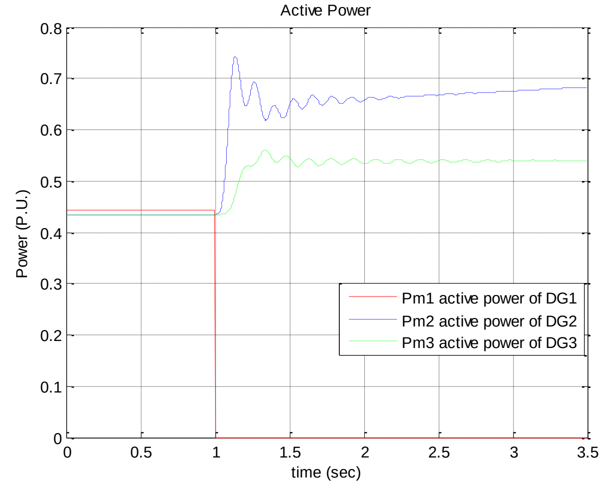

Fig. 13Output active power response of the three DGs when the DG1 has been lost

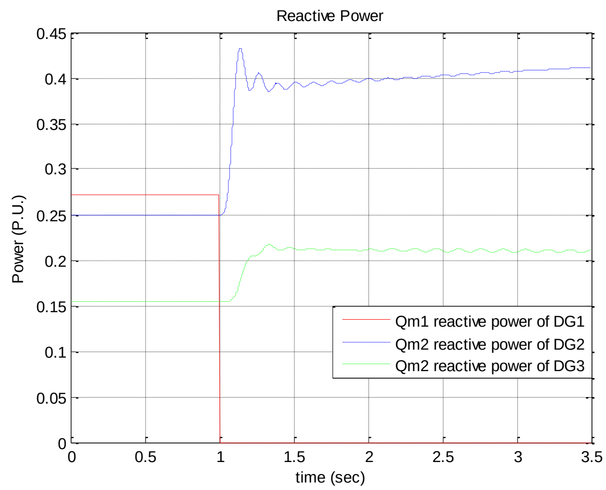

Fig. 14 Output reactive power response of the three DGs

V. CONCLUSION

In this paper, modified droop control strategy is presented to improve the performance of the existing droop control methods. The stability enhancement of the droop based decentralized inverter control in the microgrid has been investigated. An optimal control strategy based on power sharing is proposed to incorporate the information provided by phasor measurement units (PMU) to improve the microgrid stability. A step change disturbance of the generated DG output and fault disturbance have been used to verify the system stability. To optimally tune the proposed power sharing coefficients, the tuning problem has been formulated as a constrained optimization problem, and solved via an evolutionary search algorithm based on the PSO technique. Therefore, a simple and structured tuning methodology has been obtained. The results show satisfactory performance with efficient damping characteristics and confirm the effectiveness of the proposed controller. Also, we can include that the PSO technique is very useful for controlling the PI controllers which will achieve a sufficient stability to the system after getting disturbances.

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