Comparison of Different Power Sharing Methods in AC- and DC-microgrid with Power Electronic Interfaced Distributed Generations

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Abstract— **In the islanded operation of microgrids, various control strategies have been developed to guarantee stable operation of microgrids. In this paper, different power sharing methods such as droop controller, average power sharing (APS) method, and master-slave method are compared in AC and DC islanded microgrids with converter-based distributed generations (DG). The suitable controller (voltage controller and power sharing controller) for each DG is designed. Different scenarios of load variations are tested using Matlab/Simulink sofware to compare the accuracy and effectiveness of power sharing methods. Based on the simulation results, suitable power sharing method in each microgrid (AC or DC) is chosen based on its performance and minimum power sharing error.**

Keywords— Converter-Based Power Sources, Distributed Generation, Islanded Microgrid, Proportinal Resonant Controller.

I. INTRODUCTION

Emergence of new concepts such as microgrids and smart grids due to increasing penetration of renewable energy resources, distributed generations (DGs), and various kinds of storage systems is inevitable in order to increase the stability and reliability of these systems as much as possible. On the other hand, environmental, social, economical, and political issues, attract more attention toward microgrids [1].

Microgrids operate in two main control modes. First mode is while it is connected to grid and the other mode is when microgrid is islanded. In grid-connected mode, voltage source converters (VSCs) operate in current control mode in order to supply the desired power. In this mode VSCs can inject a certain amount of power to grid in order to compensate the power mismatch. But in islanded mode,the utility support is no more present so converters operate in voltage-control mode, microgrid stands alone, and VSCs take care of power mismatch between total generation and load of microgrid using power sharing methods [2]. Considering various kinds of loads and sources present in grids, necessity of having DC and AC-microgrids is strongly sensed. The interface between power sources and microgrid are generally based on power electronic converters [3].

To smooth out the injected current to microgrid, an L filter series with converter is used. But a configuration as simple as the mentioned one results in high cost and size of filter. Also in high power operation, where the switching frequency should be limited in order not to exceed a predefined value (due to switching losses) it is better to adopt an LCL configuration for filter. To control the injected current in an AC-microrid , P+Resonant controller is used for control the AC current [4-8]. DG units in microgrid's islanded operation are main sources of voltage control, power balancing, and power sharing [9].

In this paper different power sharing methods in islanded AC- and DC-microgrids are simulated in Matlab/Simulink and suitable controllers are designed to reach to an accurate power sharing for existing DGs. Investigated methods include droop method, average power sharing (APS) method, and master-slave method. In following the DC- and AC-microgrids are presented and described.

II. DC- MICROGRID

DC loads are very important and applicable in distribution grids (e.g, LEDs, lights, thermostatic loads, electric vehicles and so on). Regarding the increasing importance of DC loads, it is necessary that microgrids provide DC-buses available for DC-load users. DC-microgrids consume no reactive power, and the frequency is zero which makes it easy to understand and implement the control methods in DC-microgrids. DC power produced by renewable sources (e.g, photovoltaics and fuel-cells) has a stochastic nature and does not assure a constant and continuous power. For this reason DC/DC converters associated with storage devices are used in order to make a fixed output (voltage or current depending on operation mode of microgrid). There are various topologies for DC/DC converters and in this paper a boost DC/DC converter is used to attain the mentioned goal. Also in this paper one of the conducted studies is to compare different power sharing methods in DC-microgrid. For the reason mentioned above, to share demanded power among DGs appropriately in proportion to their capacity it is required to implement a power sharing method such as droop, APS, or master-slave

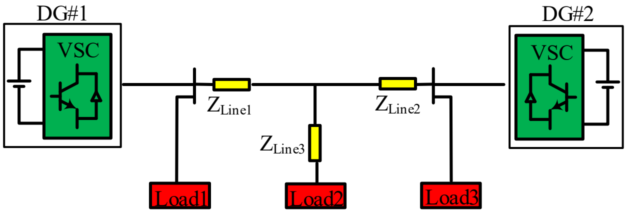

Fig. 1. DC-microgrid configuration.

method. Each method has its advantages and disadvantages but finally one should be selected based on comparison to be used in microgrid. Configuration and specifications of DC-microgrid is described below.

In DC-microgrid as shown in Fig. 1 there are two DGs feeding three constant-impedance loads through lines with impedance Z_{line} as defined in Table 1. Also it should be noted that there is a 10% fluctuation on input DC voltage. Specifications for lines, sources, and loads for DC-microgrid are given in Table 1 and Fig. 1.

A. *Controller Design*

In DC-microgrid, DGs are converter interfaced. Controller block is shown in Fig. 2. This controller works in current-mode (I_{ref}) for slave DGs when master-slave power sharing is chosen, but remains on voltage-mode status in droop, and APS methods. Also it should be noted that in master-slave power-sharing method, the master DG works in voltage-control mode.

According to [13] transfer function of output voltage to duty cycle are given in Eq. (1):

$$G_{vd} = \frac{V}{D'} \frac{(1-\frac{sL}{D'R})}{1+\frac{sL}{D'R}+(\frac{s\sqrt{LC}}{D'})^2} \tag{1}$$

Table I. DC-MICROGRID LINES, LOADS, AND SOURCES SPECIFICATIONS.

Parameters	**Values**	**Comments**
Z_{l1}, Z_{l2}, Z_{l3}	$15,3,5m\Omega$	Impedances of lines
P_1, P_2	2, 1 kVA	DG power
L_1, L_2, L_3	4.6, 3.29, 3.89 Ω	Constant impedance loads

According to [14], for boost DC-DC converter, an integral-double lead controller has been designed. The relation for integral-double lead controller is written as follows:

$$T_c(s) = \frac{B(s+\omega_{zc})^2}{s(s+\omega_{pc})^2} \tag{2}$$

where B is the gain factor, ω_{zc} is zero frequency, and ω_{pc} is pole frequency. This controller is designed so that the loop gain cross over frequency is so much smaller than switching frequency. Bode diagram of designed controller+plant is shown in Fig. 3. In this figure gain- and phase-margin at the desired cross-over frequency are achieved with very good stability.

III. AC-MICROGRID

Although renewable energy sources such as solar-cells and fuel-cells have DC output, converters translate DC output into AC power. Nowadays converters are so common in power applications and therefore it is easy to convert every form of electrical power into another one. Configuration of AC-microgrid presented in this paper is described below.

AC system is a low voltage grid, in which DGs with different maximum power outputs are connected to network via 3-leg converters. In the microgrid presented in this paper there are 3 DGs connected by resistive lines to 3 constant-impedance loads. Properties of loads, lines, and DGs are shown in Table 2 and Table 3.

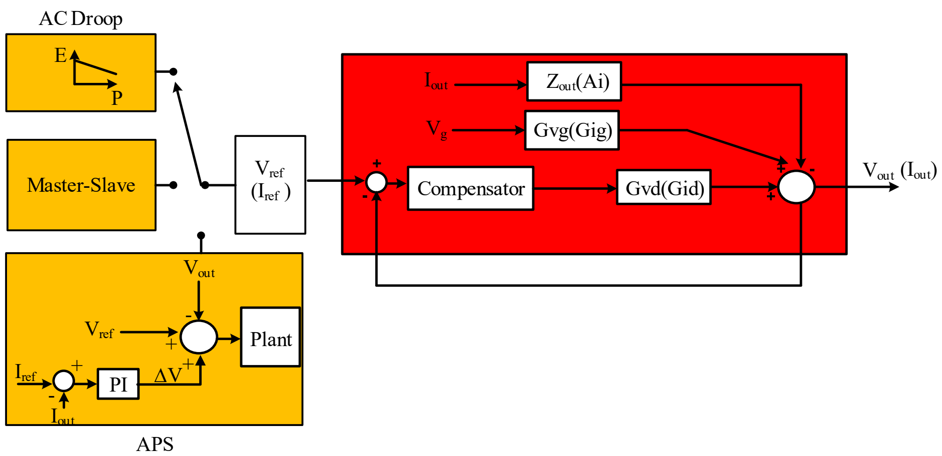

Fig. 2. Controll system of DC power sources.

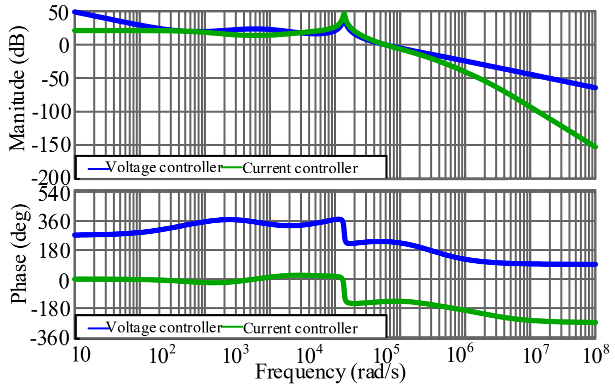

Fig. 3. Bode diagram of DC voltage and current controller of DC power sources.

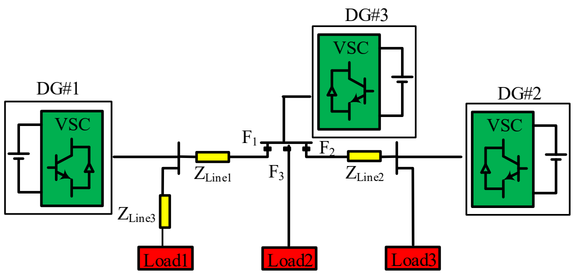

Fig. 4. AC-microgrid system configuration.

As we are working on a distribution network, it is worth noting that r/x ratio equals 3 and transmission lines are mainly resistive. DGs are connected to microgrid via DC/AC-converter and LC-filter. LC filter (as a low-pass-filter) is used to smooth out the injected current and partially remove the harmonics generated by converter. Configuration of AC-microgrid is shown in Fig. 4. In this microgrid, line impedances between DGs and loads are shown with Z_{line} as a lumped impedance. This way of showing line model in distribution networks is a good approximation, since length of lines is not as high to require accurate modeling of line. DGs are also connected through VSCs with capability of current or voltage control depending on operation mode of microgrid.

VSCs include embedded multi-loop controller. Multi-loop controller improves stability, and control options are increased as well. In following part, after a a brief description about three mentioned power sharing methods, design and implementation of controller is described.

A. Droop Power Sharing Method

Droop power sharing can be used for voltage and frequency regulation of microgrids. In droop mode, active and reactive powers are adjusted by droop coefficients (*m* and *n*) and depend on frequency and voltage values. More details on droop power sharing are presented in [10]. Considering the fact that in distribution level, lines are rather resistive (high r/x

TABLE II. AC-MICROGRID LINE, VOLTAGE, AND FREQUENCIES SPECIFICATION.

Parameters	Values	Comments
Z_{line1}	$2+j0.88\Omega$	Impedance of line1
Z_{line2}	$3.9+j1.3\Omega$	Impedance of line2
Z_{line3}	$5.7+j17.1\Omega$	Impedance of line3
f_g	50 Hz	Grid frequency
f_s	20 kHz	Switching frequency
$V_{l-l}(rms)$	400 V	Grid voltage line to line

TABLE III. DC-MICROGRID LINES, LOADS, AND SOURCES SPECIFICATIONS.

Parameters	Values	Comments
L1, pf_{l1}	45 kVA, 0.78	Load1 apparent power, and pf
L2, pf_{l2}	45 kVA, 1	Load2 apparent power, and pf
L3, pf_{l3}	45 kVA, 0.93	Load3 apparent power, and pf
S_1, S_2, S_3	200, 100, 200 kVA	DG1, DG2, DG3 apparent power

ratio), the governing equations on active and reactive power settings are as follows [10]:

$$\omega = \omega^* + m(Q - Q^*) \tag{3}$$

$$E = E^* - n(P - P^*) \tag{4}$$

In Eqs. (3) and (4), *m* and *n* coefficients are defined as follows [10]:

$$m = \frac{\delta\omega}{Q_{max}} \tag{5}$$

$$n = \frac{\delta E}{P_{max}} \tag{6}$$

It is worth noting that droop power sharing method, is specially favorable in microgrids, where there are typically numerous DGs operating as a whole, since it needs no communication link and DGs can can be controlled in a decentralized manner. Also it should be noted that in DC-microgrid, as there is no reactive power flow, only the active power droop is executed.

B. Average Power Sharing (APS)

In microgrids with communication infrastructure ready, average power sharing is executable. In this method total demand is divided by number of DGs and reference power of each DG is calculated regarding DG ratings. The equation for current reference of each DG is defined as follows [11]:

$$i_{ref} = \alpha \frac{\sum_{j=1}^{n} i_j}{n} \tag{7}$$

In Eq. (7), α is proportional to DG ratings. Again it should be noted that in DC-microgrid no reactive power sharing is accomplished, since there is no reactive power flow.

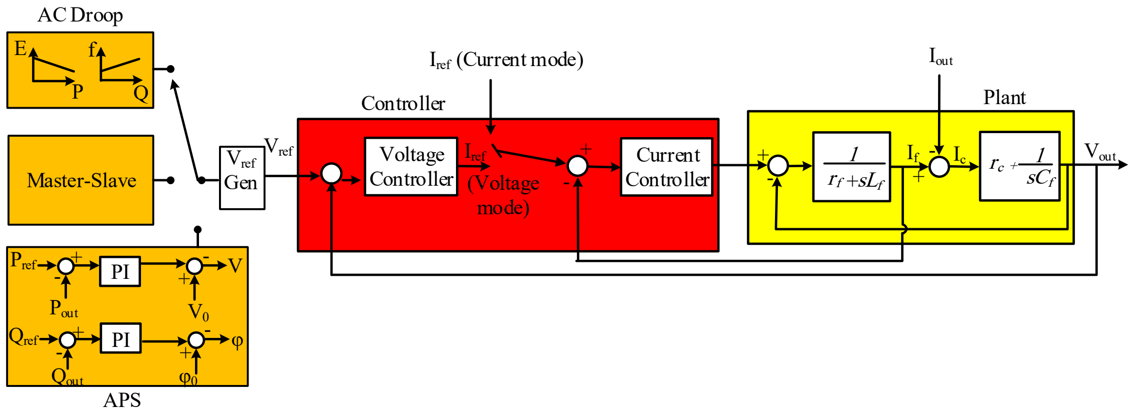

Fig. 5. Controller system of AC power sources.

Further description of this method with details is presented in [11].

C. Master/Slave

In this method as its name indicates, a DG makes support of voltage and acts like the voltage source. The master DG has the responsibility of voltage regulation, and current references for other DGs (slaves) is calculated in a central controller and is distributed to slave DGs via communication links. It is clear that master DG always runs in a voltage control mode and slave DGs operate in current control mode. In this method, as mentioned, communication infrastructure is needed. In case master DG fails, voltage stability is lost and microgrid may fail to continue its operation. A modified algorithm for operation of this method is fully described in [12].

D. Controller Design

In order to design controller using Matlab, it is helpful to use SISOTOOL toolbox. The multi-loop controller is designed step by step; i.e. first inner loop which controls converter-side inductance's current is designed and after achieving appropriate phase- and gain-margin outer loop is designed, in which capacitor's voltage is controlled. Coefficients of controller are found in order to result in good phase- and gain-margin and attain desired bandwidth. The current controller is considered as an approximate resonant controller. The general formulation of this controller is given as follows:

$$G_{PR} = K_p + \frac{2K_I \omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \tag{8}$$

Also in order to increase stability margin of system, lead controller is used as well. Controller block diagram is shown in Fig. 5.

In master-slave power sharing mode, switch shown in Fig. 5 connects to current-mode status (for slave DGs) and this switch stays on voltage-mode status in other two power sharing modes (APS and droop) and also for master DG of master-slave method. Presented controller is a P+Resonant controller which is compensated by a lead and a lag (which are designed in a way that cross-over frequency remains around $1/10 f_s$). A systematic design of controller can be a future research target. One of the possibilities in SISOTOOL is the ability of obtaining output bode diagram for any selected part of the system. In this paper bode diagram of designed multi-loop controller+plant is presented in Fig. 6 to show stability and effectiveness of plant and controller, respectively.

Fig. 6 shows that a good phase- and gain-margin is achieved and system is robustly stable. Cross-over frequency satisfies the aforementioned limits. It is important to consider different criteria in designing LC-filter for controller. One of the important limitations is that resonance frequency of LC-filter should be higher than ten times of grid frequency and lower than half the switching frequency. This criterion and all other necessary ones required for proper LC-filter design are considered in this paper and satisfied after design stage.

IV. Simulation Results

AC- and DC-microgrids with shown configuration and discussed specifications are simulated and predefined scenarios are executed. Results have been obtained and presented in this section. In AC-microgrid a 60 kVA load with 0.86 power factor connects to Load2 at *t*=1s and disconnects

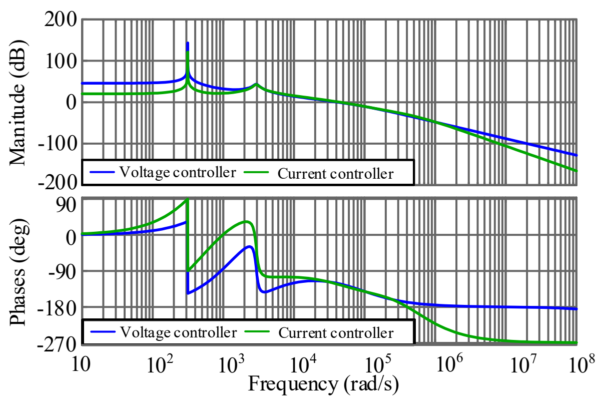

Fig. 6.Bode diagram of AC controller (voltage and current) for AC power sources.

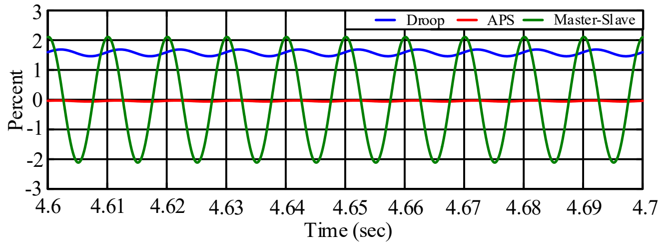

Fig. 7. Steady-state error of different power sharing methods (in percent) for the worst DG (DG1).

again at *t*=1.2s. At *t*=1.4s Load1 disconnects from microgrid. In DC-microgrid at *t*=2s, a 300 W load is added to Load1, at t=3s a 400 W load is added to Load3 and at *t*=4s, Load3 disconnects completely from microgrid.

A. DC-microgrid

Results of simulation for DC-microgrid are shown for three power sharing methods. Fig. 7 shows steady-state power sharing error for worst DG (DG1). Compared to AC-microgrid, in DC-microgrid errors are of way lower ranges. In Fig. 7 it can be seen that APS method has almost zero error of power sharing and excels the other two methods.

In Fig.8 droop power sharing between the two DGs is DC-microgrid shown. The error of droop method is caused by line resistance differences between DG and load. If there was no power sharing method, DG which is closer to a load will take more of the load change when one occurs. APS and master-slave methods for power sharing are shown in Figs. 9 and 10, respectively. It is clear by figures that the controller has a fast and accurate performance, since it follows load changes very quickly and settling time after load changes are very low.

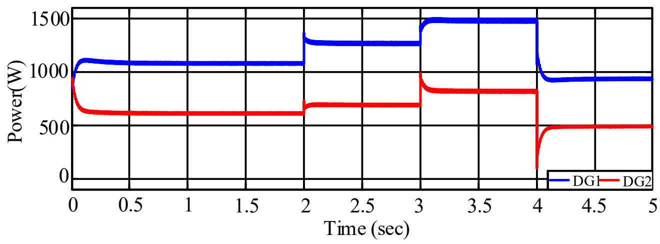

Fig. 8. Power sharing using droop method.

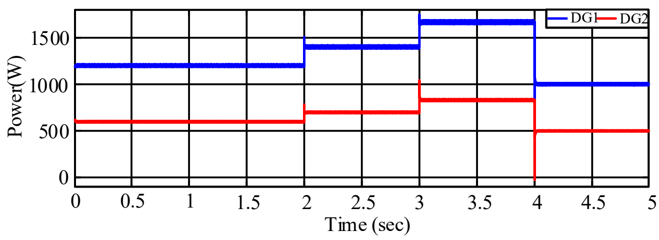

Fig. 9. Power sharing using average power sharing (APS) method.

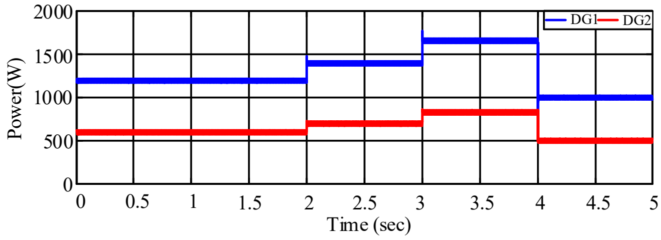

Fig. 10. Power sharing using master-slave method.

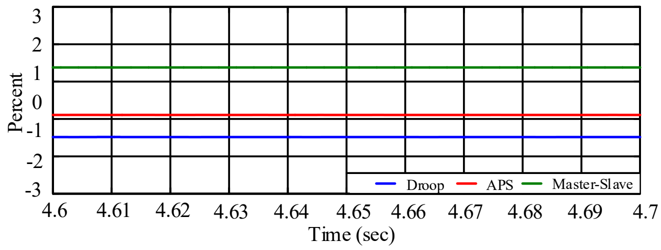

Fig. 11. Steady-state error of different power sharing methods for active power in percent for the worst DG (DG1).

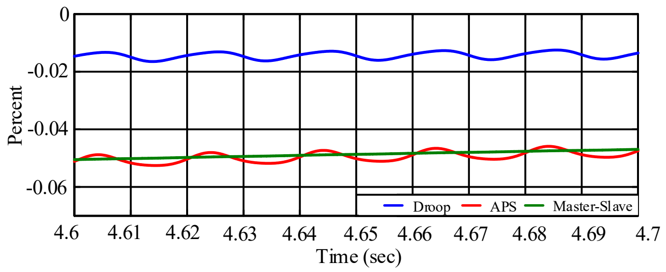

Fig. 12. The steady-state error of different power sharing methods for reactive power in percent for the worst DG (DG1).

B. AC-microgrid

Results obtained from simulations are presented in this part. Steady-state error of three power sharing methods are shown in Fig. 11 for active power in worst DG (DG1). In this figure worst error is produced by master-slave method (about 8.5%) and droop method has the lowest error percentage (6.5%). This amount of error is acceptable for all three methods but as we are to compare these methods, for active power sharing it is concluded that droop method works as best. In Fig. 12 reactive power sharing errors for three methods are shown.

In reactive power sharing almost all three method has achieved zero error and negligible amount of sharing error is caused by proposed methods. So in AC-microgrid, power sharing based on droop has the best result among these three method. Active power sharing for droop, APS, and master-slave method are shown in Figs. 13, 14, and 15 respectively.

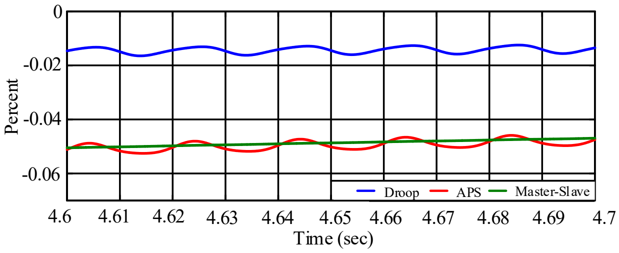

Fig. 13. The steady-state error of different power sharing methods for reactive power in percent for the worst DG (DG1).

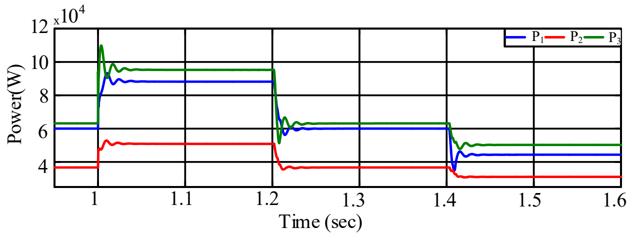

Fig . 14. Active power sharing among DGs using droop method.

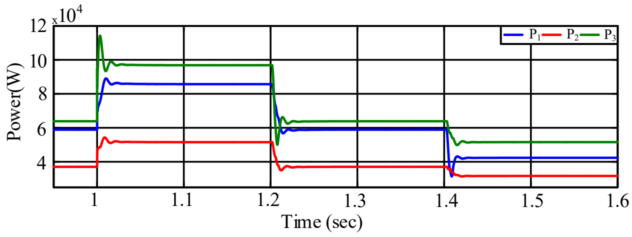

Fig. 15. Active power sharing among DGs using average power sharing (APS) method.

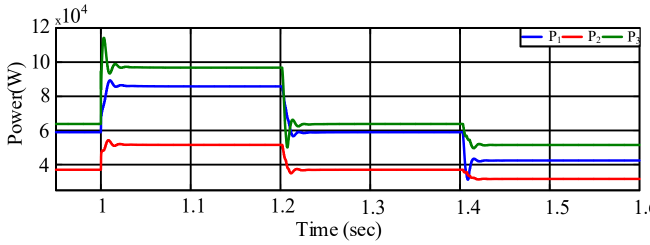

Fig. 16. Active power sharing among DGs using master-slave method.

It is worth noting that when load change occurs, controller has a great performance and quickly traces load changes. By changing load in aforementioned instants, the controller adjusts output power of each DG proportional with its maximum power and compensates the increased/decreased load. Specially in t=1.4s when Load1 disconnects from microgrid, power adjustment is done very quickly and all DGs reach their final value in less than 0.02s.

In Figs. 16, 17, and 18, reactive power sharing by three methods are shown separately for each method. Reactive power sharing has almost zero amount of error and is shared proportional to DG's reactive power ratings. Reactive power sharing has almost zero error so that in figures, reactive graph for DG1 and DG3 completely overlap each other and are seen as one graph. This is clear in all three methods for reactive power.

TABLE IV. COMPARISON OF DIFFERENT FEATURES OF THREE POWER SHARING METHODS IN DC-MICROGRID.

Feautures	**Droop**	**APS**	**Master/Slave**
Accuracy	Moderate	High	Low
Requires Communication	No	Yes	Yes
Dynamic Response	Moderate	Fast	Fast

TABLE V. COMPARISON OF DIFFERENT FEATURES OF THREE POWER SHARING METHODS IN AC-MICROGRID.

Feautures	**Droop**	**APS**	**Master/Slave**
Accuracy	Moderate	Moderate	Low
Requires Communication	No	Yes	Yes
Dynamic Response	Moderate	Moderate	Moderate

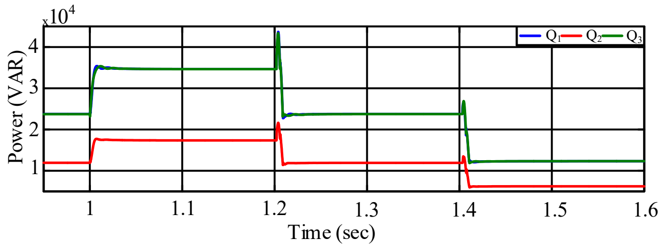

Fig. 17. Reactive power sharing among DGs using droop method.

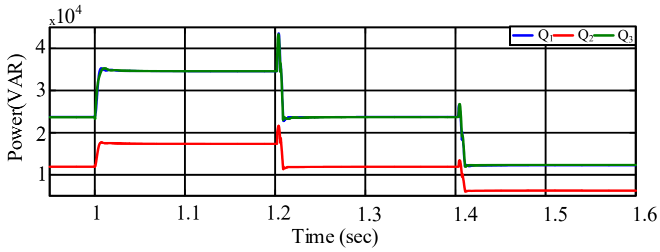

Fig. 18. Reactive power sharing among DGs using average power sharing (APS) method.

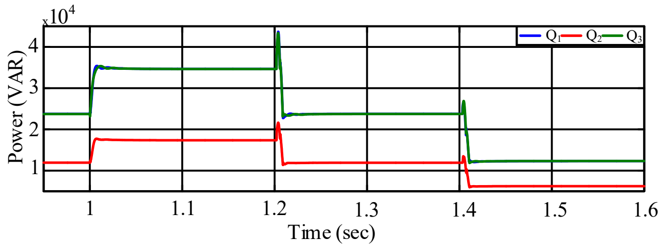

Fig. 19. Reactive power sharing among DGs using master-slave method.

V. Conclusion

In this paper AC- and DC-microgrids have been simulated and three power sharing methods (droop, APS, and master-slave) are compared in each microgrid. Controller for each DG in both microgrids is designed and shown to have a very goodperformance. In Table IV and Table V, different features of three power sharing methods are summarized for DC- and AC-microgrid, respectively. Results are obtained and by comparison it was revealed that in AC-microgrid the best method for active power sharing is droop power sharing. Also for reactive power sharing in AC-microgrid no remarkable error was observed by three methods and all methods had almost zero error of reactive power sharing, however droop method again had the best results with its error so much closer to zero. In DC-microgrid the results show that APS method works best and has lower error of power sharing compared to other two power sharing methods (droop and mater-slave).

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