

# A New Sliding Mode-Based Power Sharing Control Method for Multiple Energy Sources in the Microgrid under Different Conditions

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A single-phase distributed generation (DG) sources embedded in three-phase microgrids develop with a fast-paced trend, it is important to make use of suitable power sharing strategies among multiple DGs and utilizing the power generation of these units to the full capacity. This paper presents an innovative sliding mode-based power control strategy for microgrids. The multi-bus microgrid consists of three-phase DG units that are two photovoltaic (PV) array, and three single-phase DG units including PV, battery and fuel cell (FC). The dynamic modeling of all DGs is based on voltage source inverter (VSI). One of the three-phase DGs is responsible for frequency and voltage control, and the other one for current control. The single-phase DGs are controlled based on the three-phase DGs. Finally, the voltage and power control operations are implemented in a per-unit system. The proposed control strategy has a fast response and the ability to trace a reference signal with a low steady-state error compared with the PI controller; moreover, it provides the accurate active and reactive power sharing among energy units under various faults and loading conditions along with robustness against the microgrid parameters. Additionally, the ability to maintain the dc-link voltage and frequency constant is another feature of this controller.

## Article Info

### Keywords:

Power Sharing Control, Sliding Mode,  
Distributed Generations, Microgrid.

### Article History:

Received 2018-03-09

Accepted 2018-08-15

## NOMENCLATURE

|           |                                       |
|-----------|---------------------------------------|
| $I_{ph}$  | Photocurrent                          |
| $I_{sat}$ | Module reverse saturation current     |
| $I_{sso}$ | Short current                         |
| $Q$       | Electron charge                       |
| $K$       | Boltzman constant                     |
| $A$       | Ideality factor                       |
| $T$       | Surface temperature of PV cell        |
| $R_p$     | Parallel resistance of a PV cell      |
| $R_s$     | Series resistance of a PV cell        |
| $k_i$     | Short circuit temperature coefficient |
| $T_r$     | Reference temperature                 |
| $I_{rr}$  | Reverse saturation current at $T_r$   |
| $E_{gap}$ | Energy of the band gap for silicon    |
| $n_p$     | Number of cells in parallel           |
| $n_s$     | Number of cells in series             |
| $S$       | Solar radiation level                 |
| $V_{oc}$  | Rated open circuit voltage            |
| $E_0$     | Free reaction voltage                 |
| $F$       | Faraday's constant                    |
| $N_0$     | Number of series connected cells      |
| $r$       | Ohmic resistance                      |
| $R$       | Universal gas constant                |
| $I_{fc}$  | FC output current                     |
| $Q$       | Battery capacity                      |
| $B$       | Exponential capacity                  |

|            |                                                      |
|------------|------------------------------------------------------|
| $K$        | Polarization voltage                                 |
| $V_0$      | Open circuit voltage of the battery                  |
| $R_b$      | Internal resistance of the battery                   |
| $i_b$      | Battery charging current                             |
| $u$        | Input signal of controller                           |
| $U_i$      | VSI output voltage                                   |
| $V_f$      | Capacitor voltage                                    |
| $I_{Lf}$   | Inductive current                                    |
| $I_{Cf}$   | Output current of the capacitor                      |
| $I_o$      | Output current of the filter                         |
| $V_{dc}$   | DC link voltage                                      |
| $x$        | System state vector                                  |
| $\lambda$  | Positive number                                      |
| $\eta$     | Positive number                                      |
| $\eta_c$   | Constant positive number                             |
| $I_{max}$  | Maximum producible current of inverter-based DG unit |
| $I_{load}$ | Load current                                         |

## I. INTRODUCTION

Rapid growth of demand for fossil fuels such as coal, petroleum, and natural gas moves the world towards a general tendency for the power generation through developing Renewable Energy Source (RES) units [1-3]. The need for improving the reliability and power support in electrical grid along with a high demand for energy are becoming a major challenge encountered by modern power networks. In the last decade, the growing number of consumers in the demand

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management system needs a wide range of infrastructures such as large power plants and distributed generation (DG) units [4].

Microgrid is a new concept consisting of RES units, energy storage (ES) devices, DG units and loads. A microgrid is basically an active distribution grid, which can be operated in two operating modes, i.e., grid-connected and islanded modes [5]. In the grid-connected mode of operation, the microgrid is connected to the main grid at the point of common coupling (PCC), and the important task of each DG is to produce pre-determined values of real and reactive powers [6]. In the islanded mode of operation, the microgrid is separated from the main grid, and in order to maintain the stability of frequency, the power exchange among energy units must be balanced [7].

Renewable energy source units, such as wind, PV, etc., are highly unpredictable, intermittent in nature and sensitive to weather conditions. These units cannot provide the constant power conditions and guarantee the load demand continuously. Therefore, these units require integration with the ES devices, and this combination is called a hybrid power system (HPS) [8]. For reliable operation of a microgrid, the balance of power between production and consumption should be maintained instantaneously. Therefore, the power sharing is a challenge in the presence of RES units, ES devices and load demands. Many works have been dedicated to power management in the multiple DGs-based microgrids for various operating modes.

The performance of energy resources including SC, FC, and PV for islanded microgrids has been studied in [9] under unbalanced and nonlinear loading; however, the proposed method is not very effective for power control among DG units. Also, the DG units and loads are all three-phase, and the single phase DG units and single-phase loads not intended. In order to adjust the dc voltage, a fuzzy controller based on flatness feature is expressed in [10] for an autonomous system containing of PV, FC, and SC. The proposed control strategy is only for the three-phase DG units in the microgrid, and cannot be implemented for single-phase DG units. Also, the problems of active power sharing have been studied, but the reactive power sharing has not been evaluated. In [11], a centralized coordination control method is applied to proper power transfer between AC and DC buses. Although centralized control approaches have a higher controllability and predictability than decentralized ones, their response speed and reliability are much less. Therefore, the inappropriate performance of controller can lead to a complete network failure.

Droop method is a known approach for power management control in microgrids that include several energy generation units. In [12], a reactive power sharing approach based on hierarchical droop control method is developed. Although the droop controller does not require any communication link

between the DG units, this method can lead to system instability in conditions that the droop characteristics has small slopes [13]. Also, in this method to suitable power sharing among the DGs in the microgrid, the voltage and frequency deviate from their nominal value. A two-level structure based on multi-agent control is considered in [14] for the energy management of a microgrid that includes multiple DG units. In [15], a grid-connected microgrid is considered that includes wind, gas engine system, PV arrays, and battery storage energy unit. This microgrid supplies the power needed for electric loads. The energy management method creates a precise balance between the consumed and produced powers. In [16], an AC grid-connected microgrid is proposed that contains PV units as main sources and the battery banks as energy storage units. All energy resources are connected to the AC grid by the interfacing inverters. A central control method for energy management is designed that controls the real and reactive power of units. To real power sharing among distributed resource units in [17] an autonomous control method has been raised, in which reactive power sharing is not evaluated. In [18], a PV array, a diesel generator, and a battery bank in the microgrid are connected to the AC grid in order to support the loads within the microgrid. Moreover, in this structure, another battery bank and PV array are employed to supply power for communication and monitoring systems. Residential service is provided by three parallel battery units using droop control approach in which network frequency is applied as communication signal. Moreover, some other researches have considered the power management based on: H-infinite [19], fuzzy logic [20], network [21], Model Predictive [22], and multi-agent [23] strategies.

In particular, faults in general and short-circuit currents are the very severe operating conditions in distribution networks [24]. Different researches are discussed under the concept of transient stability subsequent to the fault event condition [25-26]. In [27], a fault analysis approach for inverter-interfaced DG units is expressed. This approach is used to estimate the initial high current that an inverter interfaced DG unit under voltage control strategy can inject during the first cycle of fault. In [28] considers a direct building method for energy sources-based microgrid during fault analysis. A novel scheme is attempted in [29] to improve microgrid performance under fault conditions with battery units. However, this scheme has some limitations for a sustainable operation; that is, the remaining storage energy of battery unit should be zero.

The control approaches mentioned in many of the pervious works suffer from some problems, such as: being inappropriate for multi-bus microgrids and complex, voltage and frequency instability, dependence on communication links, unsuitable power sharing under different faults, slow dynamic response, requiring additional control loops and

dependence on system parameters.

Sliding Mode Control (SMC) is a robust control method for nonlinear systems with variable-structure that does not require a lot of computational operations, and has little sensitivity to variations in system parameters. Additionally, the SMC approach applies a special version of on-off control, which its functional behavior provides relative immunity against external disturbances [30]. In [31], a SMC-based direct approach for the voltage control of microgrid based on converters is proposed in which the output controller due to chattering phenomena is very weak. In [32], an SMC method is proposed that contains an inner SMC for the voltage and current stability, and an outer voltage control loop to reduce the tracking error; however, application of the control method only for a single-phase inverter is implemented.

It should be noted that the aforementioned works have been often limited to the microgrid based on three-phase DGs, and few researches have been done on power sharing and control in the microgrid based on single-phase DGs. In addition, due to the aforementioned issues and some disadvantages of the SMC approach, this study presents a new reactive and real power sharing control method for multiple DG units based multi-bus microgrid. The battery, FC, and photovoltaic array are considered as the three-phase and single-phase inverter-based DGs in the microgrid. The proposed power sharing control approach is based on a new SMC, which can regulate the voltage, frequency and power components of the DGs based on inverter. In addition, the proposed approach is robust, has a high-speed response compared to the conventional PI controller and is stable under different faults and loading conditions.

## II. MICROGRID STRUCTURE

The single-line diagram of the multi-bus microgrid is illustrated in Fig. 1. The microgrid contains two DG units based on voltage source inverter (VSI), which include three-phase PV arrays (DG<sub>1</sub> and DG<sub>2</sub>). Moreover, three DG units based on VSI that consist of single-phase energy storage battery unit (DG<sub>3</sub>), fuel cell unit (DG<sub>4</sub>) and PV unit (DG<sub>5</sub>) are included. The single-phase DG units are connected to phase-A, B, and C. The DG units provide almost a constant DC-bus voltage for the inverter. The loads are modeled as constant-impedance, where L<sub>3</sub>, L<sub>4</sub>, and L<sub>5</sub> are single-phase loads, while L<sub>1</sub> and L<sub>2</sub> are three-phase loads. The single-phase loads are in the vicinity of the single-phase DG units. The loads are fed through three radial feeders, and the DGs supply feeders. Under a normal state, the entire microgrid system is in a balanced state. All information about the microgrid parameters and DG units are given in Tables I, II, and III.

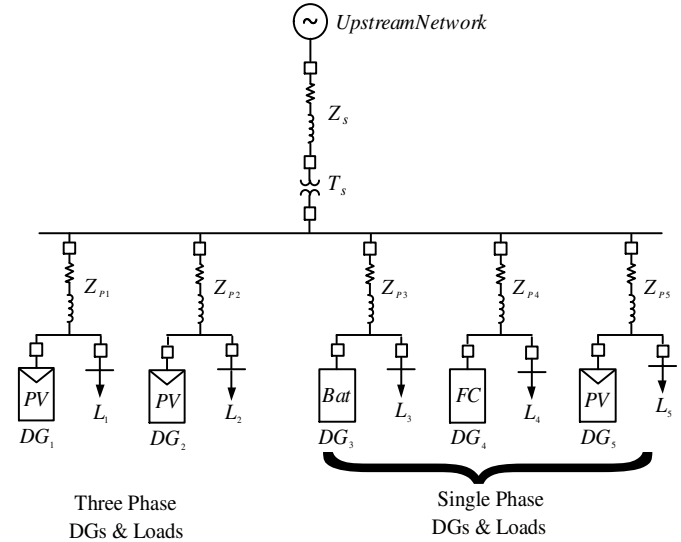


Fig. 1. Single-line schematic diagram of the grid-connected microgrid.

TABLE I.  
THE GRID PARAMETERS

| Parameter             | Value       |
|-----------------------|-------------|
| Nominal Voltage (max) | 400 V AC    |
| Nominal frequency     | 50 Hz       |
| Inverter Rating       | 1000 kW     |
| R                     | 12.62 m ohm |
| L                     | 0.27 mH     |

TABLE II.  
THE MICROGRID PARAMETERS

| Quantity                  | Value                                                    |
|---------------------------|----------------------------------------------------------|
| Line                      |                                                          |
| Base value                | $S_{base}=100 \text{ kVA} - V_{base}=400 \text{ V}_{ac}$ |
| Upstream network          | $S=1 \text{ MVA} - V=20 \text{ KV} - X/R=11$             |
| $Z_s$                     | $0.275 + j 0.346 \text{ pu}$                             |
| $T_s$                     | $1\text{MVA} - 0.4/20 \text{ kV}$                        |
| $Z_{p1}$                  | $0.012 + j 0.032 \text{ pu}$                             |
| $Z_{p2}$                  | $0.023 + j 0.036 \text{ pu}$                             |
| $Z_{p3}$                  | $0.045 + j 0.051 \text{ pu}$                             |
| $Z_{p4}$                  | $0.045 + j 0.051 \text{ pu}$                             |
| $Z_{p5}$                  | $0.045 + j 0.051 \text{ pu}$                             |
| $V_{dc}$                  | 650 V                                                    |
| $V_{ac}$                  | 400 V                                                    |
| Frequency                 | 50 Hz                                                    |
| Three Phase DGs and Loads |                                                          |
| DG <sub>1</sub>           | 80 kW, 40 kVAR                                           |
| DG <sub>2</sub>           | 160 kW, 80 kVAR                                          |
| L <sub>1</sub>            | 30 kW, 15 kVAR                                           |
| L <sub>2</sub>            | 30 kW, 15 kVAR                                           |

TABLE II (continued)

| Single Phase DGs               |             |                   |
|--------------------------------|-------------|-------------------|
| DG <sub>3</sub>                | Battery @ A | 60 kVA, cos φ=0.9 |
| DG <sub>4</sub>                | FC @ B      | 60 kVA, cos φ=0.9 |
| DG <sub>5</sub>                | PV @ C      | 80 kVA, cos φ=0.9 |
| Single Phase Loads (Symmetric) |             |                   |
| L <sub>3</sub>                 |             | 20 kW, 10 kVAR    |
| L <sub>4</sub>                 |             | 20 kW, 10 kVAR    |
| L <sub>5</sub>                 |             | 20 kW, 10 kVAR    |

TABLE III.

THE DG UNITS PARAMETERS

| Quantity                                                                         | Value            |
|----------------------------------------------------------------------------------|------------------|
| parameters of PV array                                                           |                  |
| Number of Series-Connected Modules per String                                    | 12               |
| Number of Parallel Strings                                                       | 80               |
| Number of Cells per Module                                                       | 96               |
| Open Circuit Voltage                                                             | 642.2 V          |
| Short-Circuit Current                                                            | 5.96 A           |
| Diode Quality Factor                                                             | 1.25             |
| Parallel Resistance                                                              | 1723 ohm         |
| Series Resistance                                                                | 0.0101 ohm       |
| Forward Voltage of Diode                                                         | 0.8 V            |
| parameters of Battery unit                                                       |                  |
| Nominal Voltage                                                                  | 48 V             |
| Rated Capacity                                                                   | 86 Ah            |
| Initial State-Of-Charge                                                          | 64 %             |
| Internal Resistance                                                              | 0.012 ohm        |
| Full Charged Voltage                                                             | 55.87 V          |
| Number of Series-Connected Modules per String                                    | 14               |
| Number of Parallel Strings                                                       | 52               |
| parameters of SOFC unit                                                          |                  |
| Voltage at 0 Amper                                                               | 52.2 V           |
| Voltage at 1 Amper                                                               | 52.46 V          |
| Nominal Operating Point (I <sub>rated</sub> , V <sub>rated</sub> )               | (250 A, 41.15 V) |
| Number of Cells                                                                  | 125              |
| Number of Parallel Strings                                                       | 26               |
| Operating Temperature                                                            | 318 K            |
| Nominal Air Flow Rate                                                            | 732 lmp          |
| Nominal Supply Pressure of Fuel                                                  | 1.16 Bar         |
| Nominal Supply Pressure of Air                                                   | 1 Bar            |
| SOFC Resistance                                                                  | 0.024 ohm        |
| SOFC Response Time                                                               | 1 second         |
| Nominal Composition of Fuel (H <sub>2</sub> , O <sub>2</sub> , H <sub>2</sub> O) | (95.95, 21, 1)   |

### III. MATHEMATICAL MODELING AND DESCRIPTION OF ENERGY SOURCES

#### A. Modeling of a PV unit with MPPT Algorithm

Fig. 2 shows the circuit model of a PV unit. The current output of the PV unit is obtained by dynamic equations as follows [33]:

$$I_{pv} = n_p I_{ph} - n_p I_{sat} \times \left[ \exp\left(\frac{q}{AkT}\right) \left( \frac{V_{pv}}{n_s} + I_{pv} R_s \right) - 1 \right] \quad (1)$$

$$I_{ph} = (I_{sso} + k_i (T - T_r)) \cdot \frac{S}{1000} \quad (2)$$

$$I_{sat} = I_r \left( \frac{T}{T_r} \right)^3 \exp\left(\frac{qE_{gap}}{kA}\right) \cdot \left( \frac{1}{T_r} - \frac{1}{T} \right) \quad (3)$$

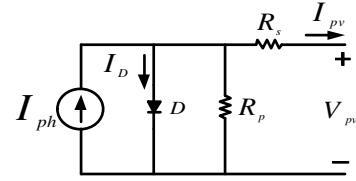


Fig. 2. Equivalent circuit model of a PV array.

Although a photovoltaic array has many benefits in energy production, its efficiency depends on some environmental effects such as temperature, radiation level, shading and the amount of dirt, which is very low. Therefore, the maximum power (MP) transmission of the PV array is essential. In this paper, to reach the available MP point tracking, the incremental conductance (IC) [34] approach is employed, in which the subject of tracking MP is resolved under rapidly changing atmospheric condition. The IC approach is based on the fact that the slope of the PV array power is zero at the MP point, positive on the left of the MP point and negative on the right.

#### B. Modeling of a Solid Oxide Fuel Cell (SOFC) Unit

The considered dynamic model of the SOFC is based on the relationship between the terminal voltage of FC ( $V_{fc}$ ) and the partial pressures of water, hydrogen and oxygen ( $P_{H_2O}$ ,  $P_{H_2}$  and  $P_{O_2}$ ), respectively [35]. The output voltage of SOFC is determined in accordance with the Nernst's equation and Ohm's law as follows:

$$V_{fc} = N_0 \left[ E_0 + \frac{RT}{2F} \left( \ln\left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}}\right) \right) \right] - r I_{fc} \quad (4)$$

#### C. Modeling of a Battery Unit

In order to show the battery energy storage model, two significant parameters are considered that consist of the terminal voltage ( $V_b$ ) and the state of charge (SOC) as follows [36]:

$$V_b = V_0 + R_b i_b - K \frac{Q}{Q + \int i_b dt} + A \cdot \exp(B \int i_b dt) \quad (5)$$

$$SOC = 100 \left( 1 + \frac{\int i_b dt}{Q} \right) \quad (6)$$

### IV. DYNAMIC MODELING OF INVERTER BASED MICROGRID

In the studied microgrid in Figure 1, DG<sub>1</sub> and DG<sub>2</sub> are three-phase DG units based on the voltage source inverter (VSI) in the microgrid, which DG<sub>3</sub> as a frequency and voltage control resource is responsible for adjusting the

voltage of the microgrid in accordance with the voltage reference signal. Additionally, DG<sub>1</sub> has considered as a power control resource, which operates based on the current reference signal and provides a certain amount of load power until its maximum capacity. It is assumed that the load currents are measurable. In order to control the single-phase DG units based on VSI (DG<sub>3</sub>, DG<sub>4</sub> and DG<sub>5</sub> resources), their current and voltage references are received from its corresponding phase of the current and voltage control units (DG<sub>2</sub> and DG<sub>1</sub> sources), respectively. After determining the power and voltage references, the single-phase controllers in the per-unit system perform the power control by using the proposed control method based on the new SMC.

A three-phase inverter-based DG unit with an output LC filter is shown in Figure 3(a). For simplicity, at first, the modeling of single-phase inverter is described, and then, the equations are developed for the three-phase inverters. It is considered that the structures of all phases in three-phase inverters are similar to each other. Figure 3(b) illustrates the model of a single-phase inverter [37].

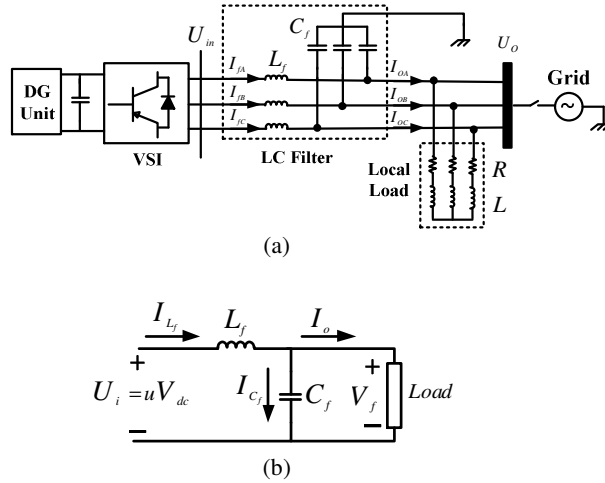


Fig. 3. (a)- Configuration of three-phase inverter system with LC filter, and (b)- the single-phase equivalent circuit of inverter.

According to Fig. 3(b), the state space equations of the single-phase inverter can be written as:

$$L_f \frac{dI_{L_f}}{dt} + V_f = U_i = uV_{dc} \quad (7)$$

$$I_{L_f} = I_{C_f} + I_o, \quad I_{C_f} = C_f \frac{dV_f}{dt} \quad (8)$$

According to (7) and (8), we have:

$$\frac{d}{dt} \begin{bmatrix} V_f \\ I_{L_f} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{L_f} & 0 \end{bmatrix} \begin{bmatrix} V_f \\ I_{L_f} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{V_{dc}}{L_f} \end{bmatrix} u + \begin{bmatrix} -\frac{I_o}{C_f} \\ 0 \end{bmatrix} \quad (9)$$

where state variables are capacitor voltage and inductive current.

## V. THE PROPOSED CONTROL STRATEGY FOR DG UNITS BASED ON SLIDING MODE

### A. Sliding Mode Control Method

Sliding mode control (SMC) is a variable structure approach, in which the controller output is the system state variables [38]. Some of the important benefits of SMC are its robust stability against load, suitable dynamic response and easy implementation. The  $n$ th order model of the system is considered by the SMC, which can be expressed as:

$$\dot{x}^{(n)} = f(x) + g(x)u + \delta(x) \quad (10)$$

where  $\delta(x)$  is the system disturbance and can be attributed to noises and/or load variation. In order to track a reference signal in SMC strategy, a sliding surface based on the system order should be defined. In this paper, state space equation of the system is considered to be of first or second order; thus, these kinds of sliding surfaces are defined as follows.

The sliding surface ( $s$ ) of the first-order system based on the error between reference signal ( $x_{ref}$ ) and output ( $x$ ) can be defined as:

$$S = x - x_{ref} \quad (11)$$

The purpose of the control strategy is to minimize the tracking error from reference signal. Therefore, the derivative of  $s$  must be equal to zero:

$$\begin{aligned} \dot{S} = 0 &\rightarrow \dot{x} - \dot{x}_{ref} = f(x) + g(x)u + \delta(x) - \dot{x}_{ref} = 0 \rightarrow \\ u_{eq} &= g^{-1}(x)[-f(x) - \delta(x) + \dot{x}_{ref}] \end{aligned} \quad (12)$$

If the error between reference signal and output is defined as  $\tilde{x} = x - x_{ref}$ , then the sliding surface of the second-order system can be expressed as:

$$S = \dot{\tilde{x}} + \lambda \tilde{x} \quad (13)$$

If  $\dot{S}$  is equal to zero, we have:

$$\begin{aligned} \dot{S} = 0 &\rightarrow \ddot{\tilde{x}} - \ddot{x}_{ref} + \lambda \dot{\tilde{x}} = 0 \rightarrow \\ f(x, \dot{x}) + g(x)u + \delta(x) - \ddot{x}_{ref} + \lambda \dot{\tilde{x}} &= 0 \\ \rightarrow u_{eq} &= g^{-1}(x)[-f(x, \dot{x}) + \ddot{x}_{ref} - \delta(x) - \lambda \dot{\tilde{x}}] \end{aligned} \quad (14)$$

In order to have a robust controller against external disturbances, the control law can be obtained as:

$$u = u_{eq} - k \text{sign}(S) \quad (15)$$

In order to verify stability of the defined control law, a Lyapunov function ( $V(x)$ ) must be considered; if the time derivative of the Lyapunov function ( $\dot{V}(x)$ ) is definitely negative, the control strategy is stable. Thus, we have:

$$\dot{V}(x) = \frac{1}{2} \dot{S}^2 \rightarrow \dot{V}(x) = S \dot{S} < -\eta |S| \quad (16)$$

### B. Voltage-Frequency Controller

In this stage, for the voltage and frequency control, the voltage error can be written as:

$$x_1 = V_f - V_{ref} \quad (17)$$

$$\dot{x}_2 = \frac{d}{dt} x_1 = \frac{d}{dt} (V_f - V_{ref}) = \frac{1}{C_f} I_{C_f} - \frac{d}{dt} V_{ref} \quad (18)$$

The reference signal ( $V_{ref}$ ) can be expressed as:

$$V_{ref} = V_m \sin(\omega t) \quad (19)$$

Based on (17) and (18), equation (9) can be rewritten as:

$$\frac{d}{dt} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{L_f C_f} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{V_{dc}}{L_f C_f} \end{bmatrix} u + \begin{bmatrix} 0 \\ D(t) \end{bmatrix} \quad (20)$$

$$D(t) = -\frac{1}{C_f} \frac{dI_0}{dt} - \frac{1}{L_f C_f} V_{ref} - \frac{d^2}{dt^2} V_{ref}$$

According to (21), the state-space equation of the system is of second order; therefore, the switching surface can be obtained as:

$$S = \lambda x_1 + x_2, \quad \lambda > 0 \quad (21)$$

Moreover, the sliding surface is obtained and set to zero so that the equivalent control is determined as:

$$\frac{d}{dt} S = 0 \rightarrow u_{eq} = \frac{L_f C_f}{V_{dc}} [-\lambda x_2 + \frac{1}{L_f C_f} x_1 - D(t)] \quad (22)$$

As a result, the control law can be expressed as:

$$u = u_{eq} - K_v \times \text{sign}(S) \quad (23)$$

In order to assess the stability, the Lyapunov function can be defined as:

$$V = \frac{1}{2} S^2 \quad (24)$$

the stability can be achieved if  $\dot{V} < 0$ , therefore, we have:

$$\dot{V} = S \dot{S} < -\eta \rightarrow K_v > \frac{L_f C_f}{V_{dc}} \eta \quad (25)$$

in which  $\eta$  is the term of maximum disturbance of  $D(t)$  and  $|D(t)| \leq \eta$ .

### C. Current Controller

In this stage, the current control strategy will be designed. According to the output current, equations (8) and (9), the state space of system is first order. Therefore, the system model can be written as:

$$\frac{d}{dt} I_0 = -\frac{1}{L_f} V_f + \frac{V_{dc}}{L_f} u - \frac{d}{dt} I_{C_f} \quad (26)$$

furthermore, the sliding surface can be expressed as:

$$S = I_0 - I_{ref} \quad (27)$$

then, by setting  $S$  equal to zero, the equivalent control can be obtained as:

$$\frac{d}{dt} S = 0 \rightarrow u_{eq} = \frac{L_f}{V_{dc}} \left( \frac{1}{L_f} V_f + \frac{d}{dt} I_{C_f} + \frac{d}{dt} I_{ref} \right) \quad (28)$$

As a result, the current control law can be expressed as:

$$u = u_{eq} - K_s \times \text{sign}(S) \quad (29)$$

To keep stability, the Lyapunov function proposed in (24) is employed to determine the boundaries of the parameter  $K_s$

$$K_s > \frac{L_f}{V_{dc}} \eta_s \quad (30)$$

The DG unit has constraints for generation power; therefore, the reference current signal magnitude must be limited [39]. Equation (31) indicates the limitation on the reference current. It is necessary to mention that a percentage of the load current is dedicated to the reference current signal. The considered formulation can be expressed as:

$$\begin{aligned} \text{if } |I_{load}| \leq I_{max} &\rightarrow \text{then } I_{ref} = I_{load} \\ \text{if } |I_{load}| > I_{max} &\rightarrow \text{then } I_{ref} = \frac{I_{load}}{|I_{load}|} I_{max} \end{aligned} \quad (31)$$

The block diagram of the proposed control strategy for DG units in the islanded microgrid is shown in Figure 4.

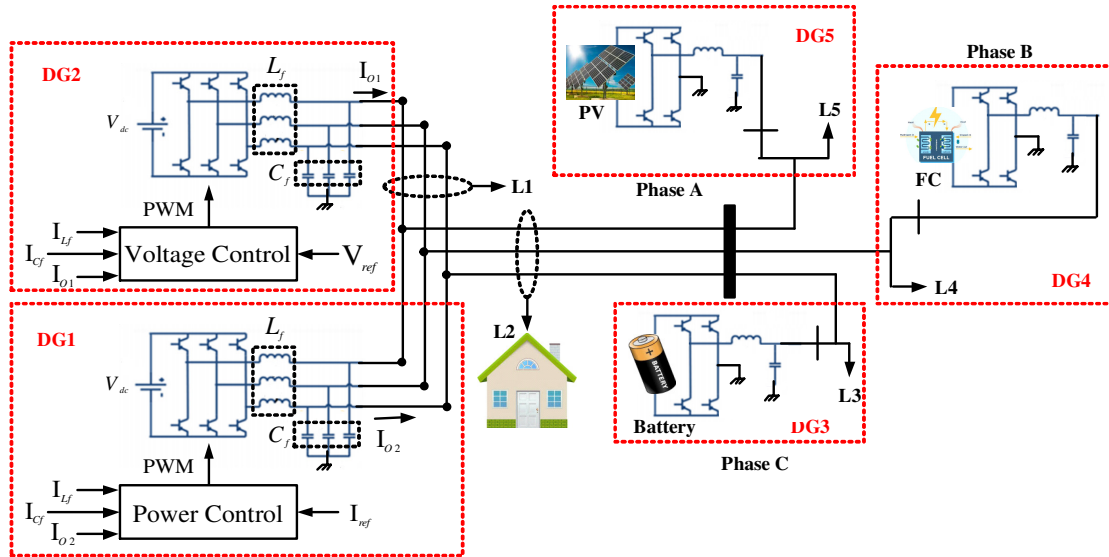


Fig. 4. The studied microgrid containing of three-phase and single-phase DG units with the control strategy.

## VI. SIMULATION RESULTS

To demonstrate the appropriateness of the proposed power sharing and control strategy, the performance of islanded AC microgrid has been studied in Matlab/Simulink environment under various scenarios, including balanced loading conditions and different types of faults.

### A. Operation under Balanced Load Conditions

In this case study, until  $t=1$  s, the loads  $L_2$  to  $L_5$  are located in the microgrid. The total reactive and active demands of all these loads are 45 kVAR and 90 kW, respectively. Power management between the three-phase and single-phase has been conducted balancedly, so that the share of each of single-phase DG units is equal to 10 kVAR and 20 kW. At  $t=1$  s, the three-phase load  $L_1$  with a demand of 20 kVAR and 40 kW is added to the microgrid, and as expected, the power sharing is performed according to the generation capacity of the three-phase DG units. At  $t=2$  s, the three-phase load  $L_1$  is removed from the microgrid and it goes to normal conditions.

During the time interval  $t=1$  s to  $t=2$  s that  $L_1$  is in the microgrid, the share of power production of each of single-phase DG units is enhanced to 5 kW. Each of the single-phase DG units including  $DG_3$ ,  $DG_4$  and  $DG_5$  feeds its local load, independently. Therefore, it is expected that all consumption of single-phase loads is supplied by these units. In figures 5, 6 and 7 the active and reactive powers of single-phase DG units such as: battery, FC and PV are illustrated, respectively. It is noteworthy that the response of the proposed control method is faster than the conventional PI controller. Also, the steady-state error is reduced.

Fig. 8 demonstrates the generated active and reactive power of the three-phase DG sources ( $DG_1$  and  $DG_2$ ). As it is seen, the proposed control method has a suitable performance compared to the PI controller.

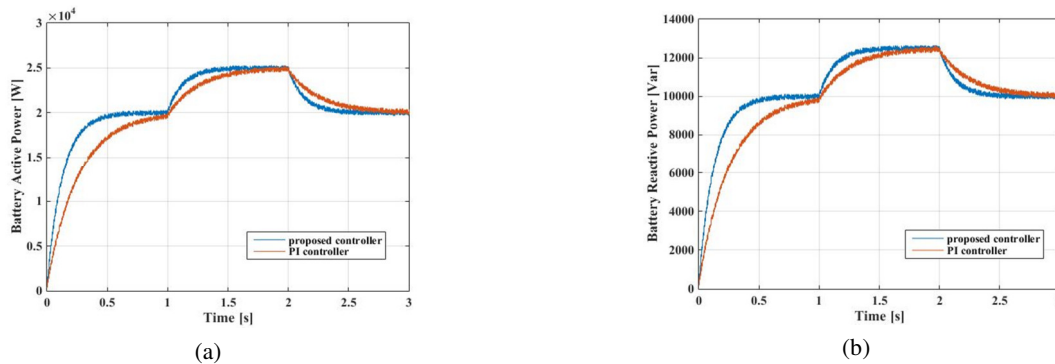


Fig. 5. Dynamic response and comparison between proposed and PI controller of single-phase DGs in balanced load conditions: (a)- Active power output of battery unit ( $DG_3$ ), (b)- Reactive power output of battery unit ( $DG_3$ ).

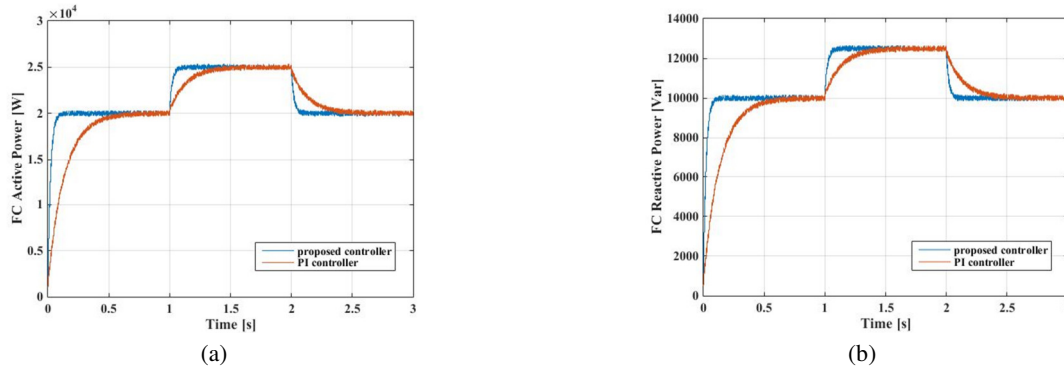


Fig. 6. Dynamic response and comparison between proposed an PI controller of single-phase DGs in balanced load conditions: (a)- Active power output of FC unit (DG<sub>4</sub>), (b)- Reactive power output of FC unit (DG<sub>4</sub>).

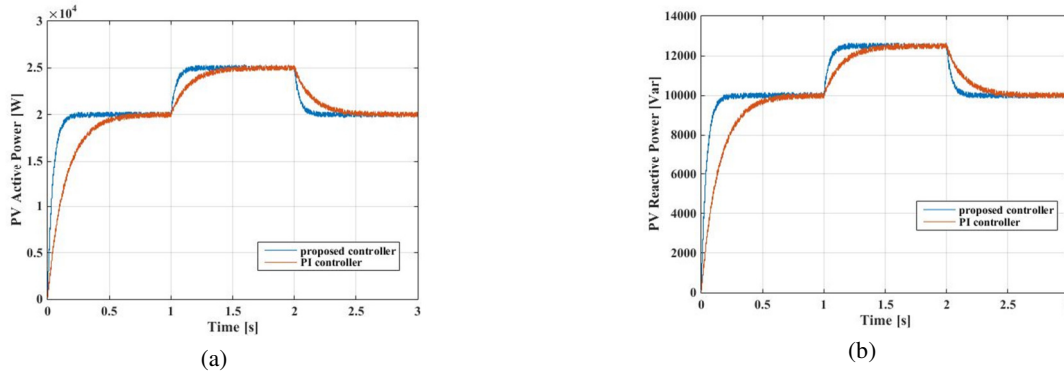


Fig. 7. Dynamic response and comparison between proposed an PI controller of single-phase DGs in balanced load conditions: (a)- Active power output of PV unit (DG<sub>5</sub>), (b)- Reactive power output of PV unit (DG<sub>5</sub>).

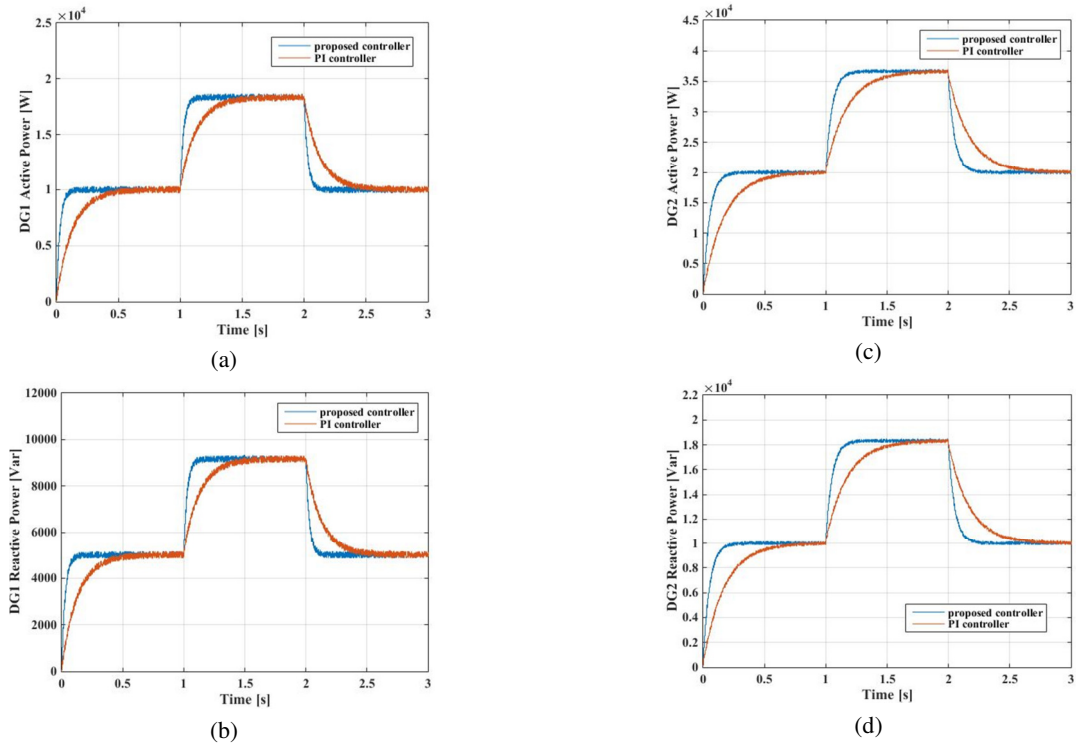


Fig. 8. Dynamic response and comparison between proposed and PI controller of three-phase DGs in balanced load conditions: (a)- Active power output of DG<sub>1</sub>, (b)- Reactive power output of DG<sub>1</sub>, (c)- Active power output of DG<sub>2</sub>, (d)- Reactive power output of DG<sub>2</sub>.

### B. Operation under Types of Faults

#### Single Line-to-Ground (L-G) Short Circuit Fault

It is assumed that the L-G fault occurs at the point of common coupling (PCC) during the time interval  $t=1$  s to  $t=2$  s. An L-G fault occurs in one of the phases and no change can be seen in other phases. Therefore, it is expected that output power of single-phase photovoltaic and battery units do not

experience much changes. Fig. 9 shows the active and reactive powers of single-phase and three-phase DG units. Because only the output power of one phase is zero, in the three-phase DG units at the time of L-G fault, their active and reactive output powers are two-thirds the values in the absence of fault.

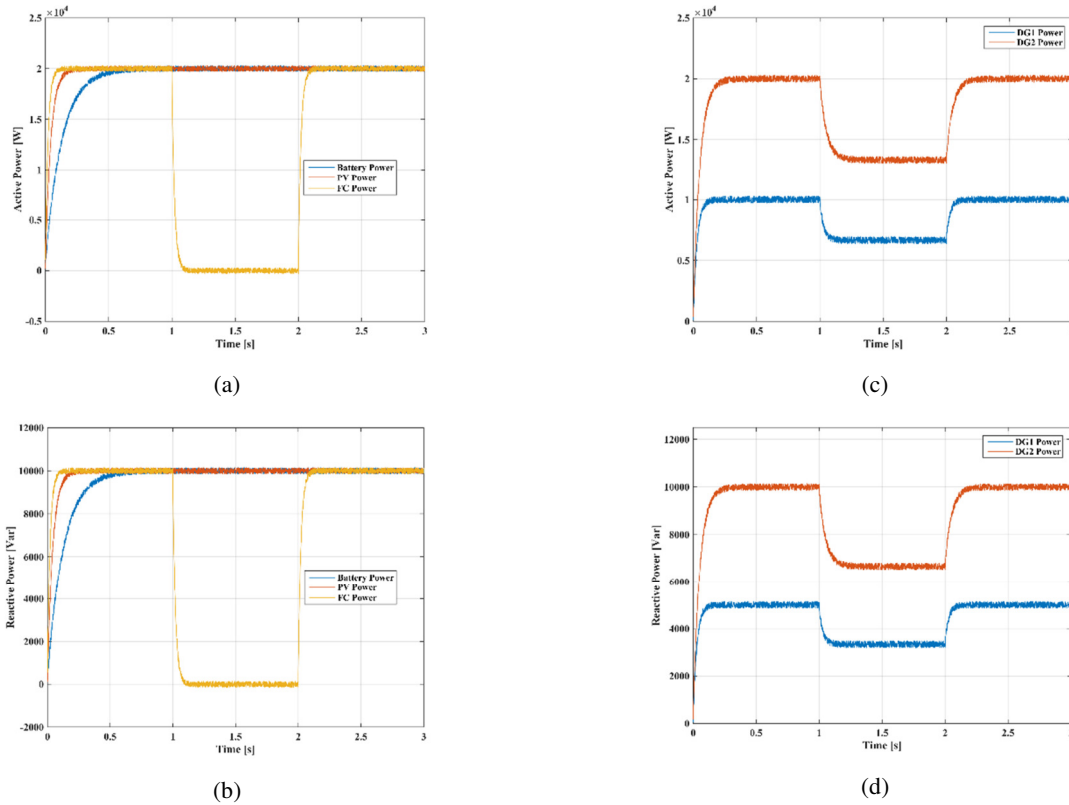


Fig. 9. (a)- Active power output of the single-phase DGs, (b)- Reactive power output of the single-phase DGs, (c)- Active power output of the three-phase DGs, and (d)- Reactive power output of the three-phase DGs under L-G fault conditions.

#### Double Line-to-Ground (L-L-G) Short Circuit Fault

Similar to previous state, an L-L-G fault occurs in phases involving the single-phase PV and FC units at the PCC. At the time of L-L-G fault, the phase that includes battery unit will not change. Fig. 10 illustrates the active and reactive output powers of single-phase and three-phase DG units.

Because the output power of the two phases is zero, in three-phase DG units at the time of the fault, their active and reactive output powers are one-third the values when the fault does not exist. After removing the fault, the power sharing among DGs is performed according to the pre-fault state.

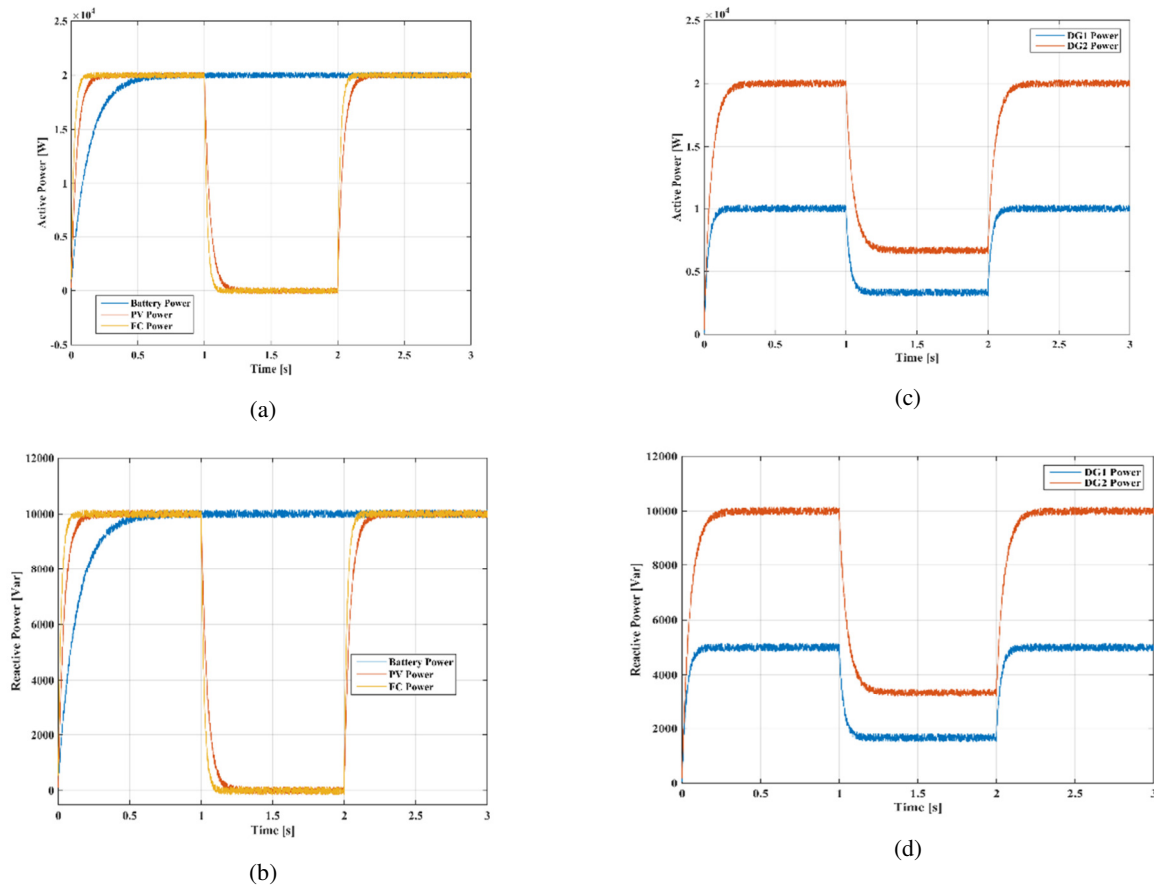


Fig. 10. (a)- Active power output of the single-phase DGs, (b)- Reactive power output of the single-phase DGs, (c)- Active power output of the three-phase DGs, and (d)- Reactive power output of the three-phase DGs under L-L-G fault conditions.

#### Three-Phase-to-Ground (L-L-G) Short Circuit Fault

In this part, an L-L-L-G fault occurs at the PCC and the active and reactive output powers of all single-phase and three-phase DG units in the range of fault will be zero due to direct connection to the fault point; this is shown in Fig. 11.

Fig. 12 demonstrates the dq- voltage at the PCC, under different faults. It can be seen that in the case of

three-phase-to-ground fault, because the voltage of all phases are simultaneously zero, the voltage of d-axis (similar to the q-axis) will also be zero. In L-G and L-L-G faults, because the voltage of only one or two phases is zero, the q-axis voltage is non-zero, and the value of the d-axis voltage is decreased.

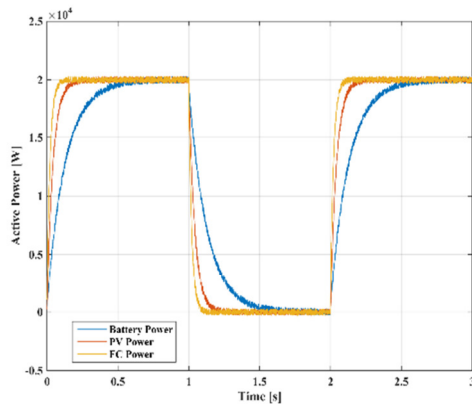


Fig. 11. (a)

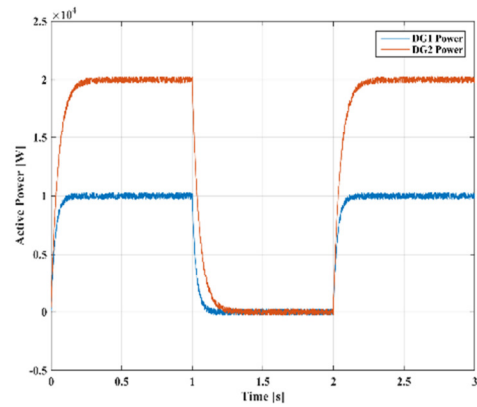
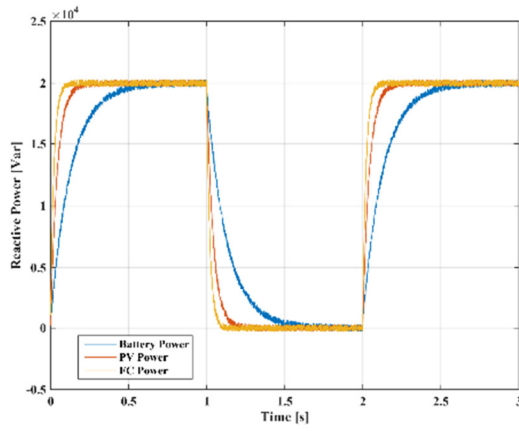
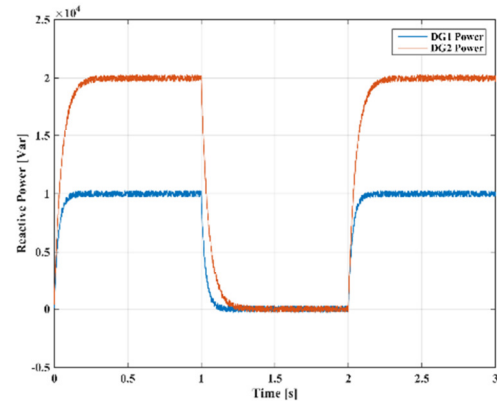


Fig. 11. (c)

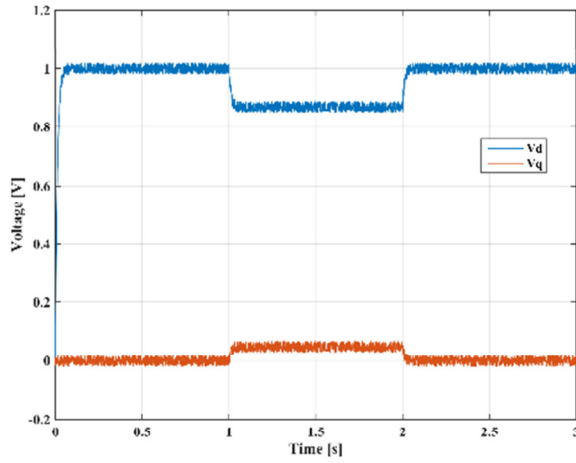


(b)

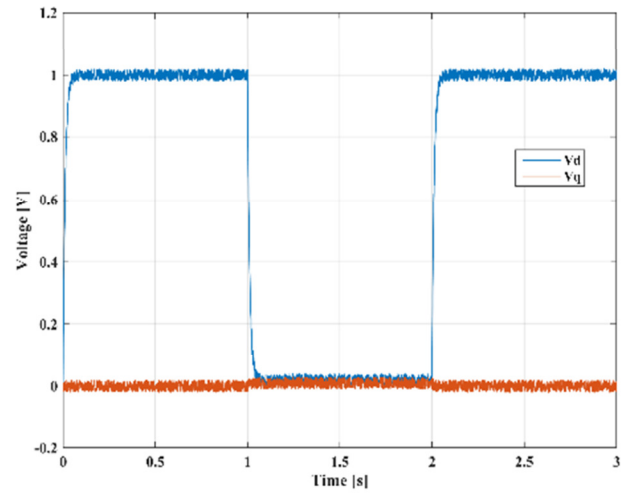


(d)

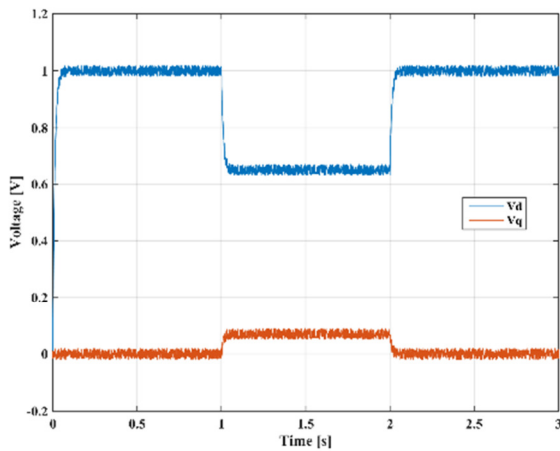
Fig. 11. (a)- Active power output of the single-phase DGs, (b)- Reactive power output of the single-phase DGs, (c)- Active power output of the three-phase DGs, and (d)- Reactive power output of the three-phase DGs under L-L-L-G fault conditions.



(a)



(c)



(b)

Fig. 12. (a)- dq-voltage under L-G fault, (b)- dq-voltage under L-L-G fault, (c)- dq-voltage under L-L-LG fault conditions.

## VII. CONCLUSIONS

The desirable power sharing among DG resources in the microgrid is necessary to keep a reliable power supply to AC electrical loads. In this paper, a power management scheme in a three-phase and single-phase DGs-based microgrid using a power control strategy based on new SMC. There were three single-phase DGs that include PV, FC and battery storage units and two three-phase PV units in a multi-bus microgrid. All DG resources were modeled dynamically. The considered robust control method was designed for power components control of DG resources in the microgrid. The proposed control strategy has many advantages such as fast dynamic response, low steady state error, voltage and frequency stability and improving the microgrid performance under balanced loading and fault conditions. The effectiveness of the proposed power control method has been verified by simulation results in Matlab/Simulink software under different types of faults and loadings, and the results were compared with the conventional PI controller. It should be noted that constraints such as the amount of load charge, filter capacity and the capacity of DG units should be considered in the design domain of the controller. At last, the future research directions can be focused on the power management strategies of AC/DC hybrid microgrids.

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FACTS devices.

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