High Accuracy Power Sharing in Parallel Inverters in an Islanded Microgrid Using Modified Sliding Mode Control Approach

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Abstract
The increased penetration level of distributed generation (DG) units in micro-grids that feed large loads in parallel connections has created the concept of power sharing. Microgrid’s voltage and frequency in islanded mode is controlled using the high inertia inverter. Therefore, the internal control loop is executed in such a manner to avoid overloading of all the DGs in the microgrid. Consequently, the reactive power sharing error is eliminated and the voltage is also kept constant within the permissible range. This paper, presents a modified control method based on sliding mode approach. The proposed control method is tested using several disturbances and three scenarios. Also, the fractional order calculus is applied to the proposed control strategy to increase the convergence speed and the system accuracy. Finally, the proposed method is compared to other well-known controlling approaches while the achieved results confirms its superiority.

Keywords: Distributed generation unit, micro grid control, power sharing, sliding mode, control.

1. Introduction

The penetration level of renewable and nonrenewable Distributed Generation (DG) units such as Wind Turbines (WTs), Fuel Cells (FCs) and Photovoltaic Arrays (PVs) have increased in power electricity networks. DG units are playing important roles in decreasing the pollutant gasses, the transmitted power losses, and enhancing the power quality indices. All these benefits are more eminent in large-scale networks. However, some main issues in power networks such as line power flows and voltage deviation should be reviewed in the presence of DG units. Since a micro-grid (MG) is composed of various DG units, the challenges of high-penetration level of these units should be addressed [1].

Fig. 1 represents the architecture of a typical MG with an Alternative Current (AC) system. PVs and Energy Storage Systems (ESSs) are connected to AC network by DC-DC, AC-DC and DC-AC converters with Local Controller (LC). Also, WTs are connected to Point of Common Coupling (PCC) by an AC-DC-AC convertor. In islanded operation mode, the local load should be supplied by renewable and nonrenewable DG units. In grid-connected operation mode, the PCC is connected to upstream High Voltage (HV) infinite bus. This bus has a major role in MG operation management while the PCC controls the power flow between the MG and the upstream network. Therefore, the protection management and the coordination insulation of PCC are highly necessary [2].

To guarantee the MG stability and its economic operation, the required active and reactive power of local loads must be shared among DG units simultaneously and effectively. Droop controller is one of the renowned controllers in this context, which has been tested on different cases [3]. A modeling approach to explain the normal and the transient modes of network operation is provided in [4], called Virtual Synchronous Generator (VSG) which is based on dynamic oscillation equations. However, the simplicity of improved droop method in power sharing has made it a popular control algorithm among researchers in islanded operation mode up to now.

In [4], a control methodology based on static compensators is provided to achieve power sharing among DG units. The steady state control of DG units is presented in [5]. To improve active and reactive power sharing based on separating and decoupling, where a developed control is needed, virtual impedance strategy is presented [6]. However, low frequency dynamic problems of inverters like current-distortion dynamics, output voltage fluctuations and attenuations have not been investigated in papers [5-6]. In order to improve dynamic stability of active and
reactive power sharing an optimized droop method is illustrated in [7]. Distributed droop method is introduced in [8] to adapt dynamic performance of power system characteristics to load variations. Furthermore, in order to obtain power sharing in complicated load sharing situations such as nonlinear load existence, a newer strategy based on power regulation algorithm is introduced [9]. In [10], power management with hierarchical control is introduced in presence of DC-AC power inverters, in which the economic assessments are affluent.

In [11-13], voltage stability is investigated in presence of a big noise and some control methods for P-V and Q-f properties based on droop controllers are presented. These approaches can be utilized in grids with indefinite feeder impedance that influences power sharing extremely. When all DG units operate in the same frequency in steady state condition, active power can be regulated according to droop control method properly. Reactive power sharing in presence of nonlinear loads and unbalanced feeder impedance is challenging [14]. In such circumstances, active power sharing might cause inappropriate reactive power flow among DG units. Due to the variation of active component of current drawn by load, the voltages of those buses connected to the loads change, while reactive power is not shared. This may cause an instability in power network [15]. To obtain successful reactive power sharing, methods that are based on droop control approaches are classified into three major categories: improved droop control methods [16], improved virtual impedance methods [17] and improved hierarchical control methods [18]. Table 1 compares advantages and disadvantages of aforementioned power sharing control methods.

Specifically, DG controlling methods in MGs can be customized in three layers. First layer: In the first layer, the initial control focuses on voltage and frequency stability. The controller is applied in this layer for power sharing without using telecommunication channels. Second layer: This layer removes voltage and frequency disturbances which may occur on waveforms in the previous step. Third layer: this layer manipulates the economic dispatch and electricity market problems such as optimal load flow and power generation plans, between the micro-grid and the upstream grid.

The structure of this paper is organized as follows: Section 2 presents the MG’s problem formulation. Section 3 describes the grid under consideration and state space equations are being extracted. Section 4 illustrates the proposed control strategy and its stability considering Lyapunov Function. In section 5 the fractional order backstepping sliding mode controller in presented and totally in the last section, the simulation results are being analyzed and investigated. Consequently, a good comparison with some well-known control methods is expressed. Finally, the relevant conclusion is presented.

2. Fractional Order Definitions

Fractional order calculations have played an important role in various scientific fields. The applications of these calculations in control and electrical engineering are myriad. Recently, scientists have shown that fractional order equations can model various phenomena more appropriately than their integer order calculations. In reality, fractional order controllers are powerful instruments to control electrical systems with complex dynamic conditions. The calculations for derivatives and integrals have some different definitions in fractional order calculations. The most depleted and the most important fractional order calculation methods are Grunwald–Letnikov, Riemann–Liouville, and Caputo [19]. In this paper, to design fractional order sliding mode controller, derivative and integral of the fractional order with Caputo definition will be used [19].

**Definition1.** Fraction derivative of Caputo is formulated as (1), in which m is a positive number [19].

\[
\frac{d^\alpha}{dt^\alpha}x(t) = \frac{1}{\Gamma(m-\alpha)} \int_0^t (t-\tau)^{m-\alpha-1} x^{(m)}(\tau) d\tau
\]

where: \( m - 1 < \alpha < m \)

Where \( \frac{d^\alpha}{dt^\alpha}x(t) \) shows derivative of order \( m \) of function \( x(t) \) with Caputo definition from 0 to \( t \) [19].

**Definition2.** Gamma function is expressing as (2):
\[ \Gamma(z) = \int_0^\infty e^{-t} t^{z-1} \, dt \quad (2) \]

**Definition 3.** Fractional integral is expressed as (3):

\[ D_{0,t}^{-\alpha} x(t) = \frac{1}{\Gamma(\alpha)} \int_0^t (t - \tau)^{\alpha-1} x(\tau) \, d\tau \quad (3) \]

**Definition 4.** Some important properties of Caputo definition which are used later in the text [20]:

\[ \mathcal{C} D_t^\alpha \mathcal{C} D_t^\alpha x(t) = x(t); m = 1 \]

\[ D_{0,t}^{-\alpha} D_t^\alpha x(t) = x(t) - \sum_{k=0}^{m-1} \frac{t^k}{k!} x^{(k)}(0) \quad (4) \]

\[ \mathcal{C} D_t^\alpha \mathcal{C} D_t^\beta x(t) = \mathcal{C} D_t^{\alpha+n} x(t); n \in \mathbb{N} \]

\[ L[\mathcal{C} D_t^\alpha x(t)] = s^\alpha X(s) - \sum_{k=0}^{m-1} s^{(\alpha-k-1)} x^{(k)}(0) \]

3. **Definition of study case: A typical Micro-grid**

A schematic diagram of a typical MG and its control scheme is depicted in Fig. 2. As illustrated, the exchange of active and reactive powers with the MG are compared to their reference values. Afterwards, the proposed controller generates the firing angle of inverter switches. Power balance between DGs in MG and loads will keep the DC link voltage constant. Considering equivalent circuit of MG shown in Fig. 3, the following formula can be concluded:

\[ \frac{dI_{Labc}}{dt} = -\frac{R_1}{L_1} I_{Labc} + \frac{1}{L_1} (V_{Labc} - V_{Labc}) \]

\[ \frac{dV_{Labc}}{dt} = \frac{1}{C_1} (I_{Labc} - I_{Labc}) \quad (5) \]

Where \( V_{Labc} \) is the output voltage of inverter across the filter, \( V_{Labc} \) is the capacitor voltage or PCC voltage, \( I_{Labc} \) is the current flow through the RL filter and \( I_{Labc} \) is the three-phase load current. Thus, the active and reactive powers exchanges with the MG are calculated as:

\[ P_{MG} = P = V_{Labc} I_{Labc} + V_{Lbc} I_{Lbc} + V_{Lce} I_{Lce} \]

\[ Q_{MG} = Q = \frac{V_{Labc} (I_{Lbc} - I_{Lce})}{\sqrt{3}} + \frac{V_{Lbc} (I_{Lce} - I_{Lia})}{\sqrt{3}} + \frac{V_{Lce} (I_{Lia} - I_{Lbc})}{\sqrt{3}} \quad (6) \]

Where:

\[ P_{MG} = P_{DG1} + P_{DG2} + P_{DG3} + P_{DG4} \]

\[ Q_{MG} = Q_{DG1} + Q_{DG2} + Q_{DG3} + Q_{DG4} \quad (7) \]
Hiring Park Transformation Matrix is yelled:

\[
\begin{align*}
\frac{dI_{l,d}}{dt} &= -\frac{R_1}{L_1} I_{l,d} + \frac{1}{L_1} (V_{l,d} - V_{L,d}) + \omega I_{l,q} \\
\frac{dI_{l,q}}{dt} &= -\frac{R_1}{L_1} I_{l,q} + \frac{1}{L_1} (V_{l,q} - V_{L,q}) - \omega I_{l,d}
\end{align*}
\]  

(8)

Therefore, to achieve control parameters like modulation index \((m_a)\) and its phase angle \((\beta)\), we can define \(V_{l,d} = m_a V_{dc} \cos(\beta)\) and \(V_{l,q} = m_a V_{dc} \sin(\beta)\). Therefore, (6) will convert to:

\[
\begin{align*}
P &= P_{DG1} + P_{DG2} + P_{DG3} + P_{DG4} = V_{l,d} I_{l,d} + V_{l,q} I_{l,q} \\
Q &= Q_{DG1} + Q_{DG2} + Q_{DG3} + Q_{DG4} = V_{l,q} I_{l,q} - V_{l,q} I_{l,d}
\end{align*}
\]

(9)

Finally, the dynamic performance of this MG is formulated as the following:

\[
\begin{align*}
\frac{dP}{dt} &= -\frac{R_1}{L_1} P - \omega Q + \frac{1}{L_1} (V_{l,d} V_{L,q} - V_{L,q} V_{L,d}) \\
\frac{dQ}{dt} &= -\frac{R_1}{L_1} Q + \omega P + \frac{1}{L_1} (V_{l,q} V_{L,d} + V_{L,q} V_{L,q} - V_{L,d}^2 - V_{L,q}^2) \\
\frac{dV_{L,d}}{dt} &= \frac{1}{C_1} (I_{l,d} - I_{L,d})
\end{align*}
\]

(10)

Here, the state space dynamic modeling with three decision variables \((P \ , \ Q \ , \ V_L)\) is finalized. By substituting \(x_1 = P\ , \ x_2 = Q\) and \(x_3 = V_L\) and defining \(x_{1d} , x_{2d}\) and \(x_{3d}\) as the desired vectors, it is concluded:

\[
\begin{align*}
z_1 &= x_1 - x_d \\
z_2 &= x_2 - x_{2d} \\
z_3 &= x_3 - x_{3d}
\end{align*}
\]

(11)

The \(Z\) vector contains the solutions which should be minimized through the proposed control process.

4. Fractional Order Back-Stepping Sliding Mode Controller

Sliding Mode Control (SMC) is widely used in nonlinear systems to track the reference signal accurately. SMC has many benefits i.e. demonstrating good performance in the presence of external and internal noise. Back-stepping algorithm intrinsically has the ability to deal with inconsistent confusion and can be combined with sliding mode controller in order to increase the robust performance. Many studies have been conducted recently on fractional order controllers [21]. One of the advantages of a fractional order controller is proper freedom degree of decision parameters. Based on back-stepping algorithm theory [22], tracking the reference signal for minimizing the error signal in each system has a pseudo-control rule. The error signal is defined as (12) and then back-stepping algorithm is applied to Maglo approach as the following:

\[
\xi = z_1 - x_{1d} 
\]

(12)

Pseudo-control rule \(\phi_1\) for mode \(z_1\) considering MG dynamic model is determined as (13):

\[
\phi_1 = -\lambda_1 \xi_1
\]

(13)

Where \(\lambda_1\) is a constant and positive coefficient. Here, the dynamic equation of network power disturbance is determined as (14):

\[
\xi_2 = z_2 - \phi_1
\]

(14)

The positive defined function written in (15) illustrates the stability of state \(z_1\) under pseudo-control rule \(\phi_1\) as:
By deriving (15) and substituting it in (12), (16) will be achieved as follows:

\[ V_1 = \frac{1}{2} \xi_1^2 \]  
(15)

\[ V_1 = \xi_1 \dot{\xi}_1 = \xi_1 z_2 \]  
(16)

Also, by substation of (13) and (14) in (16) we will have:

\[ \dot{V}_1 = \xi_1 (\dot{\xi}_2 + \varphi_1) = \xi_1 z_2 - \lambda_1 \xi_1^2 \]  
(17)

Derivative of positive definite function \( V_1 \), is negative and semi-definite; therefore state \( z_2 \) is stable under pseudo-control rule according to (13). This process is repeated for modes \( z_2 \) and \( z_3 \), similarly. Pseudo-control rule for mode \( z_3 \) is determined as (18):

\[ \varphi_2 = \varphi_1 - \lambda_2 \xi_2 - \xi_1 \]  
(18)

According to back-stepping algorithm, dynamic disturbance of \( \xi_3 \) is defined as:

\[ \dot{\xi}_3 = z_3 - \varphi_2 \]  
(19)

By specifying the positive definite function of \( V_2 \), stability evaluation of \( z_2 \) at system dynamic equations mentioned in (11) is investigated as below according to pseudo-control rule:

\[ V_2 = V_1 + \frac{1}{2} \xi_2^2 \]  
(20)

By differentiating (20) and inserting (17)-(19) in (20) we will have:

\[ V_2 = V_1 + \xi_2 \dot{\xi}_2 = (\xi_1 \xi_2 - \lambda_1 \xi_1^2) + \xi_2 (\dot{\varphi}_2 - \dot{\varphi}_1) \]  
(21)

\[ = (\xi_1 \xi_2 - \lambda_1 \xi_1^2) + \xi_2 (\dot{\varphi}_3 + \varphi_2 - \varphi_1) \]  
(21)

\[ = (\xi_1 \xi_2 - \lambda_1 \xi_1^2) + \xi_2 (\xi_3 - \lambda_2 \xi_2 - \xi_1) \]  
(21)

\[ = \xi_2 \xi_3 - \lambda_1 \xi_1^2 - \lambda_2 \xi_2^2 \]  
(21)

Differentiating positive certain function \( V_2 \) results in a negative semi-definite function. Therefore, state \( z_2 \) is stable under pseudo-control rule. In order to implement the sliding mode control theory for calculating equivalent control rule, a proper sliding surface should be chosen. In this regard, to calculate proper equivalent control rule, which causes stability in control system, a sliding surface of fractional order is proposed as (22):

\[ \sigma = k_1 \xi D_t^{-a} \xi_3 + \xi_3 \]  
(22)

In order to calculate the equivalent control rule, (19) is substituted in derivative of (22), so we have:

\[ \dot{\sigma} = k_1 \xi D_t^{-a} \xi_3 + \xi_3 \]  
(23)

\[ \dot{\sigma} = k_1 \xi D_t^{-a} \xi_3 + \dot{\varphi}_3 - \dot{\varphi}_2 \]  
(24)

Dynamic equations of control system that are illustrated in (11) are substituted in (23), so the system input \( u \) is found as in (23). The sliding mode control theory tries to keep the system modes on the sliding surface or close to it.

This condition is achieved when \( \sigma = \dot{\sigma} = 0 \). Applying these conditions to (24), the equivalent control rule is changed as the following:

\[ \dot{\sigma} = k_1 \xi D_t^{-a} \xi_3 + f(z) + g(z)u - \dot{\varphi}_2 = 0 \]  
(25)

\[ u_{eq} = - \left( g(z) \right)^{-1} \left( k_1 \xi D_t^{-a} \xi_3 + f(z) - \dot{\varphi}_2 \right) \]  
(26)

By applying (20) to the system, the state modes are converged to sliding surface which is determined by fractional order and is remained on this surface. But if any turbulence is applied to the system, or a parametric
indeterminate occurs, there is no guarantee that system modes converges to the determined sliding surface again. To solve this drawback, switching control rule is defined as (27):

$$u_{sw} = -(g(z))^{-1}(k_1\sigma + k_2 \text{sign}(\sigma))$$  \quad (27)

Therefore, in order to stabilize and create proper tracking with robust performance in the system, control rule obtained by summation of (26) and (27), is applied to inverter switches. Then we have:

$$u = -(g(z))^{-1} \left( k_1D_t^{-\alpha}\xi_3 + f(z) - \phi_2 + k_1\sigma + k_2 \text{sign}(\sigma) \right)$$  \quad (28)

Sliding mode control theory has an unfavorable phenomenon in control rule called chattering, which causes discontinuity in control rule. Chattering is occurred due to discontinuous property of function $\text{sign}$ in switching control rule [23]. To solve this deficiency in control rule presented in (28), instead of $\text{sign}$ function, a continuous function like saturation function $(sat(\sigma/e))$ could be substituted.

**Theory1.** Microgrid system defining illustrated in (10) and (11) is stable while applying fractional order back-stepping sliding mode controller and control rule (28). In other words, system modes will converge to fractional order sliding surface described in (22).

**Proof:** According to sliding mode control theory, proposed controller stability is evaluated using Lyapunov function. To achieve this, consider positive defined function as presented in (29):

$$V_3 = V_2 + \frac{1}{2}\sigma^2$$  \quad (29)

Derivative of (29) is calculated as (30):

$$\dot{V}_3 = \dot{V}_2 + \sigma\dot{\sigma}$$  \quad (30)

Inserting (24) and (21) in (30) will lead to:

$$V_3 = \xi_2\xi_3 - \lambda_1\xi_1^2 - \lambda_2\xi_2^2 + \sigma(k_1\xi_3 + f(z)u - \phi_2)$$  \quad (31)

In order to calculate the best control rule, (28) should be substituted in (31):

$$\dot{V}_3 = \xi_2\xi_3 - \lambda_1\xi_1^2 - \lambda_2\xi_2^2 + \sigma(k_1\xi_3 + f(z) - \phi_2) + g(z) \left[ -(g(z))^{-1} \left( k_1D_t^{-\alpha}\xi_3 + f(z) - \phi_2 + k_1\sigma + k_2 \text{sign}(\sigma) \right) \right]$$  \quad (32)

That will be simplified as:

$$\dot{V}_3 = \xi_2\xi_3 - \lambda_1\xi_1^2 - \lambda_2\xi_2^2 - k_1\sigma^2 - k_2|\sigma|$$  \quad (33)

According to Lyapunov’s stability theory, to confirm the stability of a system, it is obligated that certain positive function derivative must be definite negative. Since all terms in (33) have a definite mathematical sign and just $\xi_2\xi_3$ is not determined with a certain sign; therefore, considering positive certain matrix laws, it is proved that (33) will be certain negative and the system is asymptotically stable. After implementing proposed sliding surface explained in (22)-(33) it is yelled that:

$$\dot{V}_3 = \xi_2\xi_3 - \lambda_1\xi_1^2 - \lambda_2\xi_2^2 - k_1(k_1D_t^{-\alpha}\xi_3 + \xi_3)^2 - k_2|\sigma| + \xi_2\xi_3$$

$$-\lambda_1\xi_1^2 - \lambda_2\xi_2^2 - k_1\xi_3^2 - k_1(k_1D_t^{-\alpha}\xi_3)^2 - k_2|\sigma| - 2k_1^2D_t^{-\alpha}\xi_3$$

$$= -E^TQE - k_1(k_1D_t^{-\alpha}\xi_3)^2 - 2k_1^2D_t^{-\alpha}\xi_3 - k_2|\sigma|$$  \quad (34)

Where $E = [\xi_1\xi_2\xi_3]$.

To have a certain negative Lyapunov function of derivative from (34), matrix Q must be certain positive. In the following, it is shown that matrix Q is certain positive with some criteria. Matrix Q is determined as:

$$Q = \begin{bmatrix}
\lambda_1 & 0 & 0 \\
0 & \lambda_2 & -0.5 \\
0 & -0.5 & k_1
\end{bmatrix}$$  \quad (35)
To have a certain positive matrix Q, all leading principal minors of Q have to be positive. Thus, all leading principal minors of matrix Q are defined as:

\[
\begin{vmatrix}
\lambda_1 \\
0
\end{vmatrix} = \lambda_1 > 0
\]

\[
Q = \begin{vmatrix}
\lambda_2 \\
-0.5
\end{vmatrix} = \lambda_1 (\lambda_2 k_1 - 0.25) > 0
\]

Finally, if the coefficients \(\lambda_1, \lambda_2\) and \(k_1\) are applied to (36), then matrix Q is certain positive and term \(-E^T Q E\) will be certain negative in Lyapunov function derivative. According to [24], it is resulted that \(-2K_1 k_1 \xi_3 \hat{D}_t^{\alpha} \xi_3 < 0\) and \(k_1\) is determined more than zero. Therefore, according to Lyapunov stability theory, this system will be stable with the proposed controller. Theory 1 shows that our system modes converge to fractional order sliding surface of (22). In theory 2, the process of converging the fractional order sliding modes to zero will be investigated. To study the proposed sliding mode stability as described in (22), new generalized Lyapunov stability theory and presented methods in [25] are used.

**Theory 2.** Fractional order back-stepping sliding mode represented by (22) is stable and converges to \(\sigma = 0\).

**Proof:** Assume the fractional order sliding mode is as the following:

\[
\sigma(t) = k_1 \hat{D}_t^{\alpha} \xi_3 + \xi_3 = 0
\]

(37)

Based on the definitions presented in (4), after differentiating fractional order of (37) and using new generalized Lyapunov theory for fractional order, it is proved that fractional order sliding mode is converging to zero, as follows:

\[
k_1 \hat{D}_t^{\alpha} \xi_3 + \hat{D}_t^{\alpha} \xi_3 = 0; \quad \hat{D}_t^{\alpha} \xi_3 = -k_1 \xi_3
\]

(38)

Definite function at (39) is utilized to prove the stability of error \(\xi_3\) in fractional order dynamic equations. Therefore we have:

\[
V = \frac{1}{2} \xi_3^2
\]

(39)

From (39), the fractional order derivative \(\hat{D}_t^{\alpha} V\) is taken and substituted in (38), so we have:

\[
\hat{D}_t^{\alpha} V = \frac{1}{2} \hat{D}_t^{\alpha} \xi_3^2 < \xi_3 \hat{D}_t^{\alpha} \xi_3 = -k_1 \xi_3^2 < 0
\]

(40)

According to the proposed definitions in the new generalized Lyapunov stability as well fractional order derivative of this Lyapunov function, it is confirmed that \(\hat{D}_t^{\alpha} V\) is smaller than the negative term \((-k_1 \xi_3^2)\). As a result the fractional order sliding mode of (22) has a limited domain and converges to zero asymptotically.

5. Simulation Results

A single line diagram of a typical MG containing four DG units is depicted in Fig.4. These DG units are connected to four different feeders to supply different load types. The main characteristics of DG units are presented in Tables 2 and 3.

The specifications of loads and impedances of lines are given in Tables 4 and 5, respectively. In order to validate the proposed control scheme on power sharing between DG units, three different case studies are investigated. First, the achieved results are compared against basic droop control methods. In the second case study, load variation effect on the presented control strategy is evaluated. Finally, a DG unit power outage will be investigated and power sharing is presented in the third case study. Table 6 represents the required data for the proposed control scheme.

5.1. Case Study 1
In this case study, it is assumed that the micro-grid is controlled by the droop control strategy. Therefore, all DG units operate according to their droop coefficients. In this case, there is no guarantee to prevent overloading of resources via droop control strategy. It is on micro-grid operator (MO) decision to use load 1 (L1), load 2 (L2), load 31 (first fraction of L3), load 32 (second fraction of L3), and load 4 (L4) in MG. Active and reactive powers are shared among DG units as shown in Fig. 5-a and Fig. 5-b. when $t = 0.7$ s, the droop control strategy is switched to the proposed method. It is observed that the active powers return to the same as initial values after a transient condition. However, the reactive powers will be shared based on the DG’s nominal capacity of ratio 1: 1.5: 2: 2.5. Therefore, DG1, which has previously been exposed to overload, decreases its reactive power. DGs 2, 3, and 4 also provide the required powers based on their nominal capacity ratio.

Fig. 5-c also shows the voltage profile of terminals connected to DG units. In this figure, due to the inadequate share of reactive power by the droop method before $t = 0.7$ s, the system voltage does not remain at a constant value. However, after implementation of the proposed method, the reactive power helps the terminal voltages to be kept at nominal value. The system frequency during this study is depicted in Fig. 5-d which confirms the suitable performance of the proposed method. The system frequency is close to 50 Hz during the simulation period.

5.2. Case Study 2

In this case, it is assumed that the system is operated by the proposed controller. As it can be seen from the archived results, the proposed controller can share active and reactive power among the DG units in an acceptable manner. At $t=0.6$ s the local load is connected to the MG. The proposed controller shares the power among the DG units in the shortest possible time based on their nominal capacity. Therefore, active and reactive powers are shared successfully and effectively among all DG units. Fig. 6-a and 6-b show the output active and reactive powers of DG units respectively. As can be seen, in the case of reactive power sharing, the DGs’ nominal capacity ratio is also obtained. This prevents the overloading of DG units. Fig 6-c represent the terminal voltage profile. When the local load is connected to MG, the voltages of MG buses are decreased slightly. When $t = 1$s, the local load and Load L32 are switched off. Therefore, the proposed controller shares the remainder of active and reactive powers among DG units proper to their nominal capacity ratio. Fig. 6-c shows the increasing in voltage amplitude due to local load decreasing. Fig 6-d shows the slight variation in MG frequency from its nominal value.

5.3. Case Study 3

Similar to the first case study the MG starts working using the droop control method. At $t = 0.7$ s, the droop approach is switched off and the proposed controller is substituted. Up to this point, it is similar to the first case. At $t = 1.4$ s, the protective relays of DG2 disconnect it from the network. Thus, its active and reactive power is degrading to zero. Fig. 7-a and 7-b show this issue carefully. Afterwards, the terminal voltage of DG2 will be equal to zero and the open circuit voltage will rise to 220 V. Moreover, other DG units share the load power with the nominal ratio of 1: 2: 2.5. This means that the output power of each resource is increased without any overloading in DG units output powers. The active and the reactive powers are shown after $t = 1.4$ s in Fig. 7-a and Fig. 7-b, respectively. In this regard, 70 MW load with ratios of 12.72: 25.45: 31.81 is shared among DG1, DG3 and DG4, respectively. Also, the remainder of reactive power is shared via DG1, DG3 and DG4 by the ratio of 6.36: 12.72: 15.9, which is equal to their nominal capacity ratio of 1: 2: 2.5. Fig. 7-c represents the terminal voltage of all DG units and MG frequency is plotted in Fig. 7-d.

In order to compare the performance of the proposed controller with some improved SMC approaches i.e. Adaptive Sliding Mode Control (ASMC) and Adaptive Fuzzy Sliding Mode Control (AFSMC), a worthy comparison based on step response is represented in Fig. 8. As it can be inferred from this figure, the proposed strategy has the best settling time, over-shoot and the rise time values. The settling time of the proposed controller, AFSMC, ASMC and SMC approaches are 0.347 s, 0.412 s, 0.595 s and 0.661 s respectively. This means that the proposed controller converges to its final value more quickly than the others. By the way, shorter rise time and over-shoot indicate that our controller presents the better solution, effectively.
Since this control strategy is very useful for dynamic stability analysis of power systems, some control indices are expressed in (41) to (43) and all of these evaluations have been summarized in Table 7 and Table 8. In this part, it's assumed that a load variation between -0.1 pu to +0.1 pu is occurred. Table 8 confirms that our approach has the best performance compared to others.

\[
\text{Integral Square Error } \rightarrow \text{ISE} = \int_{0}^{\infty} e(t)^2 \, dt \quad (41)
\]

\[
\text{Integral Absolute Error } \rightarrow \text{IAE} = \int_{0}^{\infty} |e(t)| \, dt \quad (42)
\]

\[
\text{Integral Time Absolute Error } \rightarrow \text{ITAE} = \int_{0}^{\infty} t \, |e(t)| \, dt \quad (43)
\]

6. Conclusion

In this paper, a novel and improved control method based on sliding mode scheme is presented that allows the central controller to achieve the power sharing carefully among DG units. When some disturbances occur in an islanded MG preserving the MG’s stability is considered as the vital principle. Therefore, the proposed controller with internal loop controls voltage and frequency of the MG within an acceptable range. Afterwards, the secondary control loop begins power sharing among DGs. The achieved results show that power and voltage disturbances can be easily eliminated and reduced perfectly. Thus, the MG frequency is kept constant very close to its nominal value. The sliding mode control method can be more effective than intelligent control fashions due to its ability to damp perturbations. Finally, as the comparisons have conducted, fuzzy or adaptive methods cannot properly handle DG units as good as the presented method. The constant inverter frequency acts as another reason for the superiority of the proposed strategy.

References


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Fig. 1. A general Architecture of MG

Fig. 2. Control block diagram of MG

Fig. 3. Equivalent circuit of MG

Fig. 4. Microgrid scheme under consideration

Fig. 5. a) active power sharing; b) reactive power sharing; c) terminal voltage of DG units; d) MG frequency; all plots are calculated by droop method before t = 0.7 s, and proposed method after t = 0.7 s.

Fig. 6. a) active power sharing b) reactive power sharing; c) terminal voltage of DGs; d) MG frequency; all plots are calculated by the proposed controller with contingency of load increasing at t = 0.6 s, and decreasing at t = 1 s.

Fig. 7. a) active power sharing b) reactive power sharing; c) terminal voltage of DGs; d) MG frequency; all plots are calculated by droop method before t = 0.7 s and proposed method after t = 0.7 s. power outage is occurred at t = 1.4 s.

Fig. 8. Step response of the proposed controller strategy, AFSMC, ASMC and SMC approaches.

Table 1. A comparison for power sharing control strategies

Table 2. Specifications of the tested MG

Table 3. DG characteristics and capacities

Table 4. Load characteristics

Table 5. Impedance of Lines

Table 6. Control strategy parameters

Table 7. Comparison of the proposed controller with developed SMC method.

Table 8. Control stability indices comparison
Fig. 1. A general Architecture of MG
Fig. 2. Control block diagram of MG
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Fig. 5. a) active power sharing; b) reactive power sharing; c) terminal voltage of DG units; d) MG frequency; all plots are calculated by droop method before $t = 0.7 \, \text{s}$, and proposed method after $t = 0.7 \, \text{s}$. 
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### Table 1. A comparison for power sharing control strategies

<table>
<thead>
<tr>
<th>Control method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>droop control method</td>
<td>• High reliability</td>
<td>• Need a complex algorithm</td>
</tr>
<tr>
<td></td>
<td>• Availability</td>
<td>• Inappropriate for complex loads</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Inappropriate for complex micro grids</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Communication line delay</td>
</tr>
<tr>
<td>Virtual impedance method</td>
<td>• Proper operation to reactive power sharing</td>
<td>• Difficult to calculate the coefficients</td>
</tr>
<tr>
<td></td>
<td>• Acceptable for nonlinear and unbalanced loads</td>
<td>• Hard to design a suitable algorithm with high efficiency</td>
</tr>
<tr>
<td>Hierarchical control method</td>
<td>• Good recovery of voltage and frequency</td>
<td>• Inappropriate operation for reactive power sharing under unbalanced and nonlinear loads</td>
</tr>
<tr>
<td></td>
<td>• Power sharing with unknown feeders impedance</td>
<td>• Need a Complicated algorithm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Communication line delay</td>
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</table>
**Table 5. Impedance of Lines**

<table>
<thead>
<tr>
<th>Line Impedance</th>
<th>Per unit</th>
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<tbody>
<tr>
<td>Impedance of Line 1 (Z1)</td>
<td>0.0087 + j 0.039</td>
</tr>
<tr>
<td>Impedance of Line 2 (Z2)</td>
<td>0.0298 + j 0.098</td>
</tr>
<tr>
<td>Impedance of Line 3 (Z3)</td>
<td>0.0301 + j 0.124</td>
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<tr>
<td>Impedance of Line 4 (Z4)</td>
<td>0.0385 + j 0.266</td>
</tr>
<tr>
<td>Impedance of Line 5 (Z5)</td>
<td>0.0421 + j 0.295</td>
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</table>

**Table 6. Control strategy parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>λ₁</td>
<td>24</td>
</tr>
<tr>
<td>λ₂</td>
<td>21</td>
</tr>
<tr>
<td>γ₁</td>
<td>52</td>
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<tr>
<td>γ₂</td>
<td>82</td>
</tr>
<tr>
<td>k₁</td>
<td>0.12</td>
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<td>α</td>
<td>0.64</td>
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</table>

**Table 7. Comparison of the proposed controller with developed SMC method.**

<table>
<thead>
<tr>
<th>Step Response</th>
<th>Over Shoot</th>
<th>Settling Time</th>
<th>Rise Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC [11]</td>
<td>1.532 [pu]</td>
<td>0.661 [s]</td>
<td>0.878 [s]</td>
</tr>
<tr>
<td>ASMC [12]</td>
<td>1.492 [pu]</td>
<td>0.595 [s]</td>
<td>0.810 [s]</td>
</tr>
<tr>
<td>AFSMC [13]</td>
<td>1.398 [pu]</td>
<td>0.412 [s]</td>
<td>0.741 [s]</td>
</tr>
<tr>
<td>Proposed Approach</td>
<td>1.506 [pu]</td>
<td>0.347 [s]</td>
<td>0.655 [s]</td>
</tr>
</tbody>
</table>

**Table 8. Control stability indices comparison**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ISE</td>
<td>IAE</td>
<td>ITAE</td>
</tr>
<tr>
<td>- 0.1 pu</td>
<td>0.017</td>
<td>0.023</td>
<td>0.0087</td>
</tr>
<tr>
<td>+ 0.1 pu</td>
<td>0.036</td>
<td>0.033</td>
<td>0.011</td>
</tr>
</tbody>
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