Design an Accurate Power Control Strategy of Parallel Connected Inverters in Islanded Microgrids

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Abstract. when the overall loads change periodically, the accurate real power and reactive power sharing considered is essential for the operation of an islanded microgrid. In this work, an accurate power control strategy of parallel-connected inverters in an AC microgrid in islanded mode has been designed. The examined microgrid involves four inverters linked to the load via different system impedance conditions is performed. Also, the control strategy for islanded microgrid operation with detailed switching models is simulated by using PSCAD/EMTDC software, and all dynamic and steady-state real and reactive power sharing is explained. Moreover, the real power sharing is achieved using only the decentralized control (droop control), while the reactive power sharing control approach is proposed as a central controller (secondary controller) in order to improve the precision of fundamental reactive power sharing, gives an efficient dynamic performance, and reduce the circulating current. The central controller in the microgrid requires communications. It is used as an external loop to accomplish identical reactive power sharing according to reactive power load especially when the mismatch in voltage drops through the feeders is occurred. The control approach will still work with traditional droop control when the central controller is a failure. The obtained results show that the proposed approach is immune to the time delay in the central controller. Additionally, the active power and the reactive power is shared accurately.

Keywords: Islanded microgrid, Droop control, Central control, Reactive power sharing, Load sharing

1. Introduction
In electrical grid systems, the distributed generation (DG) units based on renewable energy sources (RE斯) are widely expanded penetration. The DG included a wide range of prime mover technologies, such as photovoltaic (PV) array, microturbines, gas turbines, fuel cells, and wind power systems have been commonly utilized in the distributed energy systems in the previous many years [1]. If compared with traditional generators, the DG units play a significant part in reducing pollution, minimizing the losses in power transmission, improving local operation, and increasing the electric power production.

The microgrid (MG) is considering as the main method to incorporate the RE斯. Basically, a MG can be defined as a collection of the distributed generators and several loads that are usually interfaced through converters which controlled intelligently by utilizing a central controller. The DG such as PV, wind turbine, and energy storage systems need to be interfaced with the load or MG by power electronics, for example, rectifier, inverter, and boost converter, which allows them to be further flexible in their working and control [2].

When increasing the penetration of DER in the main grid, new difficulties have appeared, for example, frequency fluctuations, voltage profile, stability issues (inverse power flow), and protection system coordination. One approach to managing the previously mentioned issues is to take a system
approach which includes DERs and connected loads as a MG [3]. Another method, if many DG units are tied closeness, this association can cause a MG to have the capability to solve the problems that happen by high penetration of DG efficiently and makes the application of large-scale for DG systems possible [4].

MG can work either in the islanded or grid connected modes. When the MG operating in an islanded mode of AC microgrid as unlike the grid connection mode; the frequency and voltage regulation must be regulated by every DG unit separately according to the information from the DG itself. Also, the total loads must be shared by the MG and every DG unit has the capability to generate the power proportion to its rating to achieve load/generation balance. Various papers focus on the total load sharing for real and reactive powers and how to control the frequency and voltage of an islanded droop control schemes MG [5].

To ensure the stability system during the operation of MG should be the real and reactive power of DG shared promptly. The droop control technique one type of decentralized control which considered the preferred method to control several parallel inverters without requiring communication lines between the DG units. There are, this method allows “plug-and-play” interfacing, and improves the reliability of the system [6]. There are several control structures and configurations of droop control depending on the feeder characteristic such as resistive, inductive, or both. Droop control regulating the amplitude of the voltage reference and the frequency according to the active and reactive powers provided that the load demand must be not above the power rating of the inverters. Conventional droop control uses the active power-frequency (P-w) control and the reactive power-voltage (Q-V) control [7].

The frequency droop control can accomplish precise active power sharing below some situations because the frequency of the MG is not affected by feeder impedance. Then, stays regular throughout the MG even when unequal feeder impedances are existing while the reactive power sharing is sensitive to the effects of mismatches feeder. When poor reactive power sharing, circulating current between the inverters it will happen and creates instability in the MG network because of unequal feeder impedances and different ratings of the DG units. Communication lines as a secondary control are often used to achieve global control of the MG, make precise reactive power sharing, and enhance the performance without reducing reliability [8].

Various literature supports the employ of a central controller that enhances the operation of droop control to achieve the accurate reactive power sharing. The authors in [9] propose the islanded MG could work with two operation modes, single master operation and multi-master operation. In single master operation only one master inverter regulated the frequency and voltage and achieving load balancing, this method considered a straightforward control. In multi-master operation there are more than one master inverter to regulate the frequency and voltage and make load sharing, this method considered more reliability when one the master inverter is failure.

The authors in [10] propose virtual output inductor to prevent the power control instability, this virtual output inductor located at the DG output and assume that dominant. Generally, this method developed based on simplified MG configurations and may be increase the error for reactive power because of increased impedance voltage drops. So, should be compensated the feeder voltage drop to reduce the error. To compensate the line feeder mismatches a new droop control method suggested by authors in [11]. This method controlled the reactive power in proportion to the first derivative of the voltage. It notices in this strategy, reducing the mismatch in feeder impedance with parallel connected inverters but not accomplish equal sharing and increasing the complexity of the control.

The authors in [12] propose the virtual impedance to minimize errors in reactive power sharing using different values line feeder impedances connect between the DG units and PCC. This method of the voltage controller, assuming neglected the output impedances at steady state about the reference operating frequency. Therefore, the virtual impedance is dominant below this situation, which produces accurate reactive power sharing. However, this study not consider the mismatch in the transformers, feeder’s impedance, and the interface inductors linked to each DG unit.

Proposed a unique strategy to achieve accurate reactive power sharing by the authors in [13]. This method depends on injection a small AC voltage signal in the microgrid. However, difficult achievement the generating and processing this small AC signal. Also, this method leads to reduce the quality of both the output voltage and line current. The authors in [14] propose the control method and the analysis
system need that the feeder impedances are resistive only. So, the control strategy and the analysis system give perfect power sharing with the resistive. Essentially, the feeder impedance must have inductive and resistive components and cannot neglect any part.

The authors in [15] used the central control to decrease voltage harmonic distortion and enhance reactive power sharing in an islanded MG. In [16] a secondary control method is proposed, that each DG unit using the measurements of other DG units to produce suitable control signal to control voltage, frequency, and reactive power sharing. The MGCC used as a control strategy to share real and reactive powers by the authors in [17]. The control strategy and analysis impose that the feeder impedance is inductance and the resistive is neglected. A communication link decrease reliability of MG and when loss of communication bus these methods operate incorrectly.

Communication link is used by the authors in [18] to determine the virtual impedances after estimation of the feeder impedances in order to make sure accurate reactive power sharing. So, the bus voltage information sends via a communication link to evaluation the feeder impedance for every DG unit. The power angle between the DG output and the PCC voltage is neglected in this study. Are Combined between the droop control and the MGCC by authors in [19] to accurate reactive power sharing. In this study, adjusting reactive power references by the MGCC to the corresponding DG units and compute the averaged reactive power. Essentially, the MG physical modes are complex and the reactive power can be affected by the communication delay.

In this work, enhance reactive power sharing accuracy by using a microgrid central controller (MGCC) strategy. The MGCC is used to accomplish reactive power sharing accuracy via tuning the inverter output voltage reference. Tuning the reference voltage depending on reactive power load unlike [19] which is send reactive power from every DG to the central controller in order to generate reference reactive power. The remainder of the paper represent as following. The general structure and control of each inverter unit of the proposed islanded microgrid is explained in section 2, then the secondary, primary, and inner control loop also illustrated. The power sharing strategy used in this work discussed with clarify the purpose of MGCC and working in the system in Section 3. Sections 4 and 5 illustrate the simulation results and conclusions, respectively.

2. Islanded Microgrid Structure and Control

2.1 Structure of the proposed Microgrid

In this paper, the MG structure with a one-line diagram is shown in Figure 1, assuming it is operated in island mode and each inverter operates alone to control the frequency while the local grid voltage controlled by MGCC for precise load sharing. This MG used to check the fundamental active and reactive power sharing ability. Additionally, the MG contains four dispatchable DGs indicate as DG1, DG2, DG3, and DG4. Four DG connected in parallel to supply the load, and each DG is connected to the linear load through an LC filter to mitigate VSI switching harmonics, output impedances, and an isolation transformer. Moreover, the MG considered operates with (0.48 \( kV_{LL} \)) as a low voltage distribution level. Then, this voltage converted by the isolated transformer to (4.16 \( kV_{LL} \)) as the distribution network. All quantities used in this work per unit with base power is 1 MVA, and the base voltage for the inverter side is 0.48 \( kV_{LL} \). PSCAD/EMTDC software is used to design the droop control inverter model.
2.2 Inverter Unit Control

The controls of every inverter linked in parallel are responsible for sharing the whole load demand according to their respective ratings for many reasons such as to avoid DG overload, to exchange the power between the main network and the MG, or to make sure the exchange of power in the MG, and finally to ensure the MG stable operation.

Basically, there are three topologies for inverter controls exist [20]: grid-forming unit represents the first topology that it creates a reference value for frequency and voltage, and in an islanded MG have to be at the least one DG operates in grid-forming, the grid-feeding unit represents the second topology that it has approach extraction of maximum power from its DG), and grid-supporting unit which means adjust its output real and reactive power based on control strategies and to adjust to frequency and voltage due to load changes. In an islanded MG, it is necessary to combine the grid supporting with a grid forming in order that the inverters can work in parallel.

In this work, the structure of every DG shown in Figure 2, while the voltage and current tracking loops appeared in Figure 3. A rotating dq reference frame which is used to control the VSI. There are six switches in the three-phase VSI and each switch is connected with a diode in parallel. O is determined by a frequency controller which represents an essential part of a transformation from abc to dq or vice versa. DC prime mover represented by \( V_{DC} \) and working as input for three-phase VSI; \( L_f \) and \( C_f \) represented the inductor and capacitor filters, respectively; \( i_{abc} \) represents the output currents of the inverter; and \( V_{abc} \) represents the output voltages of the inverter. Voltage and current tracking loops are known as low-level voltage and current controllers and maintain feed-forward controllers and the feedback collected with the linear control loop. The park, and Clark transformation (ABC-dq0) also used in this loop.

The system has three loops from exterior to inner: droop power control loop used to control the active and reactive power, voltage loop used to regulate the voltage of VSI, and current loop used to regulate the current of VSI. To clarify the active and reactive power flow between VSI and PCC can expressions as (1) and (2) [21].

\[
P_m = \frac{V}{R^2 + X^2} (VR + V_{PCC}X \sin \delta - V_{PCC}R \cos \delta) \tag{1}
\]

\[
Q_m = \frac{V}{R^2 + X^2} (VX - V_{PCC}R \sin \delta - V_{PCC}X \cos \delta) \tag{2}
\]

Where \( V \) and \( V_{PCC} \) represent the magnitudes of voltage output VSI and PCC voltage, respectively; \( R \) and \( X \) represent the resistance and reactance of the feeder impedance, respectively; \( \delta \) represents the phase angle between the two nodes. The value of inductive larger than resistance for high power flow,
therefore, the resistance can be neglected. Moreover, when the phase angle is small, (1) and (2) equations can be simplified as:

$$P_m = \frac{V_{VCC} \sin \delta}{X}$$  \hspace{1cm} (3)
$$Q_m = \frac{V}{X} (V - V_{VCC}) = \frac{V}{X} \Delta V$$ \hspace{1cm} (4)

It can be noticed from (3) and (4), the real power is relative to $\delta$ and can be controlled by adjusting the VSI output frequency. Additionally, the reactive power is proportional to $\Delta V$ and can be adjusted by varying the inverter output voltage value. The idea of droops control, when the power output of VSI exceeds the setpoint value, the power output will be reduced by the droop control characteristics (Q-V) and (P-w), which can be a declaration as:
\[ w_{\text{ref}} = w^* - K_p (p_m - p_{\text{ref}}) \]  
\[ V_{\text{ref}} = V^* - K_q Q_m + (k_p + k_i s^{-1})(Q_{\text{ref}} - Q_m) \]  

Where \( p_{\text{ref}} \) and \( Q_{\text{ref}} \) are the references for real and reactive power that the VSI can supply; \( V^* \) and \( w^* \) are the nominal voltage and frequency, respectively; \( p_m \) and \( Q_m \) are measurement active and reactive power of the VSI, respectively; \( V_{\text{ref}} \) and \( w_{\text{ref}} \) are the output reference voltage value and frequency, respectively; \( K_p \) and \( K_q \) are the droop factor for frequency and voltage, respectively. These factors are selected dependent on the relations:

\[ K_p = \frac{w_{\text{max}} - w_{\text{min}}}{p_{\text{max}}} \]  
\[ K_q = \frac{V_{\text{max}} - V_{\text{min}}}{Q_{\text{max}}} \]

Where \( w_{\text{min}} \) and \( w_{\text{max}} \) represent the minimum and maximum frequency deviations, respectively; and \( V_{\text{min}} \) and \( V_{\text{max}} \) are the minimum and maximum voltage deviations, respectively. The outputs of the current control loop are the modulating signals, \( u_d \) and \( u_q \), given by:

\[ u_d = v_d - i_q w_L + k_{pc}(i_{d\text{ref}} - i_d) + k_{ic}\int (i_{d\text{ref}} - i_d)dt \]  
\[ u_q = v_q - i_d w_L + k_{pc}(i_{q\text{ref}} - i_q) + k_{ic}\int (i_{q\text{ref}} - i_q)dt \]

Where \( k_{ic} \) and \( k_{pc} \) represent integral and proportional of the PI \(_p\) parameters. The voltage control loop is used to generate the reference currents, \( i_{d\text{ref}} \) and \( i_{q\text{ref}} \), and given by:

\[ i_{d\text{ref}} = k_{pv}(v_{d\text{ref}} - v_d) + k_{iv}\int (v_{d\text{ref}} - v_d)dt \]  
\[ i_{q\text{ref}} = k_{pv}(v_{q\text{ref}} - v_q) + k_{iv}\int (v_{q\text{ref}} - v_q)dt \]

Where \( k_{iv} \) and \( k_{pv} \) represent integral and proportional of the PI \(_v\) parameters for the voltage control loop. Voltage references, \( v_{d\text{ref}} \) and \( v_{q\text{ref}} \), are given by the output of the droop power control loop represents \( v_{d\text{ref}} \) as shown in (6), and the \( v_{q\text{ref}} \) is generally set to zero. Mentioning to Figures 2 and 3, all controllers and are presented in Table 3. The time constant of the LPF for the active and reactive power is \((5 \times 10^{-4})\)sec; nominal voltage 0.48 kV; nominal angular frequency 377 rad/sec; and the switching frequency of the VSI is 7.2 kHz.

| symbol | Description                | Value |
|--------|----------------------------|-------|
| PI     | Compensator proportional term | 0.8   |
|        | Compensator integral term   | 10    |
| PI\(_v\) | Voltage proportional term  | 5     |
|        | Voltage integral term       | 200   |
| PI\(_i\) | Current proportional term  | 1     |
|        | Current integral term       | 50    |

### 3. Power Sharing Strategy

Finishing equal reactive power sharing for the autonomous mode between the DG is connected to the MG is a complicated task. At the point when depending on the local current and voltage information, the VSI can't compensate for mismatches in their reactive power outputs, since the operating parameters of another DG are unknown. Therefore, to enhance the whole equivalent sharing of the reactive power
demand and the operation of the DG should use the MGCC to regulates the reactive power providing by everyone DG associated with the MG. The full loads send information to the MGCC regarding the reactive power divided to the MG. Then the MGCC at that point decides the amount of reactive power that each DG should be given and changes the reactive power of each DG during an outside loop as explained in Figure 2. Every VSI should transmit the voltage droop gain ($K_q$) to the MGCC in order to permit the perfect sharing of the reactive power. This process accomplished via the setup time just for example at the point while the DG is connected to the MG for the first time. Moreover, the reactive power demand for every DG can be specified through:

$$Q^*_x = \frac{Q_{load}}{K_{qx} \sum_{i=1}^{4} \frac{1}{K_{qi}}}$$  \hspace{1cm} (13)

Where the voltage droop gain of the inverter (x) represented by $K_{qx}$; $Q_{load}$ represents the reactive power used by the loads; $\sum_{i=1}^{4} (1/K_{qi})$ represents the collection for voltage droops of the DG linked with MG; and $Q^*_x$ represents the reactive power demand namely desired to be supplied by an inverter (x). PI controllers used by the MGCC to regulate the reactive power of everyone inverter. In this work, PI controllers provide an additional variation in voltage output which adds to the droop control output ($\Delta V^*$).

4. Simulation Results

In this work, the examined microgrid simulated with PSCAD/EMTDC software, there are five sequences of actions with each lasting three seconds. Additionally, the MGCC is supposed to regulate the voltage reference starting from the beginning of the simulation. Moreover, the four DGs have the same rating and operated together with total loads. The loads are shared between the DG units for real and reactive power load sharing according to the droop control and the equation (13). Reference points for voltage inverter output for the droop controllers were determined as previously discussed and transmitted to every DGs by the MGCC.

The rating of each DG in this case (0.3 MVA), and there are five sequences of actions with each lasting fifteen seconds. In the beginning, the loads represented by a fixed load with (0.3 MW, 0.1 MVAR). At 3 sec simulation time, the loads increased to (0.6 MW, 0.2 MVAR). Also, the real and reactive power was shared according to droop control and the equation (13). At 6 sec, the loads changed to (1 MW, 0.3 MVAR). Then, at 9 sec, the loads return back to (0.6 MW, 0.2 MVAR). Finally, at 12 sec, the loads returned to (0.3 MW, 0.1 MVAR).

Table 2 explained the parameters used for both DG and MG. In all the graphs, voltages are expressed in per unit, currents in kA, reactive powers in MVAR, and real powers in MW. The final response for real power, reactive power, and frequency is shown in Figure 4. Figure 5 is represents the voltage inverter output compared with the voltage of the common connection, and the output current from one DG.

| Table. 2 DG and MG parameters |
|-------------------------------------------------|
| **Description**                  | **Parameter** | **Value** |
| Rating of each DG system          | MVA           | 0.2       |
| Nominal voltage                  | $V_o$         | 480 $V_{L-L}$ |
| Nominal Frequency                | $w_o$         | 377 rad/s |
| Input DC voltage                 | $V_{DC}$      | 850 V     |
| Feeder 1 impedance               | $R + jX$ ($\Omega$) | 0.8 + j 0.434 |
| Feeder 2 impedance               | $R + jX$ ($\Omega$) | 1.0 + j 0.563 |
| Feeder 3 impedance               | $R + jX$ ($\Omega$) | 1.2 + j 0.372 |
| Feeder 4 impedance               | $R + jX$ ($\Omega$) | 0.9 + j 0.434 |
It can be noticed that, at the start of the simulation, the transient will be happening in active power, reactive power, and frequency droop but it is removed and reach to steady state with 0.3 sec by controlling ability. From the waves in Figure 4, notice that the active and the reactive power is shared accurately.

Figure 4. Output of (a) Active power (b) Reactive power (c) frequency
By examining the waves in Figure 5, the output voltage of each inverter must be larger than the PCC voltage to achieve the flow power and compensate for the losses in feeder impedance. When the power increased the current output increased and vice versa.

5. Conclusions
In this work, an enhanced MG reactive power load sharing strategy was proposed for parallel DGs in an islanded microgrid. This strategy uses reactive power load information to help calculated power sharing according to power rating for each DG then compared with reactive measurement, the error of reactive power load sharing is compensated by applying the PI controller. The output of the PI controller is used to adjust the voltage reference output from each inverter. The design and control of microgrid have been established by using PSCAD/EMTDC software. The simulated MG consists of four DG units with two fixed loads changing with time. DG operates with an equal power rating, so that, in this case the DG units segment the load equally. In this work, the value of feeder impedance is different from each DG to PCC. The active and reactive power is shared accurately and the obtained results show that the system remains stable through when the loads change periodically.
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