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Enhanced Reactive Power Sharing and Voltage Restoration Based on Adaptive Virtual Impedance and Consensus Algorithm

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Abstract: In this paper, power-sharing management control on an AC islanded microgrid is investigated to achieve accurate reactive power sharing. The droop control method is primarily used to manage the active and reactive power sharing among the DGs in the microgrid. However, the line impedance mismatch causes unbalanced reactive power sharing. As a solution a consensus-based adaptive virtual impedance controller is proposed, where the consensus algorithm is used to set the reactive power mismatch; then a virtual impedance correction term is generated through a proportional-integral controller to eliminate the line impedance mismatch. Thus, reactive power sharing is achieved without knowledge of the line impedances or using a central controller. Moreover, the consensus algorithm is used to restore the AC bus voltage to the nominal value by estimating the DGs average voltage using neighbor communication to compensate for the decreased magnitude of the voltage reference. Matlab/Simulink is used to validate the accuracy of reactive power sharing and voltage restauration achievement of the proposed solution through simulation of different scenarios. In addition, a dSPACE DS1104 is used within a developed experimental testbench based on two parallel DGs to validate the effectiveness of the proposed solution in the real world.

Keywords: consensus control; virtual impedance; microgrids; distributed generation; dSPACE controller; droop control

1. Introduction

The world energy demand is increasing quickly, and it is expected to reach 50% by 2050 [1]. This is due to the increase in the population of the world and the rapid development of technologies. To accommodate this growth in energy demand, the development of new power generation and massive integration of renewable energy become a priority respecting the agreements on the emission reduction of CO_2. Recently, several new technologies have been contributing to power generation plants such as the Distributed Generation (DG) using renewable energy sources, Electrolyzers (Ely) and fuel cells (FC), Electric Vehicles (EVs), and Energy Storage Systems (ESSs). Connected to a common bus with a centralized or decentralized controller and power management system with communication, they establish a new power generation system called a microgrid (MG). A MG can operate in both connected mode when it is coupled to the main grid, or autonomous mode when it is islanded [2,3].

The massive integration of Renewable Energy Resources (RES) in MGs can reduce the operation cost, increase the benefits on the environment by reducing the CO_2 emissions, and create new power sources [4]. However, the nature of these sources and sudden variations in the weather cause perturbation and instability to the MG, resulting in voltage

and frequency deviations. MGs are considered to have a low system inertia due to the low capacity of the DGs supplied by RES. Furthermore, the sudden changes in the connected loads may lead to critical frequency deviations and power flow management issues during the MG operation [5–7].

In autonomous microgrids, the connected DGs share the load power according to their power ratings for the profitability and to ensure the stability of the MG. The commonly adopted method in power sharing is the droop control approach. Active power sharing between DGs can be easily achieved using the frequency droop control method, whereas the reactive power sharing cannot be achieved easily due to the impedance mismatch between DGs which leads to voltage deviation and system instability [8,9]. To solve the inaccurate reactive power sharing issue, other ameliorated control methods have been developed [10–13]. In [10], a decentralized self-changing control was proposed using the adaptive droop control method. To increase the accuracy of reactive power sharing, an inductive virtual impedance (VI) loop was introduced; however, this method was not examined for a wide scope of working points. In [11], an adaptive droop controller was proposed to ensure dynamic stability of power sharing, where derivatives of active and reactive power are added to the traditional droop controller. Then, droop control gains were tuned adaptively conforming to the output power variations. However, the reactive power sharing was not as expected [12]. A modified Q-V droop control method was introduced in [13] to improve the power sharing accuracy. However, the reactive power sharing difference cannot be completely removed.

Other methods based on improved hierarchical control strategies have been proposed [14,15]. A secondary controller with a primary droop controller was presented in [14] to achieve accurate reactive power sharing in islanded MGs. However, a communication link between the central controller (CC) and DG's local controller is needed, increasing the response time and the total cost. In [15], virtual impedance control was applied in islanding MGs at different levels according to transient variations in the active power. A transient control term was used in the traditional droop control by injecting frequency disturbances. However, this approach could result in lower reliability and instability of the MG because of their reliance on the central controller. Moreover, the reactive power sharing was not addressed. Nonetheless, in these methods, power-sharing accuracy, especially reactive power can be influenced by communication congestion or delays regarding the number of connected DGs [16,17]. VI-based methods were widely used to improve reactive power sharing [18–20]. The VI is used to eliminate the impedance mismatch between lines and then improve reactive power sharing as well system stability. Based on injection of disturbances, online impedance estimation, or using MGCC, this approach can flexibly deal with the impedance mismatch between lines as well as the variation in load power, improving the dynamic performance of the MG. In order to enhance accurate reactive power sharing between parallel DGs, a complex VI approach including resistive and inductive factors systems was introduced [21,22] where the reactive power sharing was significantly enhanced. Furthermore, the result can be better with communication-based complex VI [23]. However, the communication delays can result in less reactive power sharing accuracy and degraded performance.

Recently, consensus algorithms were combined with the adaptive VI approach in order to guarantee accurate power sharing and current harmonics sharing. In addition, the voltage and the frequency value restoration can be achieved using these algorithms. Based on the information from neighbor communication or MGCC systems, the consensus approach is used to guarantee accurate reactive power distribution. The virtual impedance of DGs is tuned by the consensus approach to move towards a common objective in terms of reactive power sharing [24–26]. However, the communication system should be optimized to enhance the MG stability and improve the MG performance.

When only the neighbor communication system is used, the MG cost and communication time will be reduced. This kind of communication can be used in one or two directions, depending on the system specifications. Reactive current information can be used in order

to have accurate reactive power sharing. On the other hand, the active current information is used for active power sharing accuracy [27]. Moreover, to compensate for the voltage deviations and drop caused by the VI, DG output voltage restoration was introduced using a consensus algorithm [23]. The approach uses a communication system between adjacent DGs to exchange information on reactive power sharing and voltage restoration. However, this approach is dependent on communication system reliability. Microgrid reliability and efficiency are related to several parameters such as communication links and control strategy. MGCC presents a very sturdy and efficient control strategy. However, the complex communication system may increase the total cost as well as the impact of communication time delays. Therefore, decentralized control strategies are favored especially in autonomous MG where DGs, loads, and storage systems are from multiple customers. In this case, complex central communication systems should be avoided in order to reduce the information dependency on each DG.

Encouraged by this aspect, several attempts have been made by this work. Since the reactive power sharing issue is directly related to the DGs voltage and their behaviors, it can be solved based on information exchange between adjacent DGs and local information through a progressive process. The line impedance can be first estimated and tuned by each DG using the consensus algorithm; then this value can be shared with the neighbors. The VI is adaptively adjusted by the consensus algorithm to remove the mismatch between line impedance, ensuring accurate reactive power sharing without line impedance knowledge. Furthermore, the consensus control is used to compensate and restore the output voltage of each DG to the MG voltage. Therefore, the developed control contributions from this work are summarized as follows:

Adaptive virtual impedance control combined with a consensus algorithm is proposed for reactive power-sharing accuracy and parallel DGs voltage restoration with line impedance mismatch in autonomous MGs.

To achieve accurate reactive power sharing, neighbor information through a unidirectional communication link is used to estimate the VI, reducing the cost and the time delay impact of communication. Additionally, this approach cancels out the line impedance knowledge.

The proposed control approach was confirmed by experimental validation using a small-scale laboratory test bench based on MGs with two DGs.

The rest of the paper is arranged as follows: Section 2 presents the power sharing using conventional droop, the microgrid configuration, control, and modeling. Section 3 explores the proposed approach based on adaptive VI and consensus algorithms used to have accurate reactive power sharing and system voltage restoration. Then, Section 4 shows the simulation verification and Section 5 presents the experimental validation results of the proposed control approach. Finally, summary and main findings of this paper are presented in Section 6.

2. Droop Control and Reactive Power Sharing Theory

Droop control is the most used classical approach to control parallel DGs in power systems. This method presents high flexibility with good reliability and redundancy. It does not require a central controller or communication system and is mostly used in the primary control of MGs.

2.1. Droop Control

To analyze the power flow in steady state, it is assumed that the inverter is a controlled voltage source; then the dynamics of the inner control loop can be neglected. Figure 1 illustrates an inverter connected to the point of common coupling (PCC) through a line impedance Z.
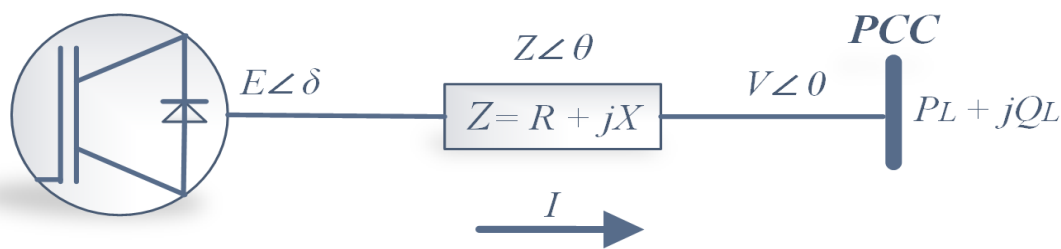
Figure 1. Inverter connected the point of common coupling.

Assuming a balanced 3-phase system, the power flowing in a transmission line can be derived by:

$$S = P + jQ = V * I = E * \left(\frac{E - V}{Z}\right)$$

$$S = E * \left(\frac{E - V * e^{j\partial}}{Z * e^{j\theta}}\right) = \frac{E^2}{Z} * e^{j\theta} - \frac{EV}{Z} * e^{j(\theta + \partial)} \tag{1}$$

where S, Q, P represent apparent, reactive, and active power, respectively. E represents the output voltage of the power inverter at an angle δ. Z represents the impedance of the transmission line between the inverter and the PCC with angles V and θ that represent the voltage at the PCC with an angle equal to zero.

Using Euler's simplification and replacing the line impedance by $Ze^{j\theta} = R + jX$, the active and reactive power equations can be written as follows [28]:

$$P = \frac{E}{X^2 + R^2}(R(E - V\cos\delta) + XV\sin\delta) \tag{2}$$

$$Q = \frac{E}{X^2 + R^2}(X(E - V\cos\delta) + RV\sin\delta) \tag{3}$$

In normal cases, the output power of a DG unit is far below the maximum transmission capability of the feeder line; thus, δ will be small. For this reason, the approximation $\cos\delta \rightarrow 1$ and $\sin\delta \rightarrow \delta$ can be adopted. In addition, assuming that the line impedance is inductive and satisfies the condition $Xi \gg Ri$ Equations (2) and (3) become:

$$\delta \cong \frac{XP}{EV} \tag{4}$$

$$E - V \cong \frac{XQ}{E} \tag{5}$$

Equations (4) and (5) show that the power angle strongly depends on the active power and the voltage difference depends on the reactive power. In other words, active power can be frequency controlled and reactive power regulated by voltage. This finding leads to the following common droop control equations:

$$\omega = \omega_0 - m_p P \tag{6}$$

$$V = V_0 - n_Q Q \tag{7}$$

where V_0 and ω_0, represent the nominal values of the voltage and the frequency, n_Q and m_P represent the droop coefficients, and V, ω, represent the nominal output of the voltage and the frequency. Then, the droop control coefficients (n_Q, m_P) can be defined by the following equations [28,29]:

$$m_p = \frac{\Delta\omega_{max}}{P_{nominal}} \tag{8}$$

$$n_q = \frac{\Delta V_{max}}{Q_{nominal}} \tag{9}$$

$$m_p = \frac{\Delta\omega_{max}}{P_{nominal}} \tag{8}$$

$$n_q = \frac{\Delta v_{max}}{Q_{nominal}} \tag{9}$$

2.2.2. Reactive Power Sharing

Accurate reactive power sharing cannot be achieved by conventional droop control. In order to solve the issue and eliminate the deviations of the voltage and frequency, secondary control was used. Figure 2 shows the investigated MG configuration. It is composed of distributed generation (DG) based renewable energy sources and a battery storage system (BSS). Each DG is connected to a common AC bus through an inverter and an LCL filter.
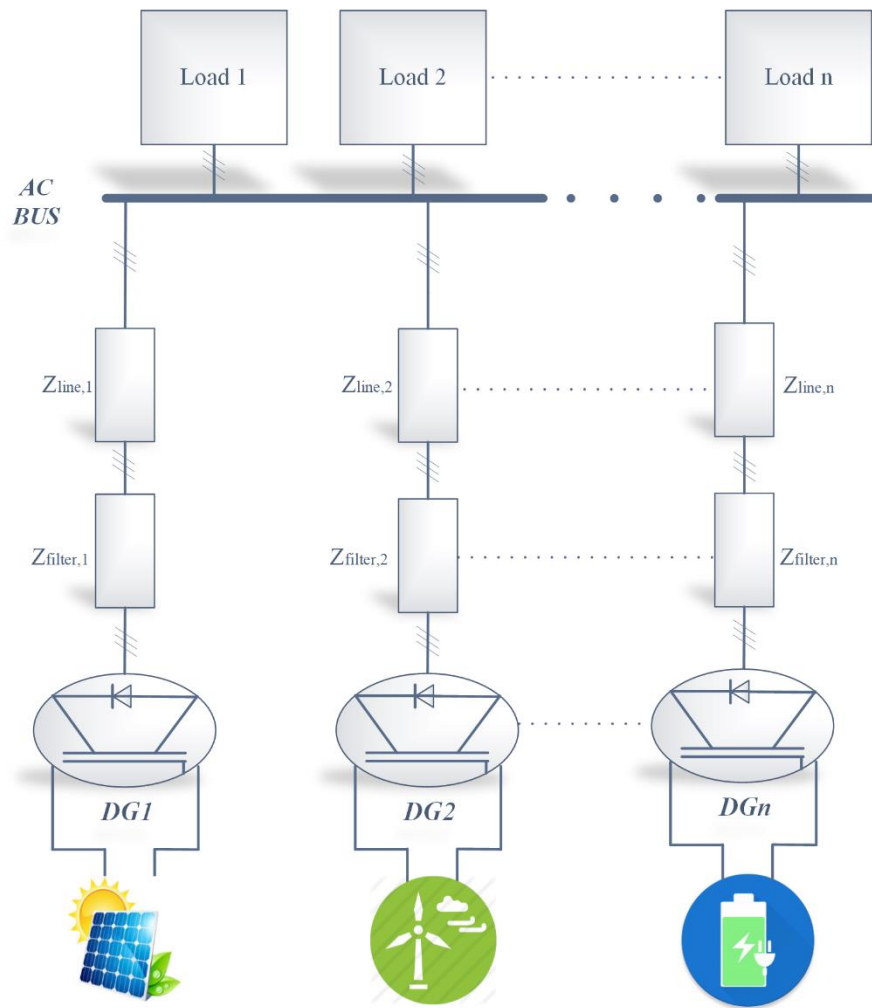
Figure 2. Configuration of the investigated islanded microgrid.

The control structure of the MG is based on hierarchical control using primary and secondary control levels. The primary control contains the current and voltage control loops. While the secondary control contains the consensus algorithm, adaptive virtual impedance, and droop control.

2.3. DGs Modeling and Global Control Strategy

The control strategy at the primary control level is based on proportional-integral (PI) controllers. Figure 3 shows the global control scheme of inverters for each DG. Secondary control level includes the droop controller, power calculation, the adaptive virtual impedance, and the consensus algorithm with the communication network. References of voltage and adaptive VI value are generated and sent to the primary control level. Afterward, inverter control signals are generated based on these references. An LCL filter is used to connect the inverter to the AC bus, where L_f is the inverter side inductor of the

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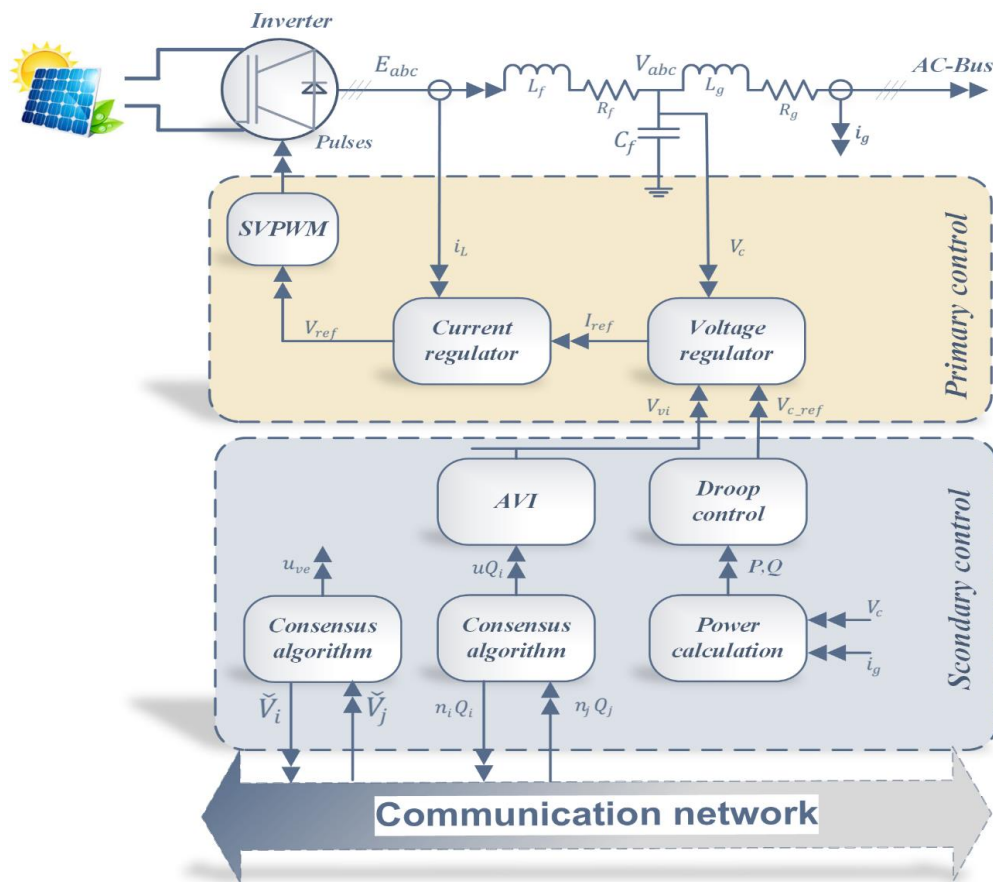
Figure 3. Global control scheme of DGs.

The dynamic equations model can be derived using voltage and current law followed by Park transformation as follows:

$$L_f * \frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} E_d \\ E_q \end{bmatrix} - \begin{bmatrix} v_d \\ v_q \end{bmatrix} - R_f \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & \omega L_f \\ -\omega L_f & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{10}$$

$$C_f * \frac{d}{dt}\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} + \begin{bmatrix} 0 & \omega C_f \\ -\omega C_f & 0 \end{bmatrix}\begin{bmatrix} v_d \\ v_q \end{bmatrix} \tag{11}$$

where E_d, E_q represent direct and quadrature voltage before the filter, V_d, V_q after the filter, and I_d, I_q the current direct and quadrature values. After simplification, the equations of the current and the voltage controllers can be written as follows [2]:

$$\begin{cases} I_{ref\_d} = \left(K_{pv} + \frac{K_{iv}}{S}\right)\left(V_{cdref*} - V_{cd}\right) - \omega C V_{cq} + i_{gq} \\ I_{ref\_q} = \left(K_{pv} + \frac{K_{iv}}{S}\right)\left(V_{cqref*} - V_{cq}\right) - \omega C V_{cd} + i_{gd} \end{cases} \tag{12}$$

$$\begin{cases} V_{ref\_d} = \left(K_{pi} + \frac{K_{ii}}{S}\right)\left(i_{ref\_d} - i_{ld}\right) - \omega L_f i_{lq} + V_{cq} \\ V_{ref\_q} = \left(K_{pi} + \frac{K_{ii}}{S}\right)\left(i_{ref\_q} - i_{lq}\right) - \omega L_f i_{ld} + V_{cd} \end{cases} \tag{13}$$

where K_{pi}, K_{ii} are the proportional and the integral coefficients of the current PI controller, K_{pv}, K_{iv} are the proportional and the integral coefficients of the voltage PI controller. V_{cdref*}

and V_{cqref*} are the voltage references calculated by the droop controller. The adaptive VI control is as follows:

$$\begin{bmatrix} V_{cdref*} \\ V_{cqref*} \end{bmatrix} = \begin{bmatrix} V_{c\_refd} - V_{vi\_d} \\ V_{c\_refq} - V_{vi\_q} \end{bmatrix} \quad (14)$$

where V_{vi_d}, V_{vi_q} represent the references from the adaptive VI controller and V_{c_refd}, V_{c_refq} the references of the droop controller.

3. Adaptive Virtual Impedance and Consensus Algorithm

In a MG, the active and reactive power are coupled and depend on the output frequency and voltage due to the nature of the line impedance, which can be resistive inductive or both. The use of VI in combination with the physical impedance can modify the total output impedance of the DG. In this section, the proposed approach based on adaptive VI and consensus algorithms is explored.

3.1. Adaptive Virtual Impedance

VI has been used for many applications recently, such as reactive power sharing by ensuring a consistent and equivalent output impedance for all parallel DGs in the autonomous MGs [2,25–27]. This VI can be adjusted adaptively in order to calculate the total impedance and then the voltage reference. Thus, the total output impedance of a DG can be written as follows [27]:

$$Z_i = Z_{line,i} + Z_{v,i} + Z_{adp,i} \quad (15)$$

Z_i represents the total output impedance of the DG_i and the line impedance can be represented by $Z_{line,i}$. The virtual impedance can be divided into two terms, $Z_{v,i}$ which represents the static virtual impedance value used to ensure an inductive total impedance. The other term, $Z_{adp,i}$ represents the adaptive VI. Equation (15) shows that the output impedance of each DG is increased by the adaptive term in order to match with other DG impedances and eliminate the mismatch. Then, reactive power sharing can be improved using droop control relations.

3.2. Consensus Algorithm

In order to have a similar output impedance between different DGs, in this work, the adaptive VI in Equation (14) is calculated and adjusted using a consensus algorithm. To have an accurate reactive power sharing, consensus control is used to reach a general agreement among all MG agents. Thus, the droop control and reactive power coefficients must be designed to be inversely proportional, according to the following equation [26–29]:

$$n_{Q1}Q_1 = n_{Q2}Q_2 = \ldots = n_{QN}Q_N \quad (16)$$

By replacing (7) in (5), the reactive power flow of each DG can be written as follows:

$$n_{qi}Q_i = \frac{V(E_0 - V)}{\frac{X_i}{n_i} + V} \quad (17)$$

Therefore, to satisfy Equation (16), the term Xi/ni of each DG must be the same in Equation (17), from which the following equation can be written:

$$\frac{X_1}{n_1} = \frac{X_2}{n_2} = \ldots = \frac{X_N}{n_N} \quad (18)$$

From Equation (18), it can be noticed that the term n_i must be proportional to the line reactance X_i. Considering Equation (16), in order to obtain accurate reactive power sharing the reactance of the line must be designed to be inversely proportional to the reactive power, then the following equation can be written [23,25,26]:

$$X_1 Q_1 = X_2 Q_2 = \ldots = X_N Q_N \tag{19}$$

The consensus control of the reactive power can be treated as a synchronization problem of a first-order linear agent system [26–28]. Then, Equation (20) is obtained from the linearization of Equation (15):

$$u_{Q_i} = n_{Qi}\dot{Q}_i = -C_{nQ}e_{niQi} \tag{20}$$

where, u_{Q_i} is the auxiliary control, e_{niQi} represents the reactive power error between the local DG and its neighbor, and C_{nQ} is the coupling gain. The local neighbor's reactive power sharing error is represented by:

$$e_{niQi} = \sum_{j=N} a_{ij}\left(n_{Qi}Q_i - n_{Qj}Q_j\right) \tag{21}$$

where a_{ij} represents the changes in connection between DGs from the adjacency matrix. The whole consensus system can be written in matrix representation as:

$$\begin{bmatrix} u_{Q_1} \\ u_{Q_1} \\ \cdot \\ \cdot \\ \cdot \\ u_{Q_N} \end{bmatrix} = \begin{bmatrix} n_{Q1}\dot{Q}_1 \\ n_{Q2}\dot{Q}_2 \\ \cdot \\ \cdot \\ n_{QN}\dot{Q}_N \end{bmatrix} = -\begin{bmatrix} n_{Q1}\dot{Q}_1 \\ n_{Q2}\dot{Q}_2 \\ \cdot \\ \cdot \\ n_{QN}\dot{Q}_N \end{bmatrix} * \sum_{j=N}\begin{bmatrix} a_{1j} \\ a_{2j} \\ \cdot \\ \cdot \\ a_{Nj} \end{bmatrix} * \begin{bmatrix} \left(n_{Q1}Q_1 - n_{Qj}Q_j\right) \\ \left(n_{Q2}Q_2 - n_{Qj}Q_j\right) \\ \cdot \\ \left(n_{QN}Q_N - n_{Qj}Q_j\right) \end{bmatrix} \tag{22}$$

Then the Adaptive VI references in Equation (14) can be presented as follows:

$$\begin{bmatrix} V_{vi\_d} \\ V_{vi\_q} \end{bmatrix} = \begin{bmatrix} R_{vi} & -\omega L_{vi} \\ R_{vi} & \omega L_{vi} \end{bmatrix}\begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} \tag{23}$$

$$\begin{bmatrix} L_{vi} \\ R_{vi} \end{bmatrix} = \begin{bmatrix} L_{vi}^* \\ R_{vi}^* \end{bmatrix} - u_{Q_i}\begin{bmatrix} k_l \\ k_r \end{bmatrix} \tag{24}$$

where, L_{vi}^* and R_{vi}^* represent the resistance and inductance of the static impedance. L_{vi}, and R_{vi} are the resistance and inductance of the VI. k_l and k_r are adjusting gains of the consensus controller. Based on these equations, the adaptive *VI* implementation is illustrated in Figure 4.
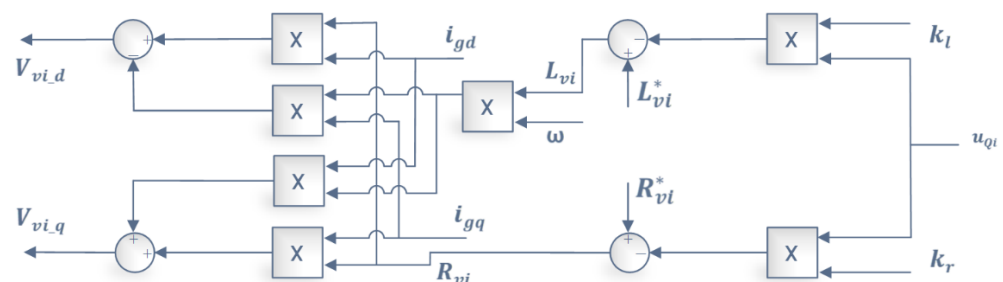
Figure 4. Adaptive VI and consensus algorithm implementation.

3.3. Bus Voltage Restoration

In order to compensate the voltage drop caused by the droop control and the VI, a secondary voltage controller based on consensus control is used to restore the average voltage of each DG to the MG nominal voltage. This will limit the voltage deviation between DGs in DG to the MG nominal voltage and will enable the operation of the MG. The average voltage of each DG can be defined as the average output voltage value of all MG DGs [23,26,27]:

$$\check{V} = \sum_{j=1}^{N}\frac{V_j}{N} \tag{25}$$

where $\check{V}$ is the average voltage, V_j is the output voltage of DG_j, and N is the total number of DGs connected to the MG. Using the consensus based adaptive *VI* control, once the virtual impedance is adaptively set and the reactive power sharing is achieved, the droop

between DGs, improve the power flow control, and ensure a reliable operation of the MG. The average voltage of each DG can be defined as the average output voltage value of all MG DGs [23,26,27]:

$$\check{V} = \sum_{j=1}^{N} \frac{V_j}{N} \qquad (25)$$

where $\check{V}$ is the average voltage, V_j is the output voltage of DG_i, and N is the total number of DGs connected to the MG. Using the consensus-based adaptive VI control, the de-dop virtual impedance is adaptively set and the reactive power sharing is achieved, rendering the DG output voltage controller output voltage of each DG becomes the same. However, the DG output voltage at the filter output level cannot be identical for all the DGs due to impedance mismatch, as explained previously. This can cause deviations in the output voltage and exceed the allowable range. Therefore, a secondary control for voltage restoration should be used to regulate the average MG voltage. The DG average voltage estimation can be expressed using its own output voltage $\check{V}_i$ and its neighbor DG voltage $\check{V}_j$:

$$\check{V}_i(t) = V_i(t) + C_v \int \sum_{j \in n_i} a^{ij} (\check{V}_i(t) - \check{V}_j(t)) \, dt \qquad (26)$$

where V_i is the voltage of DG_i and C_v is a coupling gain. Then, the dynamics of the voltage consensus control can be expressed as follows:

$$\dot{\check{V}}_i(t) = \dot{V}_i(t) + C_v \sum_{j \in n_i} a^{ij} (\check{V}_i(t) - \check{V}_j(t)) \qquad (27)$$

The implementation of the proposed approach for voltage restoration is shown in Figure 5:
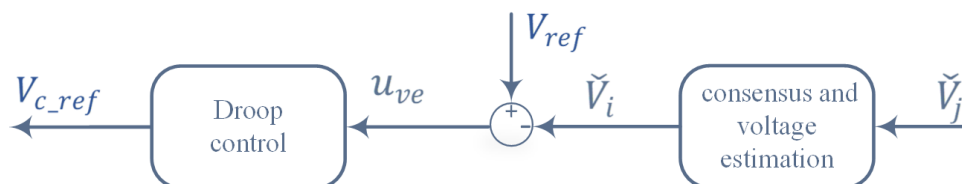
Figure 5. Implementation of the reference voltage generator.

4. Simulation Verification

In order to verify the effectiveness of the proposed control approach, simulation tests were conducted using MATLAB/Simulink software. The MG shown in Figure 2 was modeled in Simulink. The MG is composed of three DGs connected to renewable energy sources (solar or wind) with different rated powers and a battery storage system. All DGs are connected to the AC bus through an LCL filter and an impedance. Moreover, different loads are connected to the AC bus. All DGs are connected to a communication link in order to change information between neighbors. The sharing power ratio is 1:1:0.5 for DG1, DG2, and DG3, respectively. Table 1 shows the parameters used in this simulation. The simulation is divided into three parts. In the first one, reactive power sharing accuracy was verified using the proposed control approach. In the second one, the robustness of the control approach under load changes is explored, and finally, in the third one, the voltage restoration performance was investigated.

Table 1. Simulation parameters.

Parameters	Value
Inverter power rating	5 KVA
Line voltage	208 V
Bus frequency	60 Hz
Dc bus voltage	400 V
Line impedances	
line 1	7.5 mH, 0.6 Ω
line 2	4.5 mH, 0.5 Ω
line 3	7.5 mH, 0.6 Ω
Proportional gain in PI current controller Kpi	50
Integral gain in PI current controller Kii	0.5

Table 1. *Cont.*

Parameters	Value
Proportional gain in PI voltage controller Kpv	2
Integral gain in PI voltage controller Kiv	0.5
Droop coefficient	
mP1, mP2	2×10^{-4}
mP3	4×10^{-4}
nQ1, nQ2	5×10^{-4}
nQ3	7.5×10^{-4}
Load 1	4 kW, 1.1 kVAR
Load 2	2.2 kW, 0.6 kVAR
Load 3,4	1 kW, 0.25 kVAR

4.1. Case Study #1

Figure 6 represents the active power sharing between the three DGs. The active power was well shared before and after applying the proposed strategy. The reactive power sharing is shown in Figure 7, where it is not achieved using the conventional method. The proposed control strategy was applied at t = 7.5 s, which offers an accurate reactive power sharing in the desired ratio without affecting the active power sharing. The virtual resistance and reactance of each DG are illustrated in Figures 8 and 9.
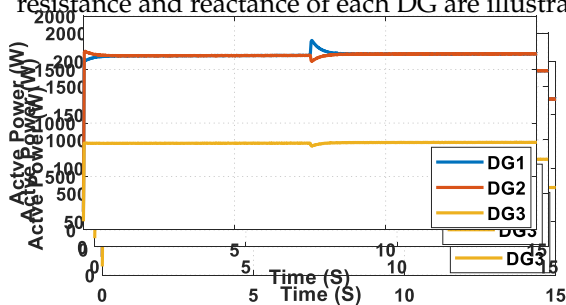
Figure 6. Active power of DGs.
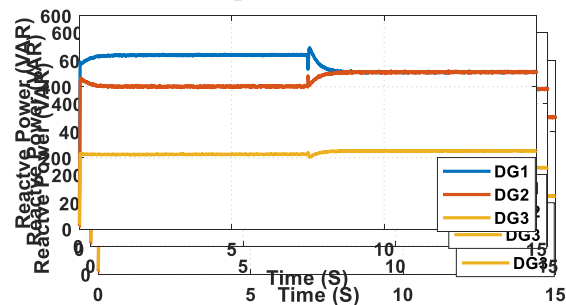
Figure 7. Reactive power of DGs.
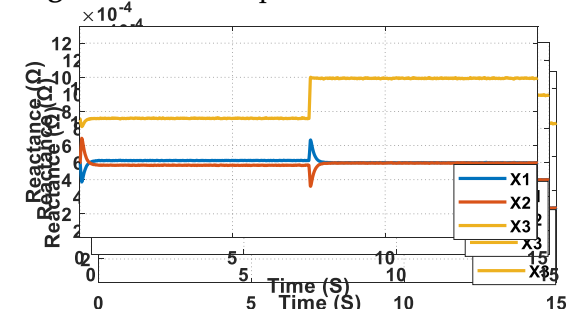
Figure 8. Virtual impedance reactance.
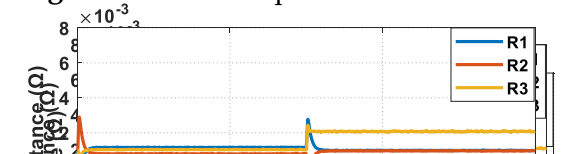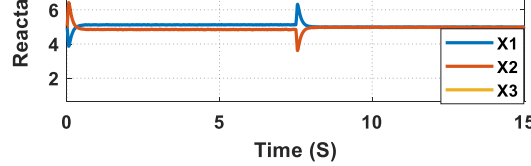
Figure 8. Virtual impedance reactance.
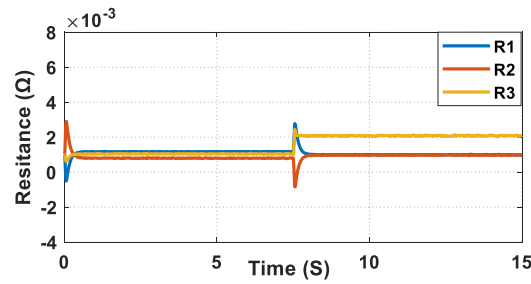
Figure 9. Virtual impedance resistances.

After activating the consensus algorithm control, DG1 and 2 resistance and reactance values become equal. This is due to their equal power-sharing ratios. While the resistance and reactance values for DG3 are larger because the sharing ratio of this DG is lower than the others. The output currents corresponding to the three DG units are indicated in Figure 11a–Figure 10c, shows a zoom, before and after the application of the proposed controller. Before the application of the proposed method, there is a phase shift between the three DGs currents. After t = 7.5 s, the output currents of DGs become synchronized and proportional to the nominal power demanded by loads and the phases are almost identical.

(a)

(b)

(c)

Figure 10. Output currents of DGs, (a) output current, (b) zoom before, and (c) zoom after applying the proposed controller.

4.2. Case Study #2

In the second part of the simulations, the performance of the system was tested during load changes. In this case study, the renewable resources are operated under deloaded mode, their maximum output power is between t = 5 s and t = 7.5. Otherwise, they are operated under deloaded mode. Initially, the system load is (2.2 kW, 0.6 kVAR), after t = 2.5 s the load was increased to (3.2 kW, 0.85 kVAR), then after t = 5 s, the load was increased to (4.2 kW, 1.1 kVAR). Finally, at t = 7.5 s the load was reduced to (3.2 kW, 0.85 kVAR). The simulation results are shown in Figures 11–14. For active and reactive power sharing and by ignoring transient periods as shown in Figures 11 and 12, the consensus control eliminates progressively the reactive power error between DGs during

Figure 11. Active power of DGs.

Figure 10. Output currents of DGs, (**a**) output current, (**b**) zoom before, and (**c**) zoom with the proposed controller.

all periods of load changes, this provides improved power sharing, as shown by these results. The reactive power is well-distributed and proportional to the power demand of each DG. The load was changing during simulation, as presented in Figure 14.
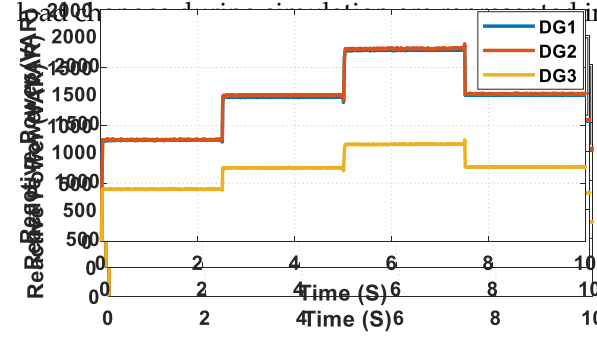
Figure 11. Active power of DGs.
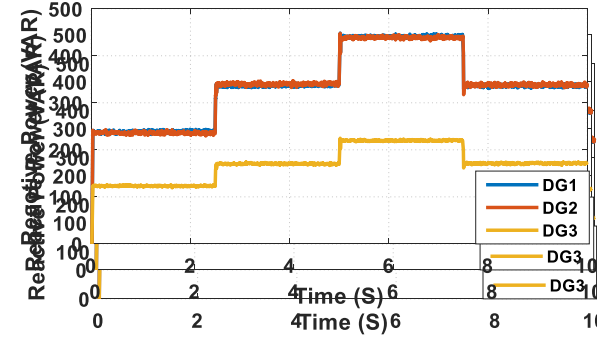
Figure 12. Reactive power of DGs.
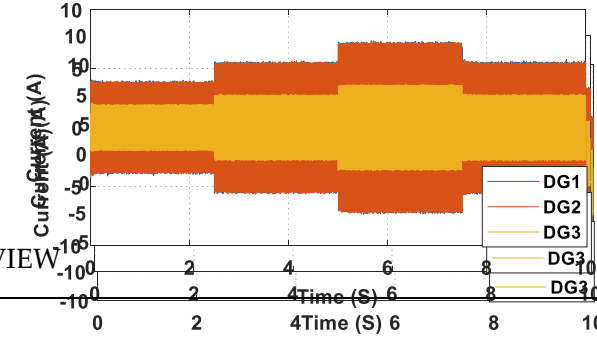
Figure 13. Output current of DGs.
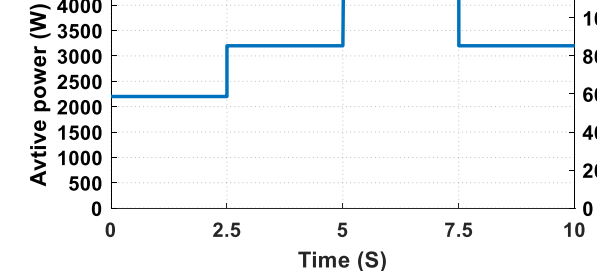
Figure 14. Load profile.

4.3. Case Study #3

The third simulation case was dedicated to voltage restoration contro ning, one load was connected to the AC bus, then at time t = 1.5 s the rest was activated. To verify the effectiveness of the voltage restoration contro

4.3. Case Study #3

The third simulation case was dedicated to voltage restoration control. At the beginning, one load was connected to the AC bus, then at time t = 1.5 s the restoration was activated. To verify the effectiveness of the voltage restoration control, one load was connected to the AC bus at t = 3 s. The results of this simulation are shown in Figures 15–20. Initially, the output voltages of the three DGs are lower than the reference, as shown in Figure 15. After application of the proposed control (at t = 1.5 s), the voltage of each DG was increased until the average voltage was set to the nominal voltage. The active and reactive power sharing was always maintained, as shown in Figures 16 and 17. Likewise, the output frequency was maintained within the limits (Figure 18). Figure 19 shows the average voltage of the AC bus. The latter represents a minimum after the activation of the restoration control which represents the nominal value. The currents of DGs are illustrated in Figure 20, an increase regarding the sharing ratio for each DG was observed after time t = 3 s due to the load increase. The load changes during simulation are presented in Figure 21. The load changes during
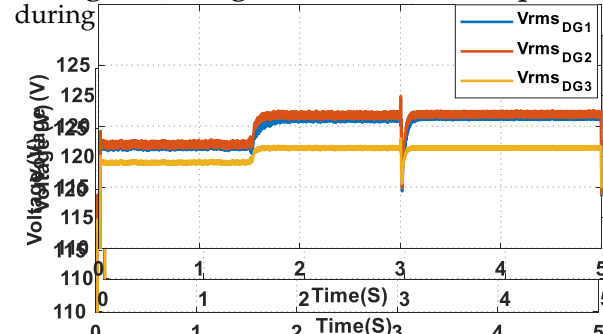
Figure 15. Output voltage of DGs.
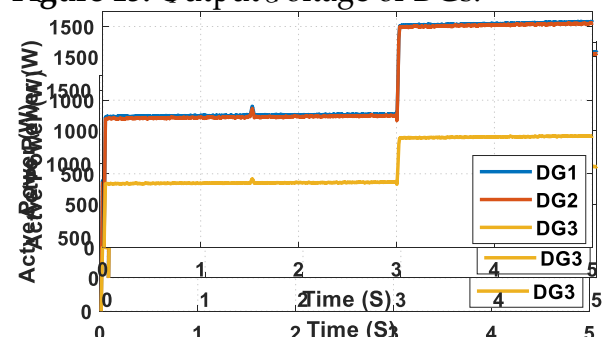
Figure 16. Active power of DGs.
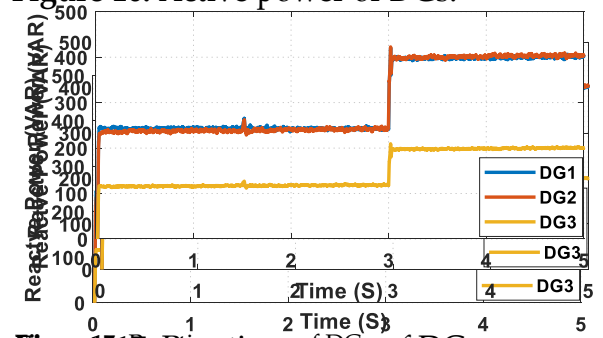
Figure 17. Reactive power of DGs.

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Figure 18. Frequency of DGs.

Figure 19. Average AC bus voltage.

Figure 20. Output current of DGs.

Figure 21. Load profile.

5. Experimental Validation

In order to validate the proposed control approach, the simulation results were compared with experimental ones. A laboratory-scale MG was constructed and used to validate the proposed control. A dSPACE DS1004 control board was used to implement different control algorithms. Two inverters were built using the KCM3…

the line impedances. Finally, two inductive resistive loads are connected to the AC bus through contactors to allow connection or disconnection of these loads. The experimental parameters are illustrated in Table 2 and the benchmark is shown in Figure 22.

Table 2. Experimental parameters.

Parameters	Value
Power rating	500 VA
Line voltage	40 V
Bus frequency	60 Hz
DC bus voltage	80 V
Line impedances	
line 1	0.82 mH, 0.02 Ω
line 2	1.2 mH, 0.03 Ω
Proportional gain in PI current controller Kpi	100
Integral gain in PI current controller Kii	0.5
Proportional gain in PI voltage controller Kpv	50
Integral gain in PI voltage controller Kiv	1.5
Droop coefficient	
mP1	2×10^{-3}
mP2	4×10^{-3}
nQ1	5×10^{-3}
nQ2	7.5×10^{-3}

Figure 22. Laboratory experimental benchmark.

5.1. Case Study #1

The first scenario of experimental validation was carried out to verify the sharing of active and reactive powers. The power sharing ratio in these tests is the same for the two DGs. Figure 23 shows the active power shared between the two inverters, before and after the application of the proposed approach. The reactive power sharing is shown in Figure 24. It was not achieved using the conventional method until the application of the proposed control strategy at t = 7.5 s, which allows a reactive power sharing. The output currents of inverters are illustrated in Figure 25. Figure 25 shows, before and after the activation of the proposed controller. A phase shift between the outputs was observed before the application of the proposed control. After 7.5 s, they become synchronized.

Figure 23. Active power of DGs (1 div = 10 W).

Figure 24. Reactive power of DGs (1 div = 10 VAR).

Figure 25. (**a**) output currents (**b**) zoom before the collapse (**c**) zoom after the collapse.

ness of the proposed approach by increasing load. The load was increased from (280 W, 30 VAR) to (380 W, 60 VAR) at time t = 10 s. As expected, the results are similar to the simulation, both DGs follow the change, and the active and reactive power was shared according as shown in Figures 26 and 27 respectively. Figure 28 shows the voltage of the load, a slight drop was observed when the load increases. Figure 29 shows the load changes during simulation. The output currents of each DG are shown in Figure 30 at the top. The currents are well synchronized with the same amplitude, then increase when the load rises, while the control scenario voltage keeps the same value as mentioned, shown at the bottom.

5.2. Case Study #2

In the second scenario, another experimental test was carried out to verify the robustness of the proposed approach by increasing load. The load was increased from...

top. The currents are well synchronized with the same amplitude, then increase when the
load rises, while the DGs output voltage keeps the same value as shown in the same figure
at the bottom. This confirmed the effectiveness of the proposed method with the same RMS
value. Finally, the output voltages of each inverter are shown in Figure 31. They
represent the phase a and b voltages. They are well synchronized with the same RMS
value.

Figure 26. Active power of DGs (1 div = 10 W).

Figure 27. Reactive power of DGs (1 div = 100 VAR).

Figure 28. Output voltage of DGs.

Figure 29. Load profile.

Figure 30. Output current of DGs (1 div = 5 A/50 V).

Figure 31. Output voltage of DGs (1 div = 5 A/50 V).

6. Conclusions

In this paper, a new power flow management algorithm was proposed to improve reactive power sharing between parallel inverters in islanded MGs. The proposed strategy was based on the adaptive VI approach with consensus algorithms in order to ensure better reactive power sharing under line impedance mismatch. The consensus algorithm was used to estimate and adjust the values of the VI. Then, the obtained VI was added to the total impedance to calculate the new reference voltage for the primary controller. This control approach improves reactive power sharing without the need of a central controller or the line impedance value. The consensus algorithm uses a simple communication link between neighbors' DGs, minimizing the cost and increasing the efficiency of the MG. Furthermore, to compensate for the output voltage drop produced by the VI, a secondary voltage controller based on a consensus algorithm was used. This controller can restore the average voltage of each DG to the nominal MG voltage. This eliminates the voltage deviation between DGs and ensures reliable operation of the MG under hierarchical control. Finally, simulations and experimental results were presented to validate the performance and feasibility of the proposed controller. These results show that the overall control system provides a complete solution for improving MGs dynamic performance, accurate reactive power sharing, and output voltage restoration, while ensuring the robustness of the MGs under connected load changes, uncertainties, and possible disturbances.

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