Reactive power sharing improvement of droop-controlled DFIG wind turbines in a microgrid

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Abstract: This study presents an innovative control scheme to improve the power sharing among doubly-fed induction generator (DFIG) wind units in a medium-voltage (MV) microgrid. The control objectives of DFIGs in an islanded mode of microgrid operation are to achieve: (i) stabilisation of the microgrid voltage amplitude and frequency, (ii) proper active/reactive power sharing among wind units. To satisfy these requirements, the DFIG control loop based on the traditional droop control is designed. This method, however, cannot satisfactorily operate in a MV microgrid with dominantly resistive line impedances from power sharing point of view. To overcome this problem, a modified control strategy is proposed in this study. The mathematical modelling is developed, and time-domain simulations are presented to verify the novel control scheme in a typical microgrid case study.

1 Introduction

A microgrid is a local network consisting of interconnected distribution generators (DGs) and controllable loads that can operate independently in an islanded mode [1]. The microgrid is connected to the utility grid in the normal mode of operation. However, after some disturbances such as faults, switching incidents or preplanned switching events, the microgrid should be isolated from the grid and supply the local load. The rapid growth of electrical consumption and the necessity to reduce the physical distance between the generation part and the demand section justifies utilisation of DGs in the microgrids which can provide electrical power with a higher reliability and quality for the local loads [2]. Moreover, due to environmental, technical and financial issues, the diesel units can be replaced by renewable energy (RE) sources. These RE units may be connected to the microgrid either directly through an AC rotating machine or through a power electronic converter. Among various types of RE sources, wind power is widely used in many parts of the world due to its cost-effective technology and commercial viability [3]. A doubly-fed induction generator wind turbine (DFIG-WT) is one of the most relevant technologies in the 1–3.5 MW range of operation. The stator of a DFIG-WT is connected directly to the microgrid, while the rotor is connected by a back-to-back partially scaled power electronic converter through slip rings.

The DFIG-WT operation in the microgrid is an active field of research that has been investigated based on different approaches. The common purpose of these investigations is to provide reliability of operation [4, 5] and to enhance the power quality that is required by consumers. In the technical literature, reduction of the voltage fluctuation in a microgrid target bus has been widely investigated and solutions such as suppression of output active power fluctuation from DFIG [6] or reactive power management [7, 8] have been proposed. In these articles, it is supposed that the voltage amplitude and frequency of the microgrid are stabilised by diesel generators or by the bulk power system. Therefore, the PQ control strategy is implemented in DFIG-WTs control block diagrams. This assumption is not valid in a microgrid with a significant number of DFIG-WTs in the isolated mode. In such a system, some of the DFIG-WTs should regulate the voltage amplitude and frequency of the microgrid, and therefore, their control strategies should be modified. In [9, 10], the DFIG-WT is employed to improve the dynamic behaviour of the microgrid by the virtual inertia control method. This scheme, however, cannot assist in long-term frequency and power regulation, i.e. the primary frequency control [11]. A conventional and yet a robust approach to obtain frequency and voltage control in an islanded microgrid is the traditional $P–f$ and $Q–U$ droop control which is based on a well-known concept in large-scale power systems [12]. The implementation of this method in a microgrid is reported with different approaches. The droop control in [11] is implemented to show the capability of DFIG-WTs to participate in the primary frequency control. In [13], the aim of optimal droop control is to minimise the necessary control action in order to track the active power demand. Reduction of mechanical stresses and equipment damages are the final results of this paper, while the stable operation and reliability are ensured. In [14], each stand-alone DFIG has autonomous frequency control over its stator voltage. Multiple units of such DFIGs are synchronised to form a common wind farm grid frequency. In all discussed papers, the main focus of research concentrates on the microgrid primary frequency control. The voltage stability of microgrid and reactive power flow in a microgrid are not studied in these papers. The study results in [15] show that the proposed droop control approach for DGs in the microgrid reduces frequency changes and improves the microgrid dynamic performance, as well as it achieves better voltage regulation in islanding and autonomous operations.

In [16], the islanded operation of an electrical grid that is supplied by wind turbines is achieved by applying droop control to the grid-side inverter of some variable speed wind turbines in the network. In [17], similar to [16], the proposed control strategy enables voltage and frequency regulation in the network and the microgrid voltage stability is also studied. However, none of the above papers consider proper case studies to investigate the power sharing among parallel DFIG-WTs. In these researches, it is assumed that the X/R ratios of the electrical lines are high. This assumption is not true in medium-voltage (MV) microgrids where the conventional droop implementation yields the circulating currents among the units because of low X/R ratio and it creates extra burden to the system. In [18], a torque- and power-droop implementation in DFIG-based units are presented by some simple modifications in the conventional droop control to evaluate the effect of both techniques on the frequency stability of a microgrid or weak grid. In spite of considering the droop implementation in weak grids in this paper, the aforementioned implementation is applied to one DFIG-WT. Therefore, the effects of proposed
method from the power-sharing point of view among parallel DFIG-WTs are not studied. This paper also concentrates on frequency stability; whereas, voltage stability and circulating powers are not considered. In [19, 20], the voltage amplitude and frequency control of an islanded microgrid are shared by the wind generators through droop characteristics. This control structure is quite suitable for cases where the wind generators supply significant part of the load power. These papers modify the standard droop method in order to force the generators to share the load according to their available wind power and not just the generator ratings. However, the main disadvantage of this approach is that the proposed method is based on the traditional droop control, which does not properly function in MV microgrids. In a typical MV microgrid, the R/X ratio is between 1 and 10 [21]. Thus, the traditional droop control performance is significantly degraded in such a network and the power sharing is not correctly achieved; hence, the circulating currents will flow among the units. In an electronically coupled DG that utilises a power electronic converter as the interface to the microgrid, the virtual impedance scheme is employed as an effective approach to overcome the circulating current problem [22–25]. Usually a virtual output impedance loop is added to balance the coupling impedances among DGs to improve power sharing. This approach, however, cannot solve the circulating current problem of DFIG-WTs, where the stator is directly connected to the microgrid and the back-to-back converter is placed in the rotor circuit. The virtual impedance implementation in a back-to-back converter adds a virtual series impedance in the rotor circuit, not in the stator. Therefore, this implementation does not compensate the output impedance mismatches of the DFIG-WTs and the coupling line impedances remain unbalanced.

Motivated by the aforementioned challenges, this paper presents a droop control method to incorporate wind generation in autonomous frequency and voltage regulation in weak microgrids with low X/R ratios. Here, the key parameters that influence the power sharing of DFIG-WTs in a resistive microgrid are discussed based on mathematical equations. It is shown that in MV microgrids, the conventional droop implementation causes reactive current circulation among units. A novel control strategy based on ‘reactive communication link’ is proposed to suppress these circulating currents. Simulation results show that the ‘reactive communication link’ only transmits the reactive power set points among DFIG-WTs and requires low bandwidth communication link with low data transmission capability. Hence, the implementation of this novel idea does not need extra cabling and extra cost in existing DFIG-based microgrids with relevant power line carrier communication (PLCC) systems. The communication delay can restrict the maximum number of installed DFIG-WTs in microgrids with PLCC systems. Simulation results show that the proposed method can be successfully implemented in PLCC-based microgrids with <6S installed DFIG-WTs that have a significant percentage of installed resistive microgrids around the world. The proposed control method consists of three main loops: an inner loop that regulates the output voltage and frequency, an intermediate loop that performs the droop control strategy, and an outer loop that adjusts the reactive power sharing among DFIG-WTs. The performance of this proposed approach is verified by the Matlab/Simulink software package.

The contributions of this paper to the microgrid research field are:

i. Developing a mathematical study for droop control implementation in DFIG-based MV microgrids.

ii. Investigating the impact of traditional droop implementation on weak microgrids operation from reactive power circulation point of view.

iii. Proposing a modified droop control implementation in DFIG-WTs control systems to solve the reactive power circulation challenge.

iv. A low bandwidth communication link is enough to implement the above method. Hence, the implementation of this novel idea does not need extra cabling and extra cost.

The rest of the paper is organised as follows. In Section 2, the primary theoretical background is reviewed. In Section 3, the DFIG operation in the MV microgrids is studied and the circulation current is investigated. Section 4 proposes the new control scheme to ensure proper power sharing among DFIG-WTs. Section 5 presents the simulation results and the conclusions are stated in Section 6.

2 Theoretical background

A microgrid is usually operated in the grid-connected mode and the voltage and frequency are imposed by the grid. Hence, the DFIG-WTs are controlled by the PQ control strategy and forced to operate in their maximum power points at constant power factor. In this mode, the grid acts as an infinite bus that stabilises the voltage and frequency of the microgrid with adequate active and reactive power support. The main challenge in a microgrid control is associated with its islanded operation. In this mode, the DFIG-WTs should participate in voltage and frequency control of the microgrid. Therefore, DFIG-WTs control strategy is switched from P–Q to U–f mode. Moreover, the local loads must be fed by these sources and any DFIG-WT should participate in the load sharing according to its nominal power. To meet this requirement, the controls of DFIG-WTs should involve the droop characteristic.

2.1 DFIG model

Prior to discussing the principles of droop control strategy, a DFIG model in rotating d-q reference frame is provided. The DFIG model under balanced conditions is given by [26]

\[
U_{Sd} = R_d I_{Sd} + \rho \lambda_{Sd} + \omega L_d I_{Qd} \\
U_{Sq} = R_q I_{Sq} + \rho \lambda_{Sq} - \omega L_q I_{Qd} \\
U_{Rd} = R_d I_{Rd} + \rho \lambda_{Rd} - (\omega L_d - \omega_m) I_{Qd} \\
U_{Rq} = R_q I_{Rq} + \rho \lambda_{Rq} + (\omega L_q - \omega_m) I_{Qd} \\
\lambda_{Sd} = L_d I_{Sd} + L_{mq} I_{Qd} \\
\lambda_{Sq} = L_d I_{Sq} + L_{mq} I_{Qd} \\
\lambda_{Rd} = L_d I_{Rd} + L_{mm} I_{Qd} \\
\lambda_{Rq} = L_d I_{Rq} + L_{mm} I_{Qd}
\]

where the subscripts d and q denote the d and q-axis components, the variables \(U_{Sd}, U_{Sq}, U_{Rd}, U_{Rq}, L_d, L_q, R_d, R_q, \lambda_{Sd}, \lambda_{Sq}, \lambda_{Rd}, \lambda_{Rq}\) are the stator and rotor voltages, currents and flux components, respectively. The operator \(\rho\) denotes time derivative operator, \(\omega\) and \(\omega_m\) are the angular speed of the synchronous reference frame and the rotor, respectively, \(R_d\) and \(R_q\) are the stator and rotor resistances, and \(L_S, L_R\) and \(L_m\) are the stator and rotor self-inductance and mutual inductance, respectively.

2.2 Vector control of DFIG in islanded mode of operation

In the islanded operation, the stator flux is set by regulating the rotor currents. Therefore, the main objective of the control strategy is to generate constant stator voltage amplitude and frequency, irrespective of the shaft speed. To implement this strategy, the most common approach is the DFIG vector control, i.e. the stator-flux oriented vector control as shown in Fig. 1.

There are two main control levels in the block diagram of Fig. 1:

i. the internal proportional–integral (PI) current controllers that regulate the rotor currents,

ii. the external PI controllers that regulate the magnitude and frequency of the stator voltage.
the condition of stator flux orientation, controlled indirectly by regulating the magnetising stator current obtained from (1)–(8) as [27]

Based on (9) and (10), the flux estimation expression can be obtained from (1)–(8) as [27]

\[ \dot{\lambda}_{\mathrm{sd}} = U_{\mathrm{sd}}/\omega_{\mathrm{sn}} = L_{m}I_{\mathrm{sn}} \]  

(9)

where \( \omega_{\mathrm{sn}} \) is the angular speed of stator flux. Thus, \( U_{\mathrm{sd}} \) can be regulated by \( I_{\mathrm{sn}} \). Moreover, considering \( \dot{\lambda}_{\mathrm{sd}} = 0 \), from (6) one can obtain

\[ I_{\mathrm{rd}} = -(L_{d}/L_{m})I_{\mathrm{sd}} \]  

(10)

Based on (9) and (10), the flux estimation expression can be obtained from (1)–(8) as [27]

\[ T_{S} \frac{d\lambda_{\mathrm{sn}}}{dt} + I_{\mathrm{sn}} = I_{\mathrm{rd}} + \frac{1}{L_{d}}\frac{\sigma_{S}}{R_{S}}U_{\mathrm{dq}} \]  

(11)

\[ T_{S} \dot{\lambda}_{\mathrm{sn}} = I_{\mathrm{rd}} + \frac{1}{L_{d}}\frac{\sigma_{S}}{R_{S}}U_{\mathrm{dq}} \]  

(12)

where \( T_{S} = L_{d}/R_{S} \) is the stator time constant and \( \sigma_{S} = (L_{S}/L_{m})-1 \) is the stator leakage factor. From (11) one concludes that the magnetising current can be controlled by the rotor current \( I_{\mathrm{rd}} \). On the other hand, from (12), current \( I_{\mathrm{rd}} \) can be used to force the orientation of the reference frame along the stator flux vector by regulating \( \omega_{\mathrm{sn}} \). It should be noted that a phase lock loop is used to derive the position of the stator flux angle \( \theta_{S} \).

From Fig. 1, the droop control block sets the reference values of \( \omega_{\mathrm{sn}} \) and \( I_{\mathrm{sn}} \) and determines the mechanism of DFIG-WT participation in power sharing process.

2.3 Droop control concept

Each DFIG-WT can be represented as a voltage source which is connected to a common bus through a line impedance (PCC) as shown in Fig. 2a. The power flow from the wind unit to the point of common coupling (PCC) bus is given by

\[ S_{A} = P_{A} + jQ_{A} = U_{A}e^{j\delta_{P}} \left( \frac{U_{A}e^{-j\beta} - U_{B}}{Z_{e}^{j\gamma}} \right) \]

\[ = \frac{U_{A}^{2}}{Z_{e}^{j\gamma}} - \frac{U_{A}U_{B}e^{-j\beta}}{Z_{e}^{j\gamma} + \delta_{P}} \]

Equations (14) and (15) show that \( P-Q \) are decoupled from each other by \( \delta_{P} \).\( \Delta U \) only in an ideal case; namely pure resistive \( (X=0) \) or pure inductive \( (R=0) \) case. Applying \( R=0 \) to (14) and (15) results in

\[ P_{A} = U_{A}U_{B}\delta_{P}/X \]

(16)

\[ Q_{A} = U_{A}\Delta U/X \]

(17)

In this case, the traditional droop sharing scheme can be implemented to regulate the output active and reactive power of the wind unit as

\[ f = f_{0} - mP \]

(18)

\[ U = U_{0} - nQ \]

(19)

where \( f_{0} \) and \( U_{0} \) are the frequency and amplitude of the wind unit voltage at no load (set points) and \( m \) and \( n \) are the frequency and
voltage droop coefficients, respectively. The frequency and voltage droop control characteristics are shown in Figs. 2b and c. Their droop coefficients are

\[
m = \Delta f / P_n \quad (20)
\]

\[
n = \Delta U / Q_n \quad (21)
\]

where \( P_n \) and \( Q_n \) are the nominal active and reactive power of the wind unit. The maximum acceptable deviations of \( \Delta f \) and \( \Delta U \) are 2 and 5%, respectively. Usually \( \Delta f \) and \( \Delta U \) are chosen to be equal for all units

\[
\Delta f = m_1 P_n = m_2 P_n = \ldots = m_j P_n \quad (22)
\]

\[
\Delta U = n_1 Q_n = n_2 Q_n = \ldots = n_j Q_n \quad (23)
\]

Therefore, the coefficients are inversely proportional to nominal powers. Selecting the droop coefficients according to (22) and (23) ensures that each unit participates in power sharing according to its nominal rating.

### 3 Circulating power

The traditional droop control strategy is only applicable to a highly inductive line, which is usually the case in traditional power systems. To solve the problem in highly resistive line, the control block diagram of a DFIG-WT is designed based on traditional droop control, and then the modifications are applied to the droop characteristics to satisfy the power-sharing requirement. It should be noted that the active/reactive power circulation between the \( i \)-th and \( j \)-th DFIG-WT (\( \Delta P_{ij} \) and \( \Delta Q_{ij} \), respectively) in a parallel system can be expressed as [22]

\[
\Delta P_{ij} = \frac{P_i}{(P_{in}P_{jn})} - P_j \quad (24)
\]

\[
\Delta Q_{ij} = \frac{Q_i}{(Q_{in}Q_{jn})} - Q_j \quad (25)
\]

where \( P_i, P_j, Q_i, Q_j \) are the active/reactive \( i \) and \( j \) values of units, respectively, and the \( P_{in}, P_{jn}, Q_{in}, Q_{jn} \) are the corresponding nominal values. The \( P_i \) and \( Q_i \) values are calculated by measuring the terminal voltages and currents of DFIG-WT as [28]

\[
P_i = \frac{3}{2} (U_{iq}I_{iq} + U_{id}I_{id}) \quad (26)
\]

\[
Q_i = \frac{3}{2} (U_{iq}I_{iq} - U_{id}I_{id}) \quad (27)
\]

where the variables \( U_{iq}, U_{id}, I_{iq}, I_{id} \) are the measured PCC voltages and currents of the \( i \)-th DFIG-WT, respectively. To clarify the main reason and the kind of circulating current among the DFIG-WTs in a MV microgrid, the model of Fig. 3a is used. In this model, two DFIG-WTs are connected to the PCC via impedances \( Z_1 \) and \( Z_2 \). They should share active/reactive powers of the load (\( P^* \) & \( Q^* \)) via the PCC bus. The nominal power of the first unit is twice the second one. Both DFIG-WTs are equipped with the traditional droop control according to (14) and (15). The \( P-f \) characteristics of the DFIG-WTs are considered to be similar as the one shown in Fig. 3b. The droop coefficient of the smaller DFIG is selected as \( m_2 = 0.02 \) (this indicates that the maximum acceptable deviation of \( \Delta f \) is 2%) where the droop coefficient of the other DFIG is obtained as \( m_1 = 0.01 \). It is worth noting that based on the \( P-f \) characteristics, at steady state, the frequency is unique as depicted by the horizontal dash lines in Fig. 3b and it ensures the proper active power sharing in the microgrid. Fig. 3b shows that the active power produced by the first DFIG-WT is twice the second one. Thus, the active circulating current between the two DFIG-WTs is approximately zero. In other words, the frequency can be employed as a virtual communication link between the two units and it guarantees the proper active power sharing.

For the \( Q-U \) droop control, however, there is no such an inherent virtual communication link between DFIG-WTs since \( \Delta U \) of each DFIG-WT is independent from the other one. Therefore, the reactive power sharing is not necessarily proportional to the DFIG-WTs nominal powers. This can lead to circulation of reactive current between the two units. Considering that \( R > X \), (14) and (15) can be approximated as

\[
\Delta U = R P_i / U_A \quad (28)
\]

\[
\delta_p = - R Q_i / U_A U_B \quad (29)
\]

Generally, it can be assumed that \( R_1 = k R_2 \) in Fig. 3a and \( k \) is a real value. Since the active power sharing between DFIG-WTs is proportional to their nominal powers, one declares

\[
R_1 = k R_2 \quad \Rightarrow \quad \Delta U_i = 2k \Delta U_2 \quad (30)
\]

Substituting for \( \Delta U \) from (30) into (28) yields

\[
\Delta U_1 = 2k \Delta U_2 \Rightarrow U_{A1} = U_{A2} \quad (31)
\]

Based on (29) and (31) one obtains

\[
\frac{Q_{A1}}{\delta_{p1}} = \frac{1}{k} \frac{Q_{A2}}{\delta_{p2}} \quad (32)
\]

Considering (16) and (17), one observes that the traditional \( P-f \) equation is concluded from \( P-\delta_p \) dependency. Thus, the power angle represents the frequency in the traditional droop scheme. Since the frequency is a unique value in the whole microgrid, the power angles of wind units can be assumed to be equal (\( \delta_{p1} = \delta_{p2} \)). Based on this assumption, (32) can be rewritten as

\[
Q_{A1} = (1/k) Q_{A2} \quad (33)
\]

It is desirable to share the DFIGs reactive powers according to their nominal power. Applying this condition on (33) results in

\[
Q_{A1} = 2 Q_{A2} \Rightarrow k = 1/2 \quad (34)
\]
Equation (34) expresses that the reactive power can be properly circulated among DFIG-WTs (see Figs. 5a–c). In each DFIG-WT, the stator-flux oriented control block of the first DFIG-WT remains unchanged and the new term is added to the control block of the second one as shown in Fig. 4a. As a result, the set point of $I_{sn2}$ is regulated such that the constraint $Q_1 = 2Q_2$ is obtained. This strategy can be extended in a multi-DFIG-WTs microgrid by the modification of $i^{th}$ DFIG-WT control system as it is shown in Fig. 4b. The nominal power of master DFIG-WT is $k_i$ times of the $i^{th}$ DFIG-WT. The PI controller regulates $I_{snj}$ set point such that the constraint $Q_1 = k_iQ_2$ is obtained.

5 Simulation results

To validate the proposed method, a simulation study in the Matlab/Simulink platform was conducted. The configuration of DFIG-WTs is that of Fig. 3a. In each DFIG-WT, the stator-flux oriented vector control of Fig. 1 is implemented. The system parameters are given in Table 1 of Appendix part. The microgrid is operated in the islanded mode, and the load is simulated by a constant $P^*$ and $Q^*$. It should be noted that the actual values of these active/reactive powers depend on the voltage amplitude and frequency of the PCC. To properly share the power demand between DFIG-WTs, the $P_f$ and $Q-U$ droop characteristics are implemented as explained in Section 4.

5.1 Effect of impedance mismatch on power sharing

The objective of this simulation is to investigate the effect of impedance mismatch on the reactive circulation current. The line impedances are given in Table 1 of Appendix part, and the $R/X$ ratios of both line impedances are 10. Two scenarios are studied and the results are shown in Figs. 5 and 6. The active and reactive power values and their circulation values are calculated based on (24)–(27). In the first one (ideal case), the DFIG-WT line impedances are inversely proportional to their nominal power (i.e. $R_1 = \frac{1}{2} R_2$), while in the second one, it is assumed that $R_1 = \frac{1}{4} R_2$. Initially, a nominal load of $(1 + j0.5) \text{ pu}$ is connected to the PCC. At $t = 20 \text{ s}$, a second load of $(0.5 + j0.5) \text{ pu}$ is added in a step-wise manner (per unit values are based on the nominal active power of the second DFIG-WT). Figs. 5a and 6a show that the active power is properly shared between two units before and after the load change. For example, during the first 20 s, the first DFIG-WT delivers $0.61 \text{ pu}$ of the total active power demand ($P^* = 0.92 \text{ pu}$) while the second one delivers $0.31 \text{ pu}$. Therefore, the active power that is circulated between DFIG-WTs (see Figs. 5c and 6c) is zero at steady-state conditions. However, in Fig. 6c and during transients, the active circulating power is not zero since the $P_f$ and $Q-U$ equations are not completely independent in resistive lines. This implies that the active power is affected by the circulating reactive power. The frequency in Figs. 5d and 6d is also kept in a permissible range by the droop controls and its variations are limited to 2%. These results confirm that the traditional $P-f$ droop control achieves proper active power sharing in all conditions.

ii. adding a modification term to the right side of $Q-U$ expression.

In practice, variation of the DFIG voltage amplitude is limited to 5% around the nominal value. Hence, the product of reactive droop coefficient ($n$) and the reactive power ($Q$) can be considered nearly constant in (19). Thus, the adjustment of ’$n$’ may be a way to control reactive power sharing. Correct determination of ’$n$’ however is not straightforward since it is affected by line impedances and reactive power demand. Thus, the second solution must be met:

i. there is no inherent communication link for this control loop,
ii. based on the problem statement, $Q_1 = 2Q_2$.

The modification of $Q-U$ is suggested according to Fig. 4a. With request to reactive power, the first DFIG-WT is assumed as the master and the second one is assumed as the slave. Thus, the control block of the first DFIG-WT remains unchanged and the new term is added to the control block of the second one as shown in Fig. 4a. As a result, the set point of $I_{sn2}$ is regulated such that the constraint $Q_1 = 2Q_2$ is obtained. This strategy can be extended in a multi-DFIG-WTs microgrid by the modification of $i^{th}$ DFIG-WT control system as it is shown in Fig. 4b. The nominal power of master DFIG-WT is $k_i$ times of the $i^{th}$ DFIG-WT. The PI controller regulates $I_{snj}$ set point such that the constraint $Q_1 = k_iQ_2$ is obtained.

4 Proposed reactive power sharing scheme

The previous section shows that the $Q-U$ droop control law in the traditional droop control must be modified to prevent reactive current circulation among DFIG-WTs. To satisfy this requirement, based on (19), there are two possibilities:

i. modification of the reactive droop coefficient ($n$),
ii. adding a modification term to the right side of $Q-U$ expression.

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5.1 Effect of impedance mismatch on power sharing

The objective of this simulation is to investigate the effect of impedance mismatch on the reactive circulation current. The line impedances are given in Table 1 of Appendix part, and the $R/X$ ratios of both line impedances are 10. Two scenarios are studied and the results are shown in Figs. 5 and 6. The active and reactive power values and their circulation values are calculated based on (24)–(27). In the first one (ideal case), the DFIG-WT line impedances are inversely proportional to their nominal power (i.e. $R_1 = \frac{1}{2} R_2$), while in the second one, it is assumed that $R_1 = \frac{1}{4} R_2$. Initially, a nominal load of $(1 + j0.5) \text{ pu}$ is connected to the PCC. At $t = 20 \text{ s}$, a second load of $(0.5 + j0.5) \text{ pu}$ is added in a step-wise manner (per unit values are based on the nominal active power of the second DFIG-WT). Figs. 5a and 6a show that the active power is properly shared between two units before and after the load change. For example, during the first 20 s, the first DFIG-WT delivers $0.61 \text{ pu}$ of the total active power demand ($P^* = 0.92 \text{ pu}$) while the second one delivers $0.31 \text{ pu}$. Therefore, the active power that is circulated between DFIG-WTs (see Figs. 5c and 6c) is zero at steady-state conditions. However, in Fig. 6c and during transients, the active circulating power is not zero since the $P-f$ and $Q-U$ equations are not completely independent in resistive lines. This implies that the active power is affected by the circulating reactive power. The frequency in Figs. 5d and 6d is also kept in a permissible range by the droop controls and its variations are limited to 2%. These results confirm that the traditional $P-f$ droop control achieves proper active power sharing in all conditions.
The reactive power sharing of DFIG-WTs is depicted in Figs. 5b and 6b which indicates that the reactive circulating power is approximately zero in ideal impedance line condition (Fig. 5c). However, under the impedance mismatch condition, the first unit is overloaded in terms of reactive power. For example, during the first 20 seconds, the first DFIG-WT delivers 0.4 pu of the total reactive power demand, while the second one delivers 0.07 pu. Thus, there is a reactive power flow between DFIG-WTs as shown in Fig. 6c. When the local reactive demand increases to 0.9 pu at $t = 20$ s, the circulating reactive power increases to 0.2 pu and the first DFIG-WT becomes even more overloaded. Hence, the traditional $Q-U$ droop scheme is not applicable in microgrids with resistive impedances.

### 5.2 Investigation of proposed control scheme

The proposed $Q-U$ control strategy of Section 4 is implemented and investigated in this section. The line impedance mismatch is $R_1 = 1/4R_2$. The simulation results are given in Fig. 7.

For $t \leq 10$ s, the nominal reactive power demand is $Q^* = 0.5$ pu and the traditional $Q-U$ droop control is implemented for both DFIG-WTs. Fig. 7c shows that the reactive circulating current flows between DFIG-WTs. At $t = 10$ s, the proposed $Q-U$ control strategy is activated. Fig. 7b shows that the first DFIG-WT reactive power decreases and the second one increases. Thus, the reactive power circulation reduces to zero as shown in Fig. 7c. To demonstrate the robustness of proposed scheme against the reactive power demand variations, $Q^*$ is changed from 0.5 to 1 pu at $t = 20$ s in a step-wise manner. Subject to such a severe load step variation, the reactive power is properly shared without any significant transient as shown in Fig. 7c.

To validate the performance of the proposed scheme, two parameters of the DFIG-WT line impedances are changed and the dependency of reactive power sharing on these parameters is studied. These parameters are: (i) the $R/X$ ratio of each line, (ii) the $R_1/R_2$ ratio. In each case, one parameter is changed while the other one is kept constant. Sequence of events is similar to the case study of Fig. 7. The simulation results which are shown in Figs. 8a and 8b demonstrate that the proposed approach is effective to restrain circulating reactive current under both conditions.

### 5.3 Communication link requirements

The ‘reactive communication link’ may raise concerns regarding the reliability issues. However, it should be noted that the proposed control algorithm is mainly based on the traditional $P-f$ and $Q-U$ droop control. This implies that the critical inner control loops are based on measuring local quantities. Therefore, these critical quantities are not transmitted between units. Furthermore, the $P-f$ droop control that is more dominant than the $Q-U$ one in terms of microgrid stability has no dependency on the communication link. The communication of information is only used in the outer level of $Q-U$ droop control to enhance the reactive power sharing. Hence, the control of microgrid is not critically dependent on the operation of communication link. The communication link only transmits the reactive power set points among DFIG-WTs. The real question is that how much bandwidth is needed to transfer these reactive power set points. Another question is that how much communication delay is permitted to transfer set points. To answer these questions, the first DFIG-WT is assumed as the master and the second one is assumed as the slave as shown in Fig. 3a. The sequence of events is similar to the case study of Fig. 7 with $R_1 = 1/4R_2$ and $R/X = 10$. For a better view, only the simulation results between 18 and 25 seconds are depicted in Figs. 8c and 8d.

First, the $Q_1$ set point command is transmitted to slave DFIG-WT every 1 ms, 10 ms, 100 ms and 1 s. As depicted in Fig. 8c, when the $Q_1$ set point is transmitted every 1 s, the reactive power circulation shows an unacceptable overshoot. However, when the $Q_1$ set point is transmitted faster (100 ms and sooner), the proposed method shows better response. It can be concluded that the 100 ms is enough time for transmission of $Q_1$ set point command between the master and slave DFIG-WTs. If each communication needs 5 bytes, each slave DFIG-WT only needs 400 bps bandwidth. This requirement can be satisfied with common narrow band PLC/CC data transmission systems such as G3 and Power Line Related Intelligent Metering Evolution (PRIME) [29].

For example, PRIME which is operating in the CENELEC/FCC/ARIB bands is able to transport at maximum 2268 bytes per packet at 128.6 kbps using uncoded DBPSK, while its most robust protocol, coded DBPSK, can transfer 377 bytes per packet at 21.4 kbps [30].

In order to answer the second question, the communication delay of transmitted $Q_1$ set point is considered to be 100 ms, 500 ms, 1 s and 2 s as depicted in Fig. 8d. When the communication delay is 2 s, the reactive power circulation starts to oscillate. However, when the communication delay of transmitted $Q_1$ set...
point is lower than 2 s, the proposed method shows stable response. Hence, the delay time of 1 s is the permitted communication delay. Hence, there is a compromise between the ‘packet size of transmitted $Q_1$ set point’ and the ‘permitted communication delay’, which determines the maximum number of installed DFIG-WTs in a microgrid. To evaluate this, a packet size with 133 bytes is considered as the data length, which can be handled either by G3 mode or by PRIME protocol. The simulation results in [30] specify the frame duration of different PRIME protocol packets, which is reported in Table 2 of Appendix part. For each protocol, the maximum number of DFIG-WTs is calculated and shown in third column. These results show that by implementing PROT2 of PRIME system, the proposed method can be implemented in all microgrids with the maximum 65 units.

Therefore, the implementation of the proposed idea requires low bandwidth with low data transmission capability and can be done with common PLCC protocols without extra cabling and extra cost. The proposed control algorithm has the benefits of both droop control and master–slave configuration without their operational restrictions.

6 Conclusions

This paper presented a novel scheme for enhancing power sharing among DFIG-WTs in a MV microgrid with highly resistive lines. The studies show that the active power is properly shared among units because frequency is operated as a virtual communication link in a microgrid. However, in the case of reactive power, there is not such an inherent virtual link. The studies show that the reactive power can also be properly shared between DFIG-WTs only if the line impedances of the units are inversely proportional to their nominal power values, which is not valid in many real scenarios. To overcome this problem, a modification was made to the $Q$–$U$ control block diagram of the slave DFIG-WT. The simulation results validate the performance of the proposed scheme to restrain the reactive power circulation among the units, despite existence of lines impedance mismatches.

7 References

8 Appendix

See Tables 1 and 2.