Improving Fault Ride-Through Capability of Variable Speed Wind Turbines in Distribution Networks

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Abstract—In this paper, a fuzzy controller for improving the fault ride-through (FRT) capability of variable speed wind turbines (WTs) equipped with a doubly fed induction generator (DFIG) is presented. DFIGs can be used as reactive power sources to control the voltage at the point of common coupling (PCC). The controller is designed to compensate for the voltage at the PCC by simultaneously regulating the reactive and active power generated by WTs. The performance of the controller is evaluated in different case studies considering a different number of wind farms in different locations. Simulations carried out on a real 37-bus weak distribution system confirmed that the proposed controller can enhance the FRT capability.

Index Terms—Fault ride-through (FRT) capability, fuzzy logic controller, weak distribution networks, wind power generation.

I. INTRODUCTION

Wind turbines (WTs) are typically located in remote and rural areas. In these areas, the feeders are long and operated at a low or medium voltage level characterized by a high R/X ratio and unbalanced voltage situations. Furthermore, weak grids are usually referred to have a “low short-circuit level” or a “low fault level.” In a weak network, a change in either active or reactive power can cause a considerable change in the voltage. The impact relies on the strength of the network and the output power of the WTs [1]. Integration of WTs into weak grids will cause the steady-state voltage level to go beyond its acceptable limits. Therefore, it can be a constraint for the exploitation of wind energy resources. Another constraint is related to the effect of the power generated by WTs on the voltage quality. Voltage level limitations and accurate control systems are required to control voltage variations as well as to improve voltage quality [2]. Variable speed WT systems can be used as reactive power sources for voltage control. In [3], the authors proposed a mathematical model of the doubly fed induction generator (DFIG) for the analysis of active and reactive power performances of a wind farm (WF). A proportional-integral (PI)-based control algorithm to modify the reactive power produced by WTs was proposed in [4]. In [5], the relation between reactive and active power required to maintain the DFIG’s operation within the maximum rotor and stator currents has been studied. In [6], the authors proposed a fuzzy controller to manage the operation of a flywheel energy storage system (ESS) connected to a dc bus. Recently, the penetration of WTs into the distribution networks has increased and the performance of the WTs under faults has become an important issue, especially for DFIGs. Several grid codes prescribed for WTs the requirement to stay connected to the grid during faults and voltage variations, referred to as the fault ride-through (FRT) capability [7]. One of the common FRT capability improvement solutions is to set up a crowbar circuit across the rotor terminals [8]. In [9], the authors achieved a FRT capability improvement by using hardware modification and inserting an additional voltage source converter connected at the generator terminal. A control strategy for improving the FRT capability by using flexible ac transmission system devices and ESS was proposed in [10]. In [11], the authors proposed a new feed-forward transient current control method applied to a rotor side converter for improving the FRT capability. In [12], a fuzzy controller to manage the rotor speed oscillations and the dc-link voltage variations of the DFIG has been proposed.

In this paper, a fuzzy controller for improving FRT capability in variable speed WTs is presented. The controller is designed to compensate the voltage variations at the point of common coupling (PCC) by simultaneously controlling the reactive and active power generated by WTs. Other authors have investigated the FRT capability improvement only considering voltage sag in previous research works; in this paper, instead, the voltage swell effect is also considered to investigate FRT capability improvement according to the Danish grid code. The novelty of the paper lies in proposing a fuzzy controller able to simultaneously regulate active and reactive power. For example, during a voltage swell, the absorbed reactive power is not adequate to lower the voltage at the PCC within its statutory limits. Consequently, the reference signal for the active power production is decreased by the fuzzy controller in order to increase the absorbed reactive power. In this case, the WTs will not generate the maximum active power according
to the WTs’ power coefficient, but this will determine two positive effects of the voltage regulation at the PCC. Due to the limited size of the power converters of DFIGs, the active power reduction will allow increasing the maximum reactive power that can be absorbed by WTs. Moreover, in low or medium voltage weak networks with long feeders characterized by a high R/X ratio, the active power reduction can also affect the voltage drop on the feeders, thus contributing toward lowering the voltage at the PCC. The performance of the controller is analyzed for both voltage sags and swells with different load values. Different locations of the WFs have been studied and simulations have been carried out on a real 37-bus weak distribution network. The Danish grid code for the voltage levels below 100 kV is used in order to evaluate the FRT capability improvement.

This paper is organized as follows. Grid code requirements and FRT capability are presented in Section II. The WT generator system and capability limits of DFIG-based WTs are explained in Sections III and IV, respectively. The description of the proposed FRT approach and the fuzzy controller design are discussed in Sections V and VI, respectively. Case studies and simulation results are discussed in Section VII. Discussion and conclusions are provided in Section VIII.

II. Grid Code Requirements and FRT Capability

In recent years, the increasing penetration of WTs into power systems has led power system operators to develop new grid code requirements for WTs in many countries. These requirements impose WTs operators to deal with some aspects, such as FRT capability, reactive power control, and voltage control. This implies that the WTs connection to a power system requires coordination with voltage and reactive power control. Several countries have provided different grid codes depending on their system characteristics and operation standards, such as the codes from E. ON Netz Germany, Denmark, Belgium, U.K., Spain, The Netherlands, the U.S., and Canadian TSO Hydro-Quebec [13]. The Nordic grid code from Nordel [14] specifies the technical requirements that new WTs should have in order to be connected to the transmission network and provide acceptable safe operation and reliability. The Belgian grid code [15], provided by the Belgian TSO, Elia, applies to the grids with the voltage levels 30–70 kV and 150–380 kV. This code discriminates different kinds of voltage disturbances. The German grid code from E. ON Netz [16] applies to the grids with the voltage levels 110, 220, and 380 kV. The Danish grid code [17] relates to the WTs connected to the grids with the voltages below 100 kV. Fig. 1 illustrates the FRT requirements of the Danish grid code. Apart from the FRT requirements, WFs must disconnect if the voltage increases above 1.2 p.u. Additional requirements for voltages below 100 kV define that a WT must remain connected after the faults in the distribution system listed as follows:

1) three-phase short circuit lasting 100 ms (five cycles);
2) two-phase short circuit with or without earth lasting 100 ms (five cycles), followed by a new fault 300–500 ms (15–25 cycles), also lasting 100 ms (five cycles);
3) at least two two-phase short circuits within 2 min;
4) at least two three-phase short circuits within 2 min;
5) at least six two-phase short circuits at 5-min intervals;
6) at least six three-phase short circuits at 5-min intervals.

When the voltage at the PCC is above the FRT curve, i.e., the area labeled “must stay connected,” the WT must remain connected. The curve can be divided into four areas according to the voltage variations. In area 1, the faults last up to 0.1 s, the voltage magnitude at the PCC is equal to or greater than 0.9 p.u., and WTs must remain connected to the network. Area 2, between 0.1 and 0.75 s, defines a growth recovery voltage from 0.2 to 0.7 p.u. in a mentioned period. The main challenge in this area is adjusting of the protection system to ensure the voltage change during the voltage restoration. Area 3, between 0.75 and 10 s, describes the system recovery with voltage sag to 0.7 p.u. Area 4, between 10 and 100 s, describes the full normalization after the 10 s voltage sag; in this case, the voltage should not be less than 0.9 p.u. Regarding the voltage swells, in the area between 0.2 and 90 s if the voltage increases above 1.1 p.u., the WTs must be disconnected.

The aim of modern grid codes is supporting voltage during a voltage drop by compensating the reactive power. During a voltage sag, the additional reactive current is relied on the value of the voltage sag. The minimum limit according to the Danish grid code for voltage sags is described by the following formulation:

\[
\left(\frac{\Delta I_q}{I_q}\right) < \frac{\Delta V}{V_n} \leq 1
\]

where

- \(I_q\) is the rated current, \(I_{iq}\) is the quadratic axis current (reactive component), \(I_{ip}\) is the prefault reactive component, \(V_{t}\) is the rated terminal voltage, \(V\) is the generator terminal voltage during fault, and \(V_{iq}\) is the prefault terminal voltage.

It is assumed that the prefault voltage and prefault reactive current are 1 and 0 p.u., respectively. According to Fig. 2, the wind power plant in area B must have a controller to control the reactive power in the presence of fault sequences. When voltage drops by 50%, the maximum reactive current must be injected by the system. As a larger amount of reactive current during the fault is needed, the controller’s objective is, therefore, increasing the amount of reactive current during voltage sag.
III. WT GENERATOR SYSTEM

A DFIG is a wound rotor induction generator with the stator connected to the grid directly and with the rotor connected to the network through a back-to-back converter. The schematic of DFIG-based WT is shown in Fig. 3. The aim of the rotor side converter (RSC) is to control the active and reactive power on the grid separately, while the grid side converter (GSC) has to maintain the dc-link voltage at a set value [18]. A detailed description of the control systems for both converters can be found in [19].

The relation between the wind speed and the aerodynamic torque in a turbine can be described by the following equations:

\[ P_w = \frac{1}{2} \pi \rho R^2 V_w^3 C_p(\theta, \lambda) \]  
\[ T_w = \frac{1}{2} \pi \rho R^2 V_w^2 C_p(\theta, \lambda)/\lambda \]  

where \( P_w \) and \( T_w \) are the power and aerodynamic torque extracted from the wind in (W, N·m), \( \rho \) is the air density (kg/m³), \( R \) is the WT rotor radius (m), \( V_w \) is the equivalent wind speed (m/s), \( \theta \) is the pitch angle WT blade (°), and \( \lambda = \omega_{rot} R/V_w \) is the tip speed ratio, where \( \omega_{rot} \) is the WT rotor speed (rad/s), and \( C_p \) is the aerodynamic efficiency of the rotor. \( C_p \) may be expressed as a function of the tip speed ratio (\( \lambda \)) and pitch angle (\( \theta \)) by the following equation:

\[ C_p = 0.22(116/\beta - 0.48 - S \beta e^{-12.5/\beta}) \]  

where \( \beta \) is defined as follows:

\[ \beta = \frac{1}{\sin(\theta)} \frac{1}{\lambda} \]  

IV. DFIG-BASED WT CAPABILITY LIMITS

In the steady state, the DFIG capability limits are obtained by considering the stator- and rotor-rated currents as well as by calculating the total capacity limits of WT. These currents are related to stator and rotor heating because of Joule’s losses.

A. Stator Current Limit

The limit of stator current considers the heating owing to the Joule’s losses of stator winding. When the rated current and voltage of stator are considered in p.u., the stator current limit can be expressed as follows:

\[ P^2 + Q_s^2 = (3U^2_s I_s^2) \]  

where \( U_s, I_s, P_s, \) and \( Q_s \) are the voltage, current, active power, and reactive power of the stator, respectively. Equation (5) expresses that the locus of the maximum stator current in the \( PQ \) plane is a circle centered at the origin, with a radius equal to the apparent power of stator, as shown in Fig. 4.

B. Rotor Current Limit

The rotor current limit considers the heating owing to the Joule’s losses of the rotor winding. The active and reactive powers of the stator can be formulated at the rated voltage of stator as follows:

\[ P_R = \frac{X_M}{X_s} U_s I_R \sin \delta \]  
\[ Q_R = \frac{X_M}{X_s} U_s I_R \cos \delta - \frac{U_s^2}{X_s} \]  

C. Total Capability Limits

The total active power of the DFIG fed into the grid is the sum of the stator and rotor active power

\[ P_T = P_s + P_R \]  

where

\[ P_s = -s P_R \]  
\[ P_R = (1 - s) P_R \]  

and \( P_T \) is the total active power of the DFIG fed into the grid, \( P_s \) is the stator active power, and \( P_R \) is the rotor active power.
D. Maximum and Minimum Reactive Power Limits

From (6), the following equation can be obtained:

$$P_2^2 + \left( Q_2 + \frac{U_2^2}{X_S} \right)^2 = \left( \frac{X_M}{X_S} U_2 I_{2s} \right)^2. \quad (10)$$

As shown in Fig. 4, (10) is a circle centered at $[-\frac{U_2^2}{X_S}, 0]$ with a radius equal to $\frac{X_M U_2 I_{2s}}{X_S}$. The active and reactive power of stator can be expressed as a function of the maximum allowable current of rotor and stator [20]

$$P_2^2 + Q_2^2 = \left( 3U_2 I_{2s} \right)^2 \quad (11)$$

$$P_2^2 + \left( Q_2 + 3\frac{U_2^2}{X_S} \right)^2 = \left( 3\frac{X_M U_2 I_{2s}}{X_S} \right)^2. \quad (12)$$

Equation (11) represents a circumference centered equal to the stator rated apparent power. Equation (12) represents a circumference centered at $[-3\frac{U_2^2}{X_S}, 0]$. Substituting (8) and (9) into (11) and (12) can be expressed as follows:

$$\left( \frac{P_1}{1-3} \right)^2 + Q_2^2 = \left( 3U_2 I_{2s} \right)^2 \quad (13)$$

$$\left( \frac{P_1}{1-3} \right)^2 + \left( Q_2 + 3\frac{U_2^2}{X_S} \right)^2 = \left( \frac{X_M U_2 I_{2s}}{X_S} \right)^2. \quad (14)$$

The DFIG capability limits according to (13) and (14) can be achieved by taking into consideration the stator and rotor maximum currents $I_{2\text{max}}$ and $I_{2\text{max}}$, respectively.

The capability curve of a 9 MW WF considered in this paper during normal operation is shown in Fig. 5. According to the capability curve of the considered WFs, the limits of the reactive power that the WFs can inject or absorb are 2.5 MVAR and 8 MVAR, respectively, and they have been considered for designing the fuzzy controller.

V. PROPOSED FRT APPROACH

In this paper, a fuzzy controller for improving FRT capability in variable speed WTs is designed in order to compensate the voltage variations at the PCC by controlling simultaneously the reactive and active power generated by WFs. The schematic and the strategy of the proposed fuzzy controller are shown in Figs. 6 and 7, respectively.

In the case of voltage sag, the reference signal for the reactive power ($Q_{\text{ref}}$) is sent by the fuzzy controller in order to reduce the active power by using the reference signal for the active power production (active power modulator).

In the case of voltage swell, when the absorbed reactive power is enough to compensate voltage swell, there is no need to reduce the active power by using the reference signal for the active power production (active power modulator).

The active power modulator, which is sent by the fuzzy controller to the RSC of WTs, varies in the range [0 1] to reduce the active power production. Furthermore, during a voltage swell, when the absorbed reactive power is not enough to lower the voltage at the PCC, the active power modulator is regulated to decrease the active power and increase the absorbed reactive power according to the following formula:

$$|Q| = \sqrt{S^2 - P^2} \quad (15)$$

where $S$ is the power converter size, given as maximum apparent power, and $P$ and $Q$ are the generated active and reactive powers, respectively. In this case, WFs will not generate the maximum active power, but this will positively affect the voltage regulation at the PCC: 1) within the limited size of the power converters of DFIG, the active power reduction will increase the maximum reactive power that can be absorbed by WFs; and 2) the active power reduction, in low or medium voltage weak networks with long feeders characterized by a high R/X ratio, can affect the voltage drop on the feeders, contributing toward decreasing the voltage at the PCC.
method is also able to compensate voltage variations in the normal operation if some network constraints are violated. For instance, in normal operation when the voltage constraints are violated at the connection buses of the WTs, the controller is able to inject or absorb the reactive power according to the capability curve of WTs up to 2.5 or 8 MVAr, respectively, in order to compensate voltage variations.

Reactive power must be injected to the grid to support grid voltage recovery during voltage sag. According to the Danish grid code, as shown in Fig. 2, when the depth of voltage sags is 50%, the maximum reactive power (100% of the generation system rating) must be injected into the grid in order to compensate voltage variations. In the proposed control strategy, when voltage drops by 50%, the maximum reactive power (current) can be injected by DFIG converters.

VI. DESCRIPTION OF FUZZY LOGIC CONTROLLER

Due to nonlinearity of power system and linearization problems, the control of variable speed WTs may not be performed correctly with conventional control methods. For example, a PI controller design may require identifying the WT transfer function, the linear model of the network, and defining an accurate tuning process.

The use of a fuzzy logic controller (FLC) can overcome these problems and deal with the nonlinearities, as well as time variances of the system without the need of an accurate model. In the case of WTs control, for example, inaccurate aerodynamic calculations, tolerance in mounting the turbine, dirt or ice on blades, time-varying aerodynamic parameters, and other unpredictable parameter variations can make fuzzy logic control preferable compared to conventional control methods [22], [23]. The fuzzy controller presents many advantages if compared to a PI controller [24]: 1) it is easy to obtain variable gains depending on the error; 2) it is simple to solve problems affected by uncertain models; 3) it gives fast convergence; and 4) it is parameter insensitive, and accepts noisy and inaccurate signals.

An FLC includes three blocks, namely, fuzzification, inference engine, and defuzzification, and is explained as follows.

A. Fuzzification

Fuzzification is a procedure for processing the input variables with membership functions (MFs) and determines the degree of input variables belonging to one of the fuzzy sets through MFs. In order to convert the value of input variables into a value between 0 and 1, MFs are used and can take different shapes, such as Gaussian, sigmoidal, and triangular shape curves. In fact, MFs should be selected in a proper way to reflect the input variables’ characteristics and meet the controller’s requirements. MFs’ overlapping is needed as it means more than one rule is fired at each time that is a main characteristic of a fuzzy controller.

In the proposed fuzzy controller, as shown in Fig. 8, the selection of the best MFs has been performed on the basis of a prior knowledge and on experimentation with the system and its dynamics. Moreover, in order to design the FLC, shrinking span MFs have been chosen: this guarantees smoother results with less oscillations, large and fast control actions when the system state is far from the set point, and moderate and slow adjustments when it is near to the set point. Thus, when the system is closer to its set point, the MFs, for those specific linguistic terms, have narrower spans.

The type of MFs is frequently chosen to fit an expected input data distribution or clusters, and can influence both the tracking accuracy and the execution time. Triangular, trapezoidal, and Gaussian MFs are the common choice even if any convex shape can be adopted. In particular, for the proposed controller, triangular and Gaussian MFs have been compared and triangular has been selected as the type of MFs for input and output variables. Although most researchers are inclined to design the input or output MFs using equal span mathematical functions, these do not always guarantee the best solution. Among all the parameters associated with an FLC, MFs have a dominant effect in changing its performance.

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The proposed fuzzy controller presents three inputs: the error, the integral of error, and the measured reactive power at the PCC and two outputs that are the reference values for both the reactive and the active power production. The reference signal for the reactive power (Qref) varies in the range [-1 1], and the reference signal for the active power production (active power modulator) varies in the range [0 1] to decrease active power production and, consequently, increase the reactive power according to (15).

The error is defined as the difference between the reference voltage (Vref) and the measured voltage at the PCC. The third input, the reactive power measured at the PCC, is used to determine when the active power modulator is required to be regulated by the fuzzy controller.

Here, the fuzzy sets of the inputs and outputs assume the following names: NVB = negative-very-big, NB = negative-big, NM = negative-medium, NS = negative-small, ZE = zero, and so forth. Triangular MFs have been selected for the inputs and outputs, as shown in Fig. 9.

B. Fuzzy Inference Engine

The fuzzy inference engine consists of the operation process, fuzzy rule implication, and the aggregation process. The fuzzified input variables are processed with fuzzy operators and IF-THEN rule implementation. The output fuzzy sets for every rule are aggregated into a single output fuzzy set. Input fuzzy sets are related to a fuzzy rule by a logical AND operator. Although each rule may have various weights, all the rules used here have the same weight.

Aggregation is the process of representing the outputs of each rule that is combined into a single fuzzy set. The input of the aggregation process is the output of fuzzy sets and its output is a fuzzy set for each output variable. The
implementation of the fuzzy controller requires an adequate knowledge.

The knowledge base has been coded in a set of rules consisting of linguistic statements linking a finite number of conditions with a finite number of conclusions. Such a knowledge can be collected and delivered by human experts and expressed by a finite number \((r)\) conditions with a finite number of conclusions.

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The inference rules for the proposed controller can be summarized by describing some rules as follows.

1) If the error is positive and the integral of error is positive and reactive power measured at the PCC is positive, then \(Q_{\text{ref}}\) is sent by the fuzzy controller to the RSC in order to inject reactive power.

2) If the error is negative and the integral of error is negative and reactive power measured at the PCC is positive, then \(Q_{\text{ref}}\) is sent by the fuzzy controller to the RSC in order to inject reactive power.

3) If the error is negative and the integral of error is negative and reactive power measured at the PCC is not NVB, then \(Q_{\text{ref}}\) is negative and the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

4) If the error is negative and the integral of error is negative, the active power modulator is zero. In other words, in the case of voltage sag only \(Q_{\text{ref}}\) is sent by the fuzzy controller to the RSC in order to inject reactive power.

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7) If the error is negative and the integral of error is negative, the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

8) If the error is negative and the integral of error is negative, the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

9) If the error is negative and the integral of error is negative, the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

10) If the error is negative and the integral of error is negative, the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

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13) If the error is negative and the integral of error is negative, the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

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15) If the error is negative and the integral of error is negative, the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

16) If the error is negative and the integral of error is negative, the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

The proposed controller is designed in order to compensate the voltage at the PCC by injecting or absorbing the \(Q_{\text{ref}}\) to the RSC and by regulating the active power modulator. Note that both signals, i.e., \(Q_{\text{ref}}\) and active power modulator, are sent by the fuzzy controller to the RSC. The active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

An easy understanding of the proposed fuzzy controller can be summarized by describing some rules as follows.

1) If the error is positive and the integral of error is positive and reactive power measured at the PCC is positive, then \(Q_{\text{ref}}\) is positive and the active power modulator is zero. In other words, in the case of voltage sag only \(Q_{\text{ref}}\) is sent by the fuzzy controller to the RSC in order to inject reactive power.

2) If the error is negative and the integral of error is negative and reactive power measured at the PCC is not NVB, then \(Q_{\text{ref}}\) is negative and the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the injected active power with the aim of increasing the absorbed reactive power in the case of voltage swell.

3) If the error is negative and the integral of error is negative and reactive power measured at the PCC is NVB, both reactive and active powers are regulated in order to decrease the voltage swell effects, the active power modulator is sent by the fuzzy controller to the RSC in order to decrease the active power, and, consequently, to increase the absorbed reactive power according to (15).

Two fuzzy surfaces of the controller are provided in Fig. 10. As evidenced from Fig. 10(b), in the case of voltage swell when the absorbed reactive power reaches 80% of its maximum value, the active power is decreased by the fuzzy controller in order to increase the maximum reactive power that WTs can absorb. Moreover, it is used in combination with a protection system for disconnecting the WTs from the grid when the controller is unable to compensate the voltage variations.
C. Defuzzification

The input for the defuzzification process is a fuzzy set and the output is a single value. Here, the centroid method is used for defuzzification. It can be evidenced that the controller does not need a mathematical model of the system; however, an understanding of the control requirements is needed.

VII. CASE STUDY AND SIMULATION RESULTS

A DFIG based WT, as shown in Fig. 3, has been considered [25]. In order to test the proposed controller, three 9-MW WFs (6 × 1.5 MW WTs) connected to a real 25 kV weak distribution system, as shown in Fig. 11, at buses 12, 16, and 35 are considered. The network is characterized by lines with high resistances and low X/R ratios. The base value for the power and voltage are 9 MVA, operating at power factor 0.9 lagging, and 575 V, respectively. According to the capability curve of the considered WFs, the limits of the reactive power that the WT can absorb or inject are about 8 and 2.50 MVar, respectively. Real wind data sets acquired by the Wind Engineering Research Field Laboratory [26] are considered. The wind speed time history consists of 17,500 observations within a 50 s interval with a sampling rate of 25 Hz. The wind profile and the generated active power profile are shown in Fig. 12.

In order to test the FRT capability of the WFs endowed with the proposed fuzzy controller considering minimum and maximum load, two different cases are studied for the following load conditions.

A. Minimum Load

The total network loads are 18 MW and 12.5 MVar assumed as minimum load.

1) Case study 1: a 30% voltage sag with a duration of 1 s starting at t = 5, considering:
   a) three WFs at buses 12, 16, and 35;
   b) two WFs at buses 16 and 35.

2) Case study 2: a 15% voltage swell with a duration of 1 s starting at t = 5, considering:
   a) three WFs at buses 12, 16, and 35;
   b) two WFs at buses 16 and 35.

### TABLE II

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<th>WF No.</th>
<th>Proposed Controller</th>
<th>PI Controller</th>
<th>Without Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (p.u.)</td>
<td>WF's Situation</td>
<td>Voltage (p.u.)</td>
<td>WF's Situation</td>
</tr>
<tr>
<td>1</td>
<td>0.745 Connected</td>
<td>0.698 Connected</td>
<td>0.688 Disconnected</td>
</tr>
<tr>
<td>2</td>
<td>0.740 Connected</td>
<td>0.695 Connected</td>
<td>0.685 Disconnected</td>
</tr>
<tr>
<td>3</td>
<td>0.715 Connected</td>
<td>0.715 Connected</td>
<td>0.691 Disconnected</td>
</tr>
<tr>
<td>4</td>
<td>0.745 Connected</td>
<td>0.698 Connected</td>
<td>0.688 Disconnected</td>
</tr>
</tbody>
</table>

1) Case Study A1:
   a) When the voltage drops by 30%, each WF injects reactive power during the voltage sag in order to help increasing the voltage to 0.725, 0.730, and 0.741 p.u. for WF2, WF1, and WF3, respectively [see Fig. 13(a)].

The injected reactive power, as shown in Fig. 13(b), varies between about 2.25 MVar for WF2 according to the voltages at the connection buses. According to the Danish grid code, all WFs can successfully fulfill the FRT requirement and, consequently, remain connected to the grid. In order to evaluate the effectiveness of the proposed controller, both the case without any controller and with a classical PI controller, as designed in [27], are evaluated. The results are given in Table II. It can be evidenced that with the fuzzy controller, all WFs can successfully fulfill the FRT requirement and remain connected to the grid while with the PI controller only WF3 can successfully fulfill the FRT requirement and remain connected to the grid while WF1 and WF2 disconnect. Moreover, without any controller all WFs disconnect.
TABLE III

<table>
<thead>
<tr>
<th>WF No.</th>
<th>Voltage (p.u.)</th>
<th>WF’s Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.709</td>
<td>Connected</td>
</tr>
<tr>
<td>3</td>
<td>0.721</td>
<td>Connected</td>
</tr>
</tbody>
</table>

According to the Danish grid code, as shown in Fig. 2, when the voltage drops by 50%, the maximum reactive power can be injected (100% of the generation system rating) by the WF. In the case of 30% voltage sag, the WF injects about 50% of the maximum reactive power (2.5 MVAr) in order to compensate voltage sag effects thus meeting the requirements of the Danish grid code. Note that the proposed controller is able to compensate voltage sags with deeper magnitudes than those assumed in the above-mentioned case study up to 80% and meet the requirements of the Danish grid code according to Fig. 1.

b) In this case, only WF1 and WF3 are considered. The reactive powers injected by the WFs increase if compared to the previous case, and WF1 and WF3 can fulfill grid code requirements and remain connected to the grid (see Table III).

2) Case Study A2:

a) Considering three WFs during a 15% voltage swell, they absorb reactive power in order to help lowering the voltage, as shown in Fig. 14. The absorbed reactive power varies between about 7 MVAr for WF1 and about 8 MVAr for WF3, as shown in Fig. 15(a), according to the voltages at the connection buses. The voltages, as shown in Fig. 14, at buses 16, 12, and 35 are about 1.060, 1.070, and 1.076 p.u., respectively. The relation between measured reactive power, active power modulator, and fuzzy controller surface is shown in Fig. 15. It is evidenced that when the fault starts at \( t = 5 \), for a period of 0.2 s, i.e., until 5.2 s, the absorbed reactive power is enough to compensate the voltage swell and the active power modulator is not regulated. According to Fig. 15(a)–(c), it can be observed that the active power modulator regulation starts at \( t = 5 \).2 s. The combined regulation of both active and reactive powers generated by WFs allows, in this case, reducing the voltage swell effects. It can be observed from Fig. 16 that the active power generated by the WFs during voltage swell is decreased by the fuzzy controller in order to increase the absorbed reactive power. In other words, when the absorbed reactive power reaches 80% of its maximum value, the active power started decreasing by the fuzzy controller in order to increase the maximum reactive power that the WFs can absorb.

TABLE IV

<table>
<thead>
<tr>
<th>WF No.</th>
<th>Proposed Controller</th>
<th>PI Controller</th>
<th>Without Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (p.u.)</td>
<td>WF’s Situation</td>
<td>Voltage (p.u.)</td>
<td>WF’s Situation</td>
</tr>
<tr>
<td>1</td>
<td>1.056</td>
<td>Connected</td>
<td>1.085</td>
</tr>
<tr>
<td>2</td>
<td>1.059</td>
<td>Connected</td>
<td>1.090</td>
</tr>
<tr>
<td>3</td>
<td>1.067</td>
<td>Connected</td>
<td>1.111</td>
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</tbody>
</table>

According to the Danish grid code, all WFs can successfully fulfill the FRT requirement and, consequently, remain connected to the grid. In order to assess the effectiveness of the proposed controller, the performance of the fuzzy controller is compared with that of a PI controller, as designed in [27] and without any controller. As shown in Table IV, with the PI controller, WF1 and WF2 can successfully fulfill the FRT requirement and remain connected to the grid while WF3 disconnects. Moreover, without any controller all WFs are disconnected.

b) When considering only WF1 and WF3, it can be observed that the reactive power absorbed by the WFs is increased if compared to the previous case, while more active power is reduced. For example, for WF3, in case a) the absorbed reactive power is about 7.8 MVAr, while a reduction of about 55% of active power is achieved. In case b), these values are about 8 MVAr and 62%, respectively. According to Table V, both WF1 and WF3 can successfully fulfill the grid code requirements and remain connected to the grid.
Table V

<table>
<thead>
<tr>
<th>WF No.</th>
<th>Voltage (p.u.)</th>
<th>WF's Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.071</td>
<td>Connected</td>
</tr>
<tr>
<td>2</td>
<td>1.062</td>
<td>Connected</td>
</tr>
<tr>
<td>3</td>
<td>1.062</td>
<td>Connected</td>
</tr>
</tbody>
</table>

Fig. 17. (a) Voltage and (b) reference reactive power at the PCC during the normal operation.

Fig. 18. Voltage at the PCC.

Note that, during the normal operation of network, the proposed controller is also able to compensate voltage constraints' violations. As shown in Fig. 17, for WF2 the voltage drop is higher than the other WFs. Therefore, the reactive power injected by the fuzzy controller in order to compensate voltage sag effect is higher than the others.

B. Maximum Load

A total maximum load of 24 MW and 15 MVAr has been assumed. The same case studies investigated in Section VII-A for minimum load are also studied for maximum load.

1) Case Study B1: When the voltage drops by 30%, each WF injects reactive power during the voltage sag in order to help increase the voltage. The injected reactive power varies between about 2.35 MVAr for WF3 and about 2.50 MVAr for WF2 according to the voltages at the PCC. By increasing the value of the loads, the voltage at the PCC decreases and the reactive powers injected by WFs increase. As shown in Fig. 18, all WFs can fulfill the grid code requirements and can remain connected to the grid. In the case with two WFs, both WF1 and WF3 can fulfill the grid code requirement and remain connected to grid.

2) Case Study B2: Considering three WFs during a 15% voltage swell, the absorbed reactive power varies between about 6 MVAr for WF1 and about 7 MVAr for WF3. A reduction of about 28% and 46% of active power is achieved for WF1 and WF3, respectively. According to the Danish grid code, all WFs can successfully fulfill the FRT requirements and, consequently, remain connected to the grid.

In the case with two WFs, both WF1 and WF3 can fulfill the grid code requirement and remain connected to grid.

VIII. Discussion and Conclusion

This paper proposed a fuzzy controller for improving the FRT capability of WTs. It is designed in order to compensate the voltage at the PCC by controlling both the reactive and active powers generated by WFs. The FRT capability improvement, considering both voltage sag and voltage swell effects, is investigated considering the Danish grid code. The proposed method is able to simultaneously regulate active and reactive power during voltage variations. During voltage sag, only the reactive power is injected by using the controller in order to improve the voltage sag effects, while during a voltage swell when the absorbed reactive power is not enough, the active power generated by WFs is decreased by using the active power modulator. In this case, according to both the WTs’ power curve and capability curve, the WFs will not generate the maximum active power, but it has positive effects on voltage regulation at the PCC, i.e., within the limited size of the DFIG converters, the reduction of active power increases the maximum reactive power absorbed by WTs. Furthermore, in medium voltage weak networks with long feeders characterized by a high R/X ratio, the active power reduction can also increase the voltage drop on the feeders, thus contributing toward lowering the voltage at the PCC.

The performances of the proposed fuzzy controller were analyzed for both voltage sags and swells, considering different load values as well as different numbers and locations of WFs. The performances of the proposed controller were compared with a previously designed PI controller in the SymPowerSystems toolbox of MATLAB [27]. The results revealed that the performances of the proposed controller are better than those of the PI controller for both compensating voltage sag and swell effects. In other words, with the proposed controller all the WFs in different cases fulfill the FRT requirement and remain connected to the grid, while with the PI controller, in some cases, WFs cannot fulfill the FRT requirement. Note that during the normal operation of the network (without faults), the proposed controller is also able to compensate bus voltage when its constraints are violated.

REFERENCES


