Improved crowbar protection technique for DFIG using fuzzy logic

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ABSTRACT

A doubly-fed induction generator is the most widely used as a wind turbine generator. Due to its drawbacks, doubly fed induction generator (DFIG) is extremely sensitive to grid disturbances, and the fragility of some components which are costly to the producer. Also, its acquisition value is very high in terms of maintenance time or component cost, causing substantial harm to both the energy production and power supplier. It is required that the DFIG components must be protected, especially power electronics devices and DC-Link capacitor. Therefore, this paper presents an improved crowbar strategy for DFIG. This method is based on the AI technique concept of utilizing a fuzzy logic controller. The main goal of this project is to improve the system performance by reducing the dangerous oscillations of electromagnetic torque, DC-link voltage, and rotor current during fault. This work consists of replacing the hysteresis control for the crowbar with fuzzy logic to realize crowbar-FLC. The proposed crowbar is based on free light chain (FLC) depending on rotor currents and DC-link voltage measurements. The control strategy is simulated in the MATLAB Simulink platform to evaluate the efficiency of the suggested technique.

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1. INTRODUCTION

The increase in the price of fossil fuels, the observation of global warming, and the environmental degradation caused by the growth in daily consumption of polluting and non-renewable energy, these factors are leading us to rethink energy strategies Wind energy is the most significant and potential renewable energy sources in terms of global development. Indeed, it is non-polluting and economically reliable. The penetration of wind turbines into the power system has progressed considerably, meanwhile, in the wind industry. The manufacture of wind turbines continues to develop new technologies and control methods that allow wind energy to face the challenge of drastic climate changes and contribute to the overall energy supply. Various technologies are advanced, but a variable-speed wind turbine concept has attracted interest and possesses a greater development perspective. Due to its numerous advantages, such as diminution of construction cost, the ability to produce at a variable speed, and the potential to operate at a wide range of wind speeds to capture the maximum supply power.

However, the doubly fed induction generator (DFIG) is more liable to any grid disturbances. Because of its direct link to the grid, which contains components, which are very sensitive to grid faults. Taking this into account, with the increased integration of DFIG wind turbines into power systems, the behavior of DFIG based wind turbines has become significant. The fault grid may lead to an overcurrent in the stator windings, which pass through the rotor windings resulting in an overvoltage and overcurrent in the rotor circuit. A high current and voltage can occur in the rotor converter side, and a DC-link capacitor creates an over-voltage [1]. These failures are imposing protection systems to disconnect the wind turbine. Otherwise, the impact of damage to wind turbine equipment is very prejudicial. That is because of the wind turbine's non-availability, the high cost of spare parts, the energy that is not distributed during the breakdown, and the eventual penalties imposed on the investor or producer if the energy supply contract provides them.

For this reason, the network operator has imposed new grid code requirements requiring wind turbines to connected to the grid. Therefore, it's imperative to protect and avoid any risk of damage that can occur to the converter setup and DC-Link capacitor. The DFIG requires a protection system to ensure safe operation. Numerous measures of protection have been proposed to enhance the functioning of the DFIG during grid occurrence. In this regard, several types of approaches have been developed and generally divided into two categories. The first one is Internal control Techniques, which optimize and control parameters to improve the dynamic performance of DFIG-WTs, where are applied on wind turbines, roll stability control (RSC) and geotextile sand container (GSC).

During grid faults, an electromotive force (EMF) is induced in the rotor circuit due to the DC and negative sequence components appearing in the machine flux linkages and the rotor speed. The investigation proposed controlling the rotor-side converter by injecting the appropriate or the opposite current in the rotor windings [2]. The authors in [3] implemented an approach that combines the proportional-integral (PI) controllers with Lyapunov-based auxiliary control to ameliorate the transient behavior of DFIG-WTs. The DTC method has been applied as a robust control strategy, it is based on the application of hysteresis controllers by selecting the electromagnetic torque, the flux, and the position of rotor flux to set up a switching table. This method is developed to reduce the rotor, torque, and DC link ripples [4].

Furthermore, the second category is external retrofit techniques, which add protective devices to the DFIG system and advanced control strategies, such as rotor-side and stator-side external retrofit techniques, limiting the DC-link and rotor overvoltage and overcurrent, also to remain the stator current and stator voltage on an acceptable level. In light of these findings, different device topologies using protective circuits and storage methods such as damping resistances [5], DC-Chopper, series dynamic braking resistor [6] energy storage system (ESS) [7], [8] are discussed in many types of research. A combination of parallel crowbars and DC Chopper is presented in [9] to reduce the overcurrent in rotor converts and control the DC-link. Besides, the crowbar is an old hardware protection device investigated to secure the safe functioning of the rotor windings of DFIG, which protects the rotor side inverter and the DC-link capacitor during faults [10]. Many researchers focus their attention on studying the crowbar effect and improving its performance, and many types of crowbar protection have been presented in [11]. According to the operation [12], a method is adopted to reduce the crowbar's activated time and improve the hysteresis control strategy. Conventionally, the use of the hysteresis control is a classical technique that needs to carefully choose the threshold for crowbar application.

Subsequently, many researchers have always intended to develop methods to design and analyze complex processes employing input-output data. In this regard, the main categories of artificial neural networks include genetic algorithm (GA), fuzzy logic, and neural network. The authors in [13] evaluate that the fuzzy control provides a robustness control of the active and reactive powers of a DFIG. Another use of fuzzy logic is applied to the feedback linearization approach to improve the DFIG against unbalanced voltage [14].

Therefore, this work proposes an intelligent approach based on fuzzy logic for the crowbar of a DFIG. Hence, the primary purpose of this strategy is to regulate the system parameters based on rotor current and DC link voltage under grid faults as inputs, as required by the rules of the fuzzy controller to activate the switch of the crowbar. Furthermore, it needs the self-training process, and its design does not demand the knowledge of the model, which provides an optimal response and a good controller performance.

The rest of this paper is arranged as follows: section 2 provides a short description of the mathematical modeling of the DFIG connected wind turbine system, section 3 introduces the structure of fuzzy logic, and Section 4 describes the design of the intelligent protection approach for the DFIG using FLC. The simulation of the DFIG under grid fault with and without the new technique is performed using MATLAB/Simulink. The results are reported in section 5 to verify the effectiveness of the proposed strategy. Section 6 states the conclusion.

2. MODELING THE SYSTEM

In terms of the electrical part of DFIG, it operates as a wound rotor induction generator. Its stator is directly linked to the electrical grid, while the rotor is connected to the bidirectional (AC/DC/AC) power converter. The model of the DFIG system in the d-q reference frame is as follows [15]:

$$u_{ds} = R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \quad (1)$$

$$u_{qs} = R_s i_{qs} - \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (2)$$

$$u_{dr} = R_r i_{dr} - \omega_r \psi_{qr} + \frac{d\psi_{dr}}{dt} \quad (3)$$

$$u_{qr} = R_r i_{qr} - \omega_r \psi_{dr} + \frac{d\psi_{qr}}{dt} \quad (4)$$

where u_{ds}, u_{qs}, u_{dr}, u_{qr}, i_{ds}, i_{qs}, i_{dr}, i_{qr}, ψ_{ds}, and ψ_{qr} are the stator and rotor voltages, current and fluxes linkages in the d-q frame respectively, R_s, R_r, are stator and rotor phases resistances, finally, ω_s, ω_r are the angular frequencies of stator and rotor currents.

2.1. AC/DC/AC converters

The DFIG-WTs is directly connected to the electrical network via the stator, and the rotor windings are fed via back-to-back indirect PWM converters (AC/DC/AC) [16], known as a rotor side converter (RSC) and grid-side converter (GSC). The power transferred by converters is generally 25–30% of the generator's nominal power equipped with electronic components bidirectional IGBTs to generate AC voltage from the DC voltage source [17]. The DC voltage source is provided via a shunt capacitor connected on the DC side. Converter controllers are classified into two primary parts: RSC controllers and GSC controllers. The objective of RSC is to ensure the control separately by decoupling between the active and reactive powers; it is accomplished by controlling the rotor current component (i_{qr}) in the dq-reference frame, which is mapped to the torque or stator power. On the other hand, the GSC includes the grid filter, and its primary objective is to regulate the voltage capacitor. Furthermore, GSC enables bidirectional power flow by exchanging active power to the power grid and reactive power from DFIG to the grid through the stator.

Even distant from the turbine's placement, faults in the power system can create a sudden decrease in grid voltage, resulting in an over-voltage in the DC bus and an over-current in the generator's rotor circuit. Alternatively, without any protection provided, the output voltage of the RSC would be augmented during grid fault scenarios caused by high rotor EMF and may be damaged. Furthermore, it may boost the turbine's speed over the rated limits if it is not correctly designed to endanger its safety. The rotor crowbar must be activated to bypass the RSC in such cases. Converters, by nature, are highly subtle in structure and have a capital role simultaneously. Therefore, it is crucial to develop innovative solutions to ensure the functionality of components.

3. STRUCTURE OF FLC

The core contribution of this paper is to introduce a mathematical tool to design a fuzzy model of a system, as it presents the advantages of approximate reasoning and learning ability. The concept of fuzzy logic was introduced by Zadeh [18]. This invention significantly improved the control system by emulating the human decision process using fuzzy logic. Later on, in 1975, Ebrahim Mamdani invented the principles of the fuzzy interface system by introducing linguistic analysis control rules based on human thinking, which fuzzify and deffuzify crisp input value to obtain crisp results [19]. Takagi-Sugeno devised a new fuzzy interface system similar to the Mamdani approach a decade later, except that the membership function of the output must be either linear or constant [20]. Recently, fuzzy logic controller (FLC) based on algorithm of Mamdani and Takagi-Sugeno methods had been widely widespread interest in several applications such as power systems [21] and power electronic converters [22]. The fuzzy Logic approach is an artificial intelligence that imitates human reasoning in control. The basic idea behind fuzzy logic is that each object's partial may belong to to partial membership sets rather than belong to a single set entirely. Instead of being either 0 or 1, as in conventional logic, the degree to which a variable may range between 0 and 1. FLC variables are linguistic variables that use the fuzzy membership function concept (MFs). MFs come in various shapes, including Triangular, Trapezoidal, Gaussian, Sigmoid, and Singleton fuzzy sets, which are all used in the modeling of energy systems [23], [24]. Triangular MFs, on the other hand, are the most frequent and commonly utilized because to their simplicity and omputationally efficient. In general, the FLC operation consists of four steps [25], as shown in Figure 1.

Fuzzification is the process of transforming deterministic crip input into fuzzy set. by specifying the selected MFs for each system input variable to be controlled. Second, the fuzzy rule-base specified by a set of fuzzy IF-THEN rules is adopted to associate between input and output variables. The fuzzy rules in sugeno

system is presented in two models as decribed in [26]. Each rule of sugeno fuzzy inference operates in zero-order methods as in (4) with (p_i= q_i= 0), while z_i is constant, or first-order method as in (5).
Rule i:

$$IF\ x \text{ is } A_j\ and\ y\ is\ B_k\ THEN\ z_i = r_i \tag{4}$$

rule i:

$$IF\ x \text{ is } A_j\ and\ y\ is\ B_k\ THEN\ z_i = p_i x + q_i y + r_i \tag{5}$$

where A_j and B_k are the fuzzy sets for inputs x and y, j and k are the membership functions that defined the input, z_i represent an output (consequent function) and it is a linear or constant consequent function, p_i, q_i and r_i are the consequent parameters and finally, i indicates the number of rules. The third step, the interface engine, calculates the output value for each rule defined in the previous step. Lastly, defuzzification transforms the fuzzy output set getting from the inference mechanism into a single crisp output.

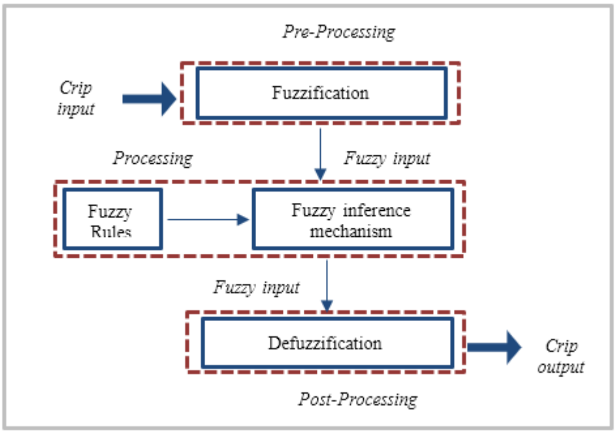


Figure 1. FLC architecture

4. CROWBAR APPROACH PROTECTION DRIVEN BY FUZZY LOGIC CONTROLLER

The purpose of fuzzy logic is mapping an input space to an output space by the statements rules mechanism. Before generating an efficient system to interpret rules, it must first define all the terms intended to use and the linguistic label that characterizes them. Otherwise, the fuzzy inference system process (FIS) concept is to enact the ranges of the different input vectors according on some set rules, assigning a value to the output vector. The Figure 2 presents the diagram of a roadmap for the fuzzy inference process as a description of the fuzzy system.

This paper provides a novel contribution by replacing the conventional hysteresis control with fuzzy Logic to reach two main goals: First, improving the protection of windings rotor from overvoltage, then the converter back to back, and second shielding the DC-link from overvoltage. The crowbar configuration consists of three resistors with controllable circuit breakers parallel with the rotor side converter. The proposed fuzzy controller is trained on different measurable data from the investigated system in both normal and abnormal cases. When a fault occurs, the controller detects it and closes the circuit breaker switches, allowing the fault current to dissipate via the crowbar resistors. This section explains the fuzzy inference process, which uses the two-input, one-output. The controller design consists of the following steps.

4.1. Fuzzifaction

As shown in Figure 3, the proposed fuzzy controller presents two inputs: the measured three-phase current of rotor windings of DFIG and the Vdc. In particular, the selected type of MFs for inputs is Triangular. Meanwhile, the MF shape of the outputs is defined to be constant, where are presented as “FO” = Fault Occurrence” and “NF” = No-Fault,” which have two values: 0 or 1. This output is 0 to indicate no fault occurrence and 1 if there is fault occurrence. The inputs of the FLC are as follows:

a. VDC: DC-Link voltage

b. Rotor current: $I_r = \sqrt{I_{ra}^2 + I_{rb}^2 + I_{rc}^2}$

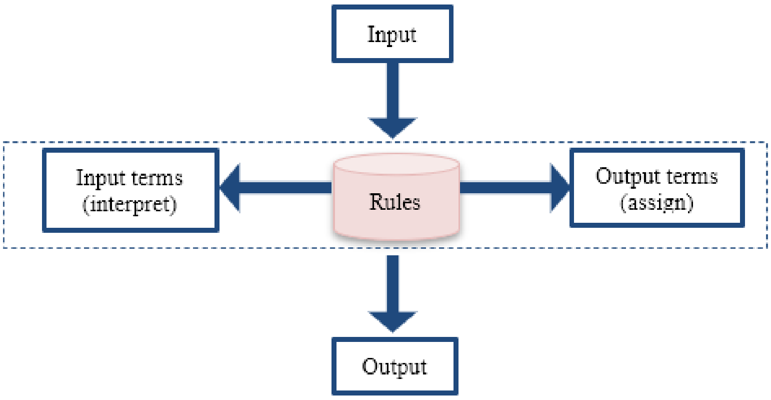


Figure 2. Block diagram of a general description of fuzzy system

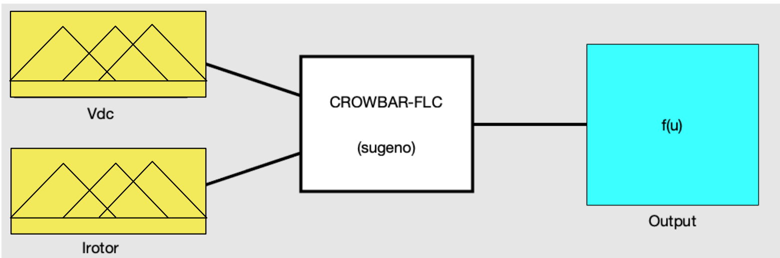


Figure 3. FLC inputs and output for crowbar protection

In this case, the fuzzy sets of current rotor input, DC-link voltage input respectively are referred to the rules base as "NRF" = Negative Range of Fault, "ZF" = No-Fault (Zero Fault), "PRF" = Positive Range of Fault, "SRF" = Small Range of Fault, and "BRF" = Big Range of Fault. The FLC output is a control signal used to activate or deactivate the crowbar; Table 1 indicates the target output for FLC under different conditions.

Table 1. Target output for FLC

Conditions	NF	FO
NRF-SRF	0	1
ZF	1	0
PRF-BRF	0	1

4.2. Fuzzy rules

After fuzzifying the inputs, the fuzzy rules must be designed according to the input and output variables, the conditional statements that compose fuzzy rules can be represented in the widely used format of (IF-THEN) statements. The following form is an expression of a fuzzy if-then rule:
if <input variable1> **is** <MF_name> (**and/or**) <input variable2> **is** <MF_name> then <outputvariable> is <MF_name>.

Our control rule is defined as the following: IF ($I_{ra,b,c}$ is A) AND (VDC is B) THEN (S is Oi). Where the IF-part rule A (NRF, ZF, PRF) and B (SRF, ZF, BRF) are the fuzzy set of the input variables are called antecedent, while THEN-part of the rule Oi (NF, FO) the fuzzy set of the output variables is called the consequent. By applying the fuzzy AND operator, which allows the system to resolve the antecedent into a rule support degree and then construct a fuzzy output set known as a consequent, which is represented by a membership function determined to be constant in this case. In general, the output of each defined rule is a fuzzy set; therefore, the fuzzy output sets are aggregated to form a single set. Aggregation, in other words, is the process of combining the outputs of each rule into a single fuzzy set whose input is a list of the truncated output functions provided by the implication process for each rule. Finally, the final set is defuzzified.

The number of MFs determines the number of rules used in designing the fuzzy controller utilized, with 9 rules used for 3x3 MFs, corresponding to three fuzzy sets for each input. The inference rules for the proposed controller are simulated with human reasoning to evaluate the values of output variables based on if-then rules. FLC rules are constructed using the deterministic method proposed by Takagi and Sugeno. Therefore, the rules are formed using a fuzzy process model or self-learning fuzzy. These rules can be grouped in the Table 2:

Table 2. Set of fuzzy rules

$I_{ra,b,c}$ / VDC	NRF	ZF	PRF
SRF	FO	FO	FO
ZF	FO	NF	FO
BRF	FO	FO	FO

1. IF {Vdc is SRF AND Irotor is NRF} THEN Oi is FO
2. IF {Vdc is SRF AND Irotor is ZF} THEN Oi is FO
3. IF {Vdc is SRF AND Irotor is PRF} THEN Oi is FO
4. IF {Vdc is ZF AND Irotor is NRF} THEN Oi is FO
5. IF {Vdc is ZF AND Irotor is ZF} THEN Oi is NF
6. IF {Vdc is ZF AND Irotor is PRF} THEN Oi is FO
7. IF {Vdc is BRF AND Irotor is NRF} THEN Oi is FO
8. IF {Vdc is BRF AND Irotor is ZF} THEN Oi is FO
9. IF {Vdc is BRF AND Irotor is PRF} THEN Oi is FO

4.3. Defuzzification

As a final phase, the aggregation of fuzzy sets incorporates a range of crips output that are the inputs of the defuzzification process. It consists of converting them into a single set output value. This process supported two built-in defuzzification methods: weighted average (wtaver) and weighted sum (wtsum). The output of the fuzzy inference system is composed of two values of the crowbar switches that are splitting into two fuzzy sets, zero and one (opened or closed, respectively). Table 3 shows the characteristics of the fuzzy logic structure for the crowbar protection approach.

Table 3. Parameters of FLC structure

Parameters	Values/types
Crip Inputs	2
Crip Outputs	1
Number of the input membership function	3
Shape of the input membership function	Triangular
Shape of the output membership function	Constant
Rules	9
Inference engine	TSK-Takagi and Sugeno
Defuzzification Method	'Wtaver' Weighted average

5. SIMULATION RESULTS AND DISCUSSION

This part investigates the behavior of the DFIG outfitted with the suggested on fuzzy logic technique. The overall system model is developed using Simpowersystem toolbox under MATLAB/Simulink. The performance of DFIG-WTs without protection and with the rotor parallel crowbar driven by the FLC is compared during 3-symmetrical fault conditions. The DFIG wind farm produces 9 MW from six 1.5 MW wind turbine generators connected to a 120-kV grid via a 30 km transmission line in length. The DFIG operates at a constant wind speed of 15 m/s. The DC-Link voltage is set at 1150V during steady-state conditions, and the active and reactive power are 9 MW and 0 MVar, respectively. The fault under examination is the triple line to the ground, subjected to the system at the point of common coupling (PCC) for 500 ms. The Figure 4 shows a schematic illustration of DFIG with the proposed crowbar protection device.

5.1. Analysis of DFIG during symmetrical 3-phase fault condition without crowbar protection

The DFIG simulation outcomes show the behaviors of the studied system during the occurrence of a triple-line fault. When the fault happens on phases a, b and c, the stator voltage lowers, and stator currents increase to a high value, causing a variation of the electromagenic torque rotor current and bus voltage, and the reactive power delivered by the DFIG.

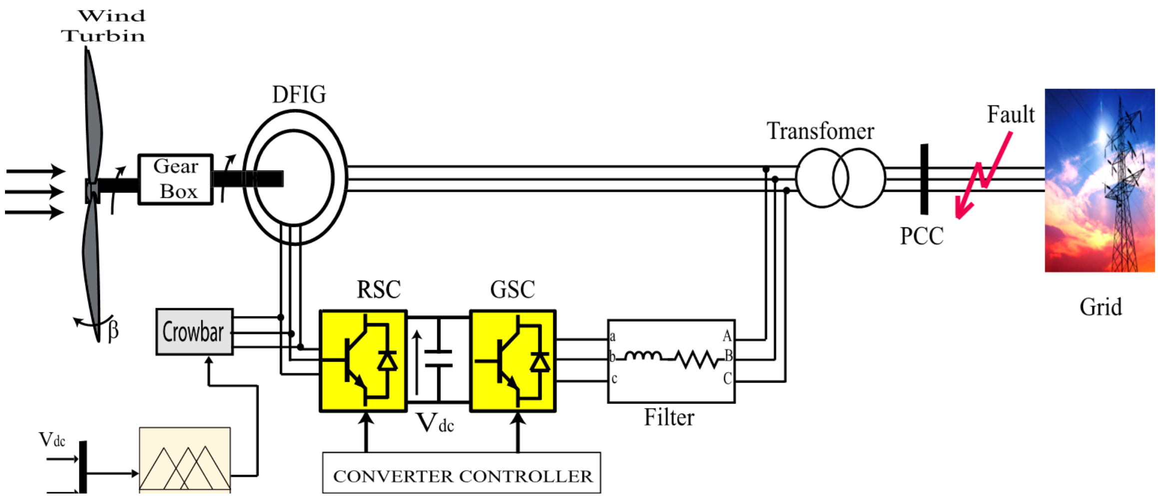
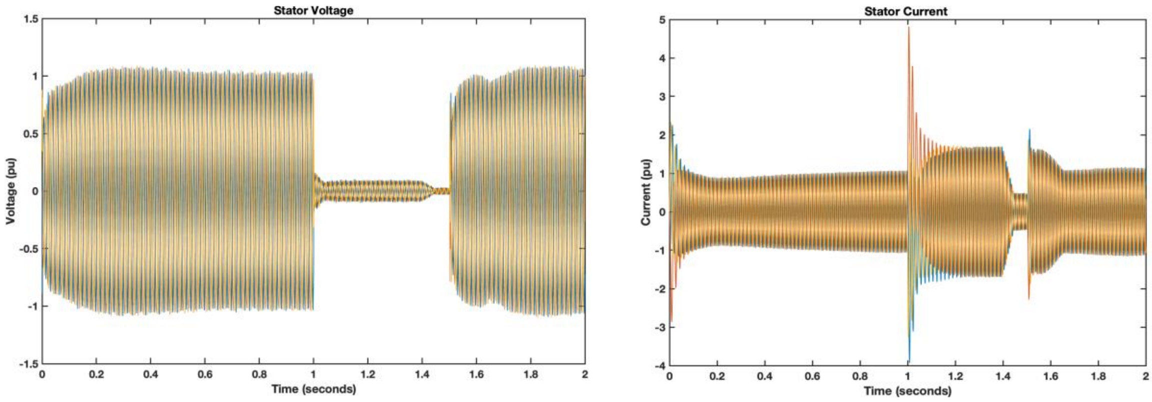


Figure 4. Schematic illustration of DFIG with the proposed crowbar protection device

5.1.1. Variation of stator current and voltage

The Figures 5 (a) and 5(b) depict the terminal voltage fluctuations of wind turbines in the event of a three-phase failure, which occurred at 1s when DFIG supplied 9 MW of power to the grid as well as the wind speed remained constant at 15 m/s throughout the simulation. The voltage at the PCC is nearly zero at this point, but the stator current has increased to 4.92 pu.

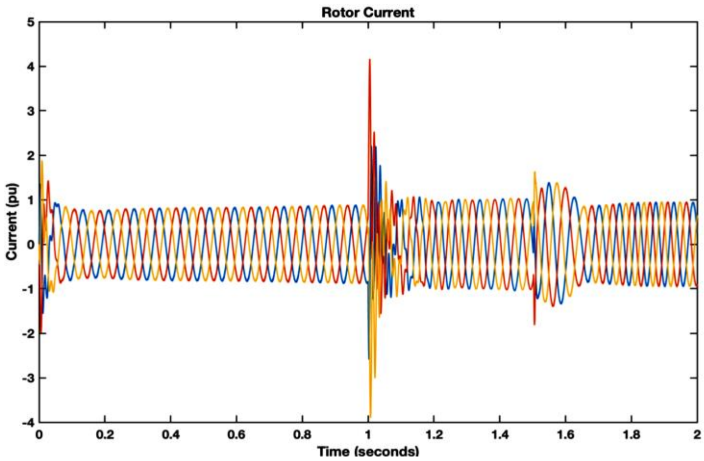


(a) (b)

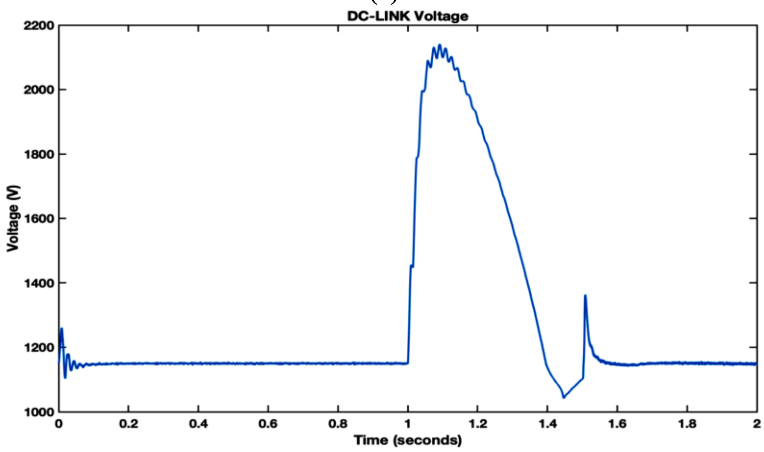
Figure 5. Variations of stator voltage (a) stator current and (b) during the three-phase fault

5.1.2. Variation in Rotor current, capacitor voltage, and electromagnetic torque

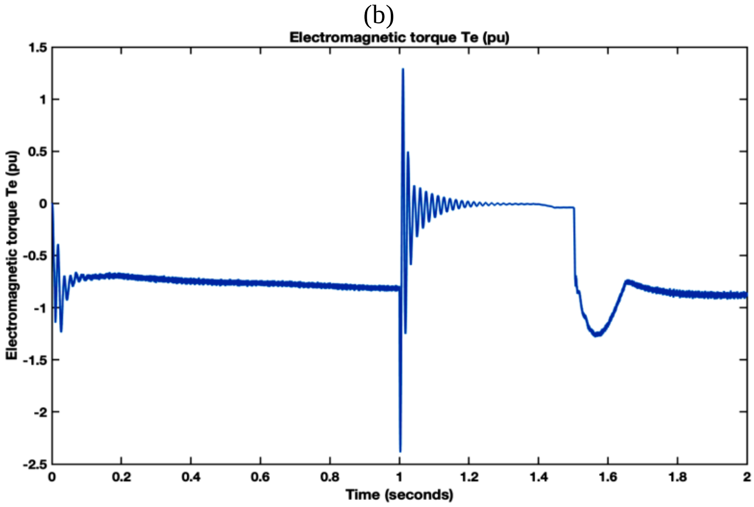
The figure below presents the variations of the rotor current, torque, and DC-Link voltage without any protection. For a system without a protection approach, the rotor current has a dangerous peak to reach values of 4,152 pu at the beginning of the fault occurrence, as is depicted in Figure 6(a). Those oscillations subject the side rotor converter to very high stress, which is unacceptable because they significantly affect the RSC, and potentially damage it. The GSC regulates the DC capacitor's voltage; however, when the fault occurs, the Grid voltage drops, and the GSC is unable to transmit power from the RSC to the grid. As a result, the extra energy charges the DC link capacitor, causing its voltage to rise rapidly; the DC link voltage swells up to 2153 V, as shown in Figure 6(b); as a consequence, this will severely damage the DC link capacitor. In addition, the electromagnetic torque in Figure 6(c) fluctuate with the rotor current. This torque presents significant fluctuations that will affect the mechanical of DFIG performance. When a grid fault appears, the electromagnetic torque oscillations reduce to -2,481 pu and rise to 1,261 pu.



(a)



(b)

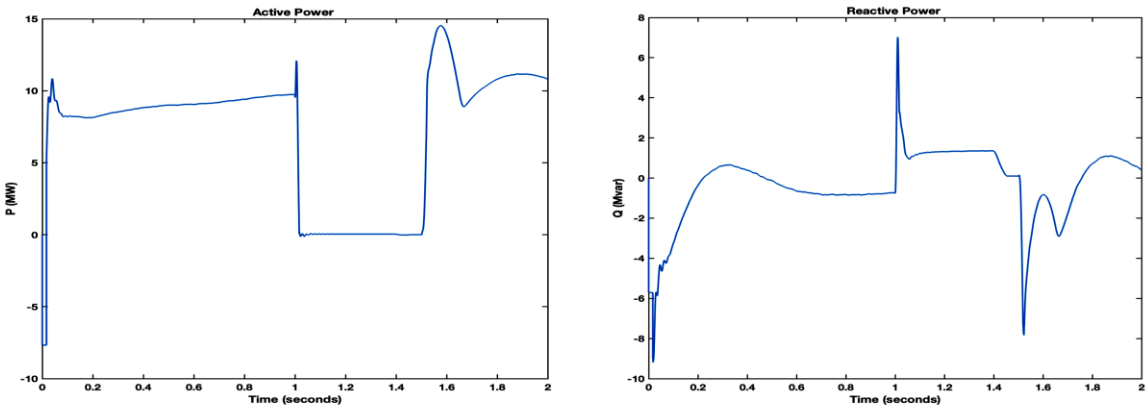


(c)

Figure 6. Illustration for rotor current (a) DC-link voltage, (b) electromagnetic torque and (c) variations during-three phase fault

5.1.3. Impact of a grid three-phase fault on active and reactive power

The active and reactive powers supplied from the wind are depicted in the figure below. During the fault, the active power is rapidly decreased to zero. Moreover, the DFIG injects the reactive power generated by the GSC into the grid to keep the voltage stable. The effect of the fault causes a total loss of energy production and inefficient reactive power regulation. With the massive introduction of wind energy in the electrical network, the grid operator imposes grid code requirements considering LVRT, which must spread to the voltage condition ranges established by the grid code. The generated powers are depicted in Figures 7(a) and 7(b).



(a) (b)

Figure 7. Variations of active power (a) reactive power and (b) during three-phase fault

In general, wind farms are located at remote grid connection points. In a three-phase fault condition, the short circuit current for these types of failure is very high. Then the fault current (in the order of 10 kA) will be provided mainly by the wind turbines. Thus, disconnection of the farm is strongly recommended in this circumstance to preserve the installations from damage.

5.2. Behavior of DFIG equipped with the proposed approach during symmetrical three-phase fault

This subsection illustrates the effect of the proposed control technique and behavior of DFIG when subjected to the symmetrical three-phase fault at the PCC. The key outcome of this work is to develop a robust and effective fuzzy logic controller for activating switches of crowbar resistors. The Figure 8 presents the flowchart of different steps of the proposed control scheme for the crowbar. The simulation outcomes are illustrated in the Figure 9.

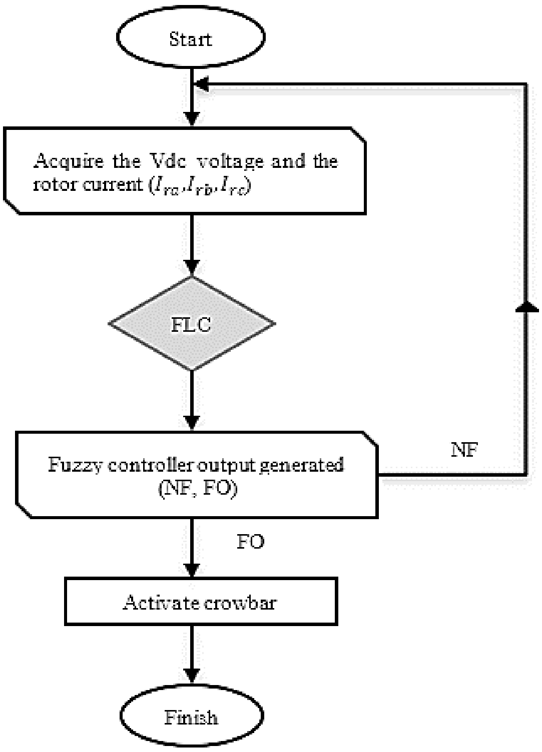
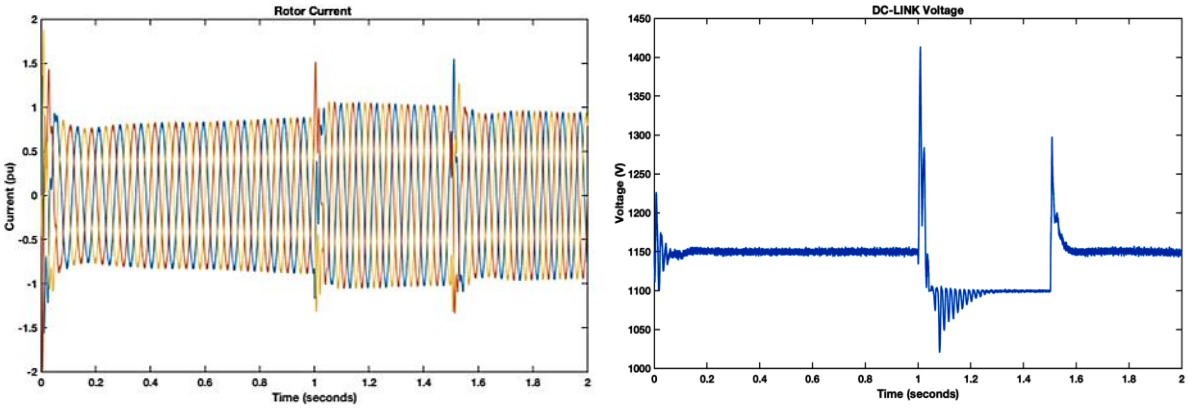


Figure 8. Flowchart of different steps of the proposed control scheme for the crowbar

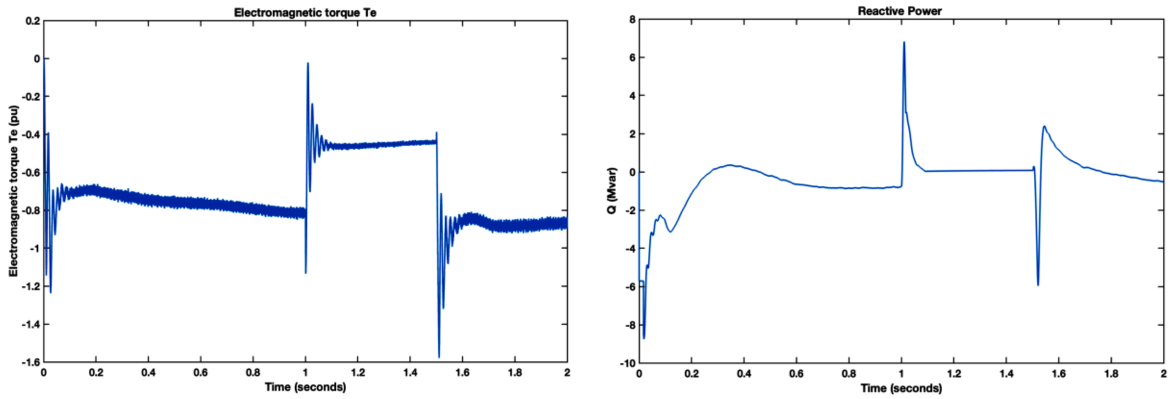


(a) (b)

Figure 9. Variations of measured rotor current (a) DC-link voltage and (b) during three-phase fault with the proposed crowbar protection

In the Figure 9(a), it can be remarked that the approach reduces the rotor current most efficiently during the grid fault occurrence and recovery. The peak current is decreased with the activation of the crowbar, which provides a bypass for the fault currents. Thus, the present value is lowered to 1,4 pu. On the other hand, the peak current is significantly lowered at the instant of voltage recovery. Hence, the peak rotor current is reduced before and after recovery, preventing the converters from being damaged.

The variation of DC-link voltage is another important phenomenon. It is worth mentioning that the most severe DC-link voltage variations occur during the fault period, and the highest voltage exceeds the safety limits. Figure 9(b) presents the enhancement obtained for Vdc in decreasing the over-voltage created during grid fault. Figure 10 shows the fluctuations in electromagnetic torque and reactive power caused by a symmetrical three phase fault using the investigated protection technique. Figure 10(a) demonstrates that the transient in electromagnetic torque reduced to the secure region. Also, in figure 10(b) the reactive power is decreased to Zero. The above results demonstrate the robustness and reliability of the fuzzy controller used for the crowbar. This technique offers a significant reduction in oscillations of the main parameters of the DFIG.



(a) (b)

Figure 10. Variations of measured electromagnetic torque (a) reactive power and (b) during three-phase fault with the proposed crowbar protection

6. CONCLUSION

This paper concentrated on the hardware approach for protecting the DFIG WT outfitted with three crowbar resistors linked in parallel with a controlled single-phase switch against severe grid faults. The objective is to enhance the crowbar performance. An improved FLC strategy is developed in detail to reduce violent oscillations of the high current during the occurrence and the clearance of the faults to safeguard the

DFIG, DC-link capacitor, and converters from damage. The controller employed fuzzy logic and used the average values of three-phase rotor currents and DC- link voltage to activate the crowbar. The accuracy of the proposed strategy is evaluated during 3-Φ fault at the terminal of DFIG using MATLAB/ Simulink. The variations of rotor current, DC-Link voltage, electromagnetic torque, active and reactive power are examined in steady-state and faulty state conditions. The simulations results show the system performance with and without the crowbar based on FLC for 500ms. The measured DC-Link voltage becomes more stable during the fault period and reaches an acceptable value. Also, the rotor current and torque have little fluctuations throughout and after the fault period. Thus, the power electronics devices are saved. After the clearance of disturbance, the RSC is reconnected to the grid, and the DFIG provides reactive power to the grid to stabilize the grid voltage. Furthermore, the DFIG results show low variations during and after the fault when the proposed technique is applied. Finally, the new crowbar approach based on fuzzy logic successfully controlled the active crowbar to eliminate the failure of variations in DC-link voltage, rotor current, torque, active and reactive power during fault operation.

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