Impact of Symmetrical Voltage Dips Faults on a DFIG Driven by a Wind Turbine System with Direct Torque Control

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Abstract **-** With over 50% of the wind energy industry, the doubly fed induction generator (DFIG) is a well-liked and common technology in variable-speed wind turbine systems. The voltage dips in the grid have the potential to disrupt DFIG operation by inducing substantial distortion and current spikes in both the stator and rotor circuits. In the absence of adequate protective measures, the rotor-side converter (RSC) is also at risk of exceeding its current limit, potentially causing damage to both the RSC and the generator itself. This study provides an in-depth analysis of the impact of symmetrical voltage dips within a wind turbine system equipped with direct torque control (DTC). All simulations were conducted using Matlab/Simulink.

Keywords **-** Voltage dips, Doubly fed induction generator (DFIG), Direct torque control (DTC), Wind Turbine (WT).

I. INTRODUCTION

The Doubly Fed Induction Generator (DFIG) represents a popular and prevalent technology in variable-speed wind turbine systems, constituting nearly 50% of the wind energy market. Its appeal lies in its efficiency, cost-effectiveness, and adaptability to diverse wind speeds, highlighting the integral role that wind energy is poised to play in the future of renewable energy[1],[2].

This technology employs a unique setup where the stator is directly connected to the power grid, while the rotor is driven by an electronic power converter, facilitating variable-speed operation and power factor control through the rotor-side converter. In this context, a control strategy known as DTC (Direct Torque Control) has been introduced for managing the DFIG, utilizing two hysteresis controllers to regulate generator electromagnetic torque and rotor flux. The central challenge lies in the selection of an appropriate rotor voltage vector for the rotor-side converter, crucial for maintaining prescribed rotor flow and torque values within defined limits [3] .

The voltage dips, a temporary and sudden dips in voltage amplitude ranging from 10% to 90% of the RMS voltage, impacts one or more phases within the electrical network, characterized by its amplitude and duration. The stator windings of the DFIG are directly linked to the network, severe voltage dips trigger high peak currents within the stator windings. These currents are a consequence of the coupling between the stator and rotor circuits, causing over currents in the rotor winding and the rotor side converter (RSC).

This, in turn, increases voltage in the DC bus capacitor and induces torque oscillations. Without protective measures in place, these transient high currents can lead to damage to the rotor side converter and the generator[4],[5].

The primary objective of this research document is to investigate and validate the effects of a voltage dips in the grid on a wind energy system based on a doubly fed induction generator (DFIG) controlled by direct torque control (DTC). To achieve this goal, the research team will conduct simulations using the Matlab/Simulink environment.

These simulations are designed to explore the behavior of the DFIG under various conditions, both under normal circumstances and in the presence of a voltage dips, while analyzing the impact of this fault on the quality of energy delivered to the grid. The findings of this study will be crucial in enhancing our understanding of how the wind energy system responds to voltage dips and in developing effective diagnostic techniques for detecting and mitigating these faults. The researchers will present the results of their simulations, which should significantly contribute to the body of knowledge in this field.

This research paper is divided into various sections. Section 2 presents the mathematical model of the turbine. Moving on to Section 3, we present Maximum Power Point Tracking (MPPT). In Section 4, we focus on the mathematical model of the Double Fed Induction Generator (DFIG). Then, Section 5 addresses Direct Torque Control applied to the WT-DFIG system. The results of the system's simulations are discussed and analyzed in Section 6. Lastly, significant conclusions are provided in Section 7.

II. MODELE OF TURBINE

The input power of the wind turbine is generally[6]:

$$P_v = \frac{1}{2}.\rho.S_w.v^3 \quad (1)$$

Where ρ is air density; S_w is the swept area of wind turbine blades in the wind; and v is wind speed.

The mechanical output power of a wind turbine is:

$$P_m = C_p.P_v \quad (2)$$

Where C_p is the power coefficient, which is defined as:

$$C_p = \left(0.5 - 0.0167.(\beta - 2)\right).sin\left[\frac{\pi.(\lambda+0.1)}{18.5-0.3.(\beta-2)}\right] - 0.00184.(\lambda - 3).(\beta - 2) \quad (3)$$

Where β the blade pitch is angle and λ is the tip speed ratio, λ is given by:

$$\lambda = \frac{R.\Omega_t}{v} \quad (4)$$

Where R is the blade radius and Ω_t is the turbine's angular speed.

The Equation (5) can be used to calculate the aerodynamic torque on the slow axis [7]:

$$T_{aero} = \frac{P_{aer}}{\Omega_{turbine}} = C_p \frac{1}{2}\rho S_w v^3 \frac{1}{\Omega_{turbine}} \quad (5)$$

The total inertia J is:

$$J = \frac{J_{turbine}}{G^2} + J_g \quad (6)$$

Where the turbine's inertia is represented by $J_{turbine}$ and J_g is the inertia of generator.

The dynamic equation is given by:

$$T_g - T_{em} = J.\frac{d\Omega_{mec}}{dt} + f.\Omega_{mec} \quad (7)$$

Where;T_{em} Electromagnetic torque; *f*: coefficient of friction; Ω_{mec} ; Mechanical speed.

III. MAXIMUM POWER POINT TRACKING

The electromagnetic torque T_{em} of the DFIG is controlled by an MPPT algorithm for maximum operating power, it requires the measurement or the estimation of the wind speed.

The electromagnetic torque references can be expressed as[8]:

$$T_{emref} = \frac{C_p(\lambda,\beta)}{\gamma^3{}_{opt}}.\frac{\rho.\pi.R^3}{2}.\frac{\Omega^3{}_{mec}}{G^3} \quad (8)$$

In this work, the blade pitch angle, tip speed ratio are maintained at constant values (β = 0, λ = λopt = 9).

IV. MATHEMATICAL MODEL OF DFIG

The general model is as follows after applying the Park transformation to the three phases of the DFIG[9]:

$$\begin{cases} V_{sd} = R_S I_{sd} + \frac{d}{dt}\varphi_{sd} - \omega_s.\varphi_{sq} \\ V_{sq} = R_S I_{sq} + \frac{d}{dt}\varphi_{sq} + \omega_s.\varphi_{sd} \\ V_{rd} = R_r.I_{rd} + \frac{d}{dt}\varphi_{rd} - \omega_r.\varphi_{rq} \\ V_{rq} = R_r.I_{rq} + \frac{d}{dt}\varphi_{rq} + \omega_r.\varphi_{rd} \end{cases} \quad (9)$$

Where;

The parameters V_{sd}, V_{sq}, V_{rd}, V_{rq}, I_{sd}, I_{sq}, I_{rd}, I_{rq}, φ_{sd}, φ_{sq}, φ_{rd}, and φ_{rq} represent the components of stator and rotor voltages, currents, and flux along the d and q axes in a doubly fed induction generator (DFIG). The symbols R_s, R_r, ω_s, and ω_r indicate the resistances and pulsations of the stator and rotor, respectively.

For DFIG magnetic flux, the equations are given by:

$$\begin{cases} \varphi_{sd} = L_s I_{sd} + M.I_{rd} \\ \varphi_{sq} = L_s I_{sq} + M.I_{rq} \\ \varphi_{rd} = L_r I_{rd} + M.I_{sd} \\ \varphi_{rq} = L_r I_{rq} + M.I_{sq} \end{cases} \quad (10)$$

Where $L_s, L_r,$: Stator and rotor phase leakage inductances respectively, M: Stator-rotor mutual inductance.

The torque generated by DFIG:

$$T_{em} = PM\left(I_{rd}.I_{sq} - I_{rq}.I_{sd}\right) \quad (11)$$

Where P is the number of poles.

V. DIRECT TORQUE CONTROL(DTC) APPLIED TO WT-DFIG SYSTEM

The DTC technique uses hysteresis controllers to choose an ideal rotor voltage vector based on rotor flux and electromagnetic torque inaccuracies that arise from comparing the estimated and referential values. Fig.1 depicts the DTC system.

The magnitude of the rotor flux is estimated from its components along the α and β axes [10]:

$$\varphi_{r\alpha,\beta}(t) = \int_0^t (v_{r\alpha,\beta} - R_r i_{r\alpha,\beta})dt \quad (12)$$

$$\varphi_r = \sqrt{\varphi_{r\alpha}^2 + \varphi_{r\beta}^2} \quad (13)$$

Starting with the estimated flux value ($\varphi_{r\alpha}$,$\varphi_{r\beta}$) and the calculated current values ($i_{r\alpha}$, $i_{r\beta}$).

The electromagnetic torque can be calculated as[11]:

$$T_{em} = P\left(\varphi_{r\beta}\, i_{r\beta} - \varphi_{r\beta}\, i_{r\alpha}\right) \quad (14)$$

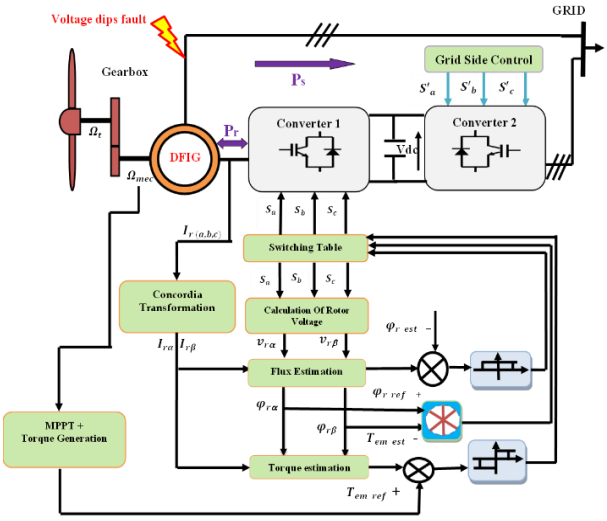

Fig. 1. Structure of the DTC technique applied to the DFIG.

VI. SIMULATION RESULT

The WT-DFIG system is simulated using the MATLAB/SIMULINK platform with the application of Direct Torque Control (DTC). This study aimed to assess the impact of voltage dips faults on the system's performance. Specifically, a 40% symmetrical three-phase voltage dips was applied for a duration of 1 second, starting at t=1 second and ending at t=2 seconds (as illustrated in Fig.3). The wind profile must be kept constant at a speed of 9 m/s in order to make the impact of voltage dips faults clearly identifiable.

The system parameters were derived from a previous study (reference[12]) and are detailed in Table 1 and Table 2.

Table 1. Parameters of a wind turbine.

Rated Power	7.5 kW
Blade radius	R = 3.24 m
Gearbox	G = 5.065
Air density	ρ = 1.1225 kg/m^3

Table 2. Parameters of DFIG.

Rated Power	7.5 Kw
Frequency	f = 50 Hz
DC-link voltage	V_{dc} = 880V
Number of Pole pairs	p = 3
Stator Resistance	R_s = 1.02Ω
Rotor Resistance	R_r = 0.8 Ω
Stator Inductance	l_s = 0.093 H
Rotor Inductance	l_r = 0.081 H
Mutual inductance	M = 0.0664 H

Figure 2 depicts the mechanical speed. It can be observed that the speed reaches a constant value of 1176 rpm, The generator operates in hyper-synchronous mode.

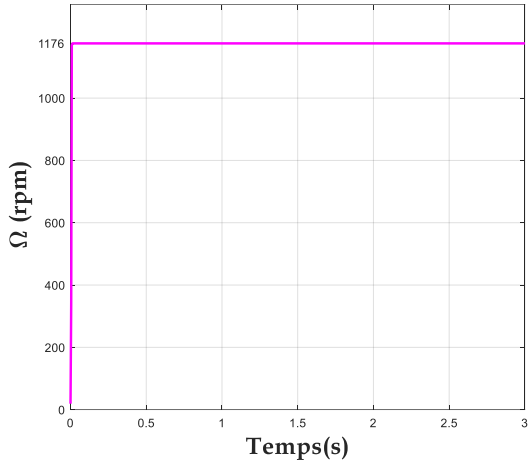

Fig. 2. Mechanical speed.

Figure 3 depicts the Stator Voltage (Vs) during a voltage dip of 40%.

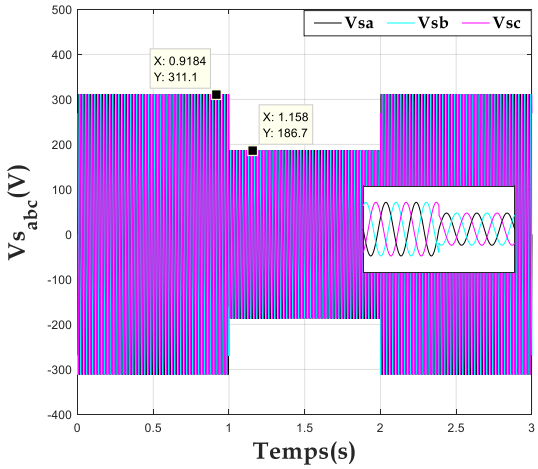

Fig. 3. Stator Voltage Vs during a voltage dip of 40%.

The electromagnetic torque and its reference are depicted in Fig. 4. When faults occur in the electrical network within the time interval t = [1s-2s], a series of peaks reaches a value of T_{em} = 51 (N.m). These peaks will exert significant pressure on the drive train.

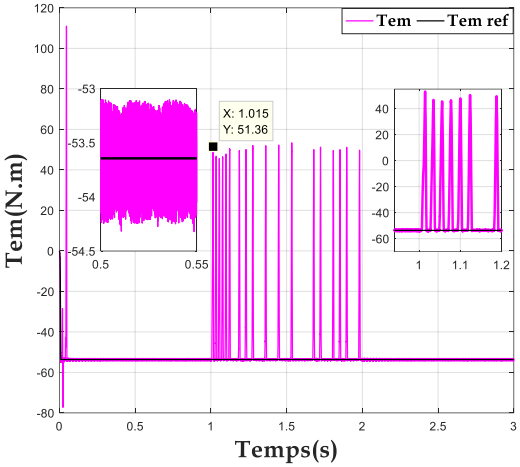

Fig. 4. Electromagnetic torque and its reference.

The Figure 5, present the rotor flux amplitude. The rotor flux is kept constant at its reference value (1.2 Wb).

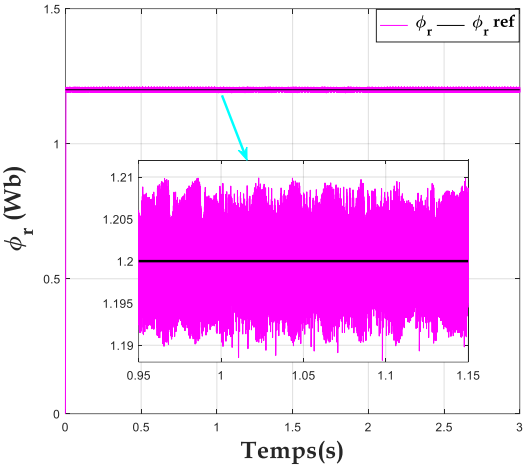

Fig. 5. Rotor flux and its reference.

Figures 6 and 7 illustrate the representation of the active power of the stator and rotor respectively. It is noteworthy that the stator's power is negative, approaching nearly -5280 watt, as it is supplied to the grid. This power experiences a significant increase following the occurrence of a fault at t=1 second, evidenced by high-amplitude peaks, with most of these peaks

reaching 6475 watt. At the moment of fault clearance, at t=2 seconds, the power reaches its peak at -9289 Watt, then returns to its previous value at t=2.37 seconds, i.e., ps = - 5280 watt.

The same to rotor active power. A negative sign indicates that it dissipates into the grid. Before the fault, it remains constant at a value of -658 watts, and after the fault, its value increases with a series of large peaks. At the moment t=2.37s, the power returns to its initial value.

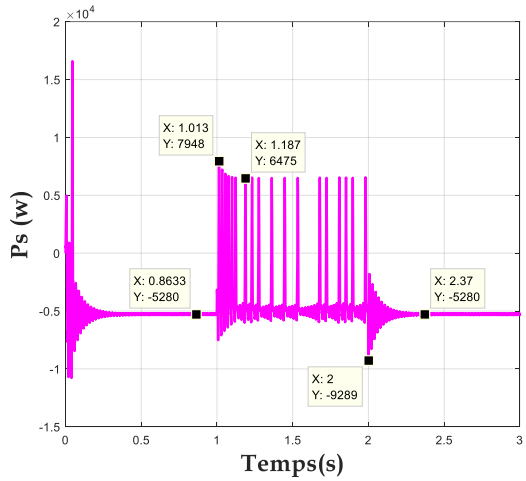

Fig. 6. Stator active Power.

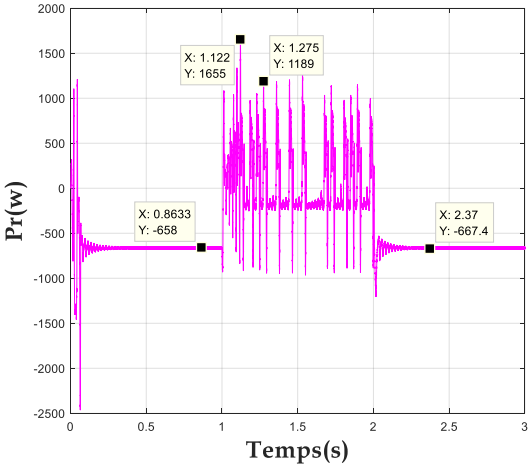

Fig. 7. Rotor active power.

Figures 8 and 9 respectively show the stator current and its zoomed waveform sent by the DFIG to the network. A distortion in the waveform is noticeable when faults t[1-2] are present, with the appearance of a series of peaks reaching a value of Is= 2 Is.

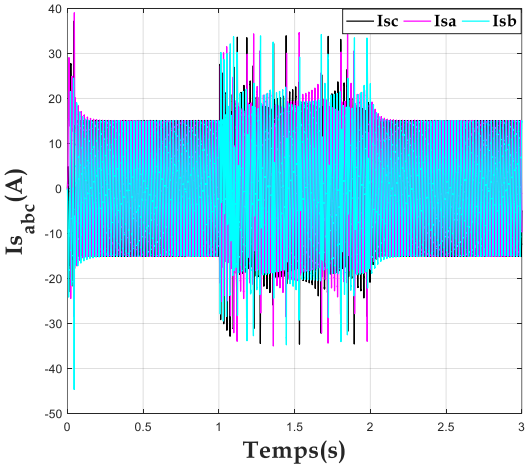

Fig. 8. Stator current Is (abc).

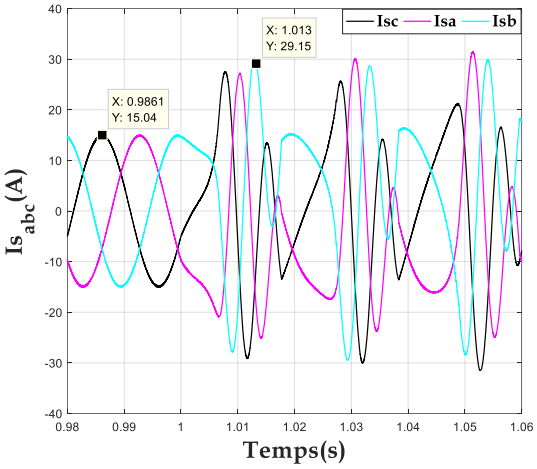

Fig. 9. Stator current zoom.

The illustrations presented in Figures 10 and 11 provide a detailed representation of the variation in rotor currents Ir, with a specific emphasis on the moment of the fault. It is relevant to note that when a disturbance occurs in the electrical network, such as a voltage dips, it results in a significant alteration of the signal's configuration, with peaks reaching a value equivalent to 2.4 times Ir.

It is essential to underline that exceeding the overcurrent limit can lead to adverse consequences for both the rotor-side converter and the generator. Therefore, understanding these phenomena is of paramount importance in the context of system maintenance and preservation.

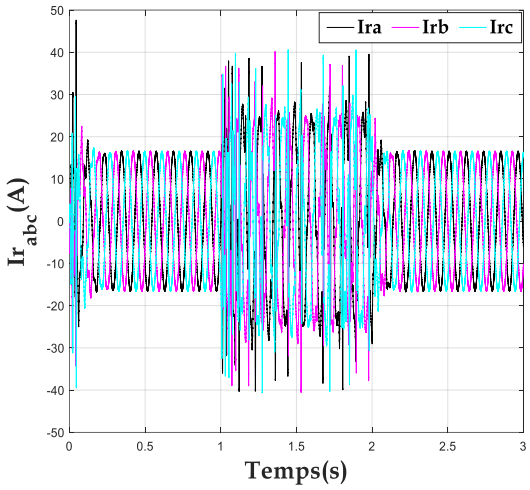

Fig. 10. Rotor current Ir (abc).

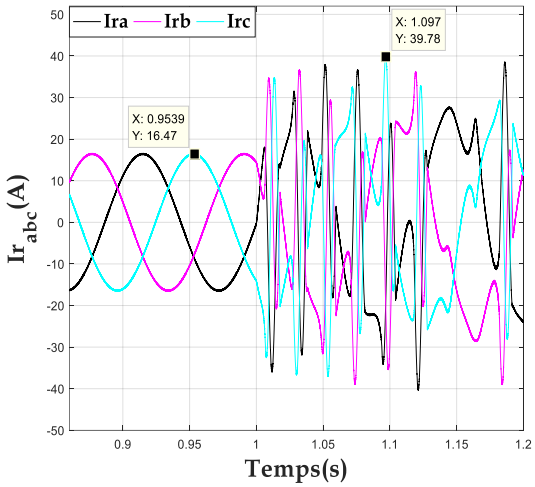

Fig. 11. Rotor current zoom.

To underscore the effects of a voltage dips fault on the quality of the signal generated by the DFIG (Doubly Fed Induction Generator), a spectral analysis of the stator current was conducted (as depicted in Figures 12 and 13).

This analysis was performed over three operational cycles, both prior to and during the fault occurrence. Upon comparing the THD values before the fault (THD = 0.72%) and at the time of the fault occurrence (THD = 78.47%), it becomes evident that the fault causes distortion in the current waveform, resulting in an increased THD value.

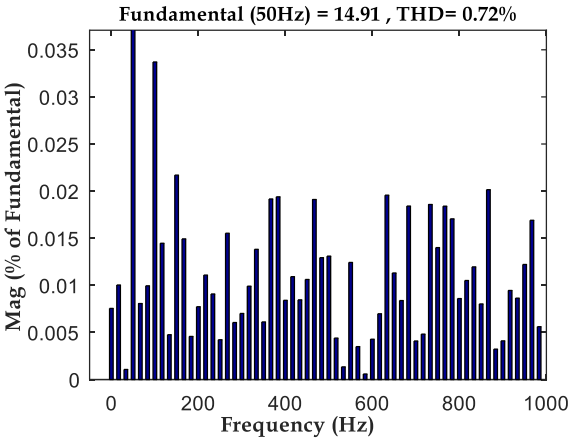

Fig. 12. THD of Stator current Isa (three cycles before fault).

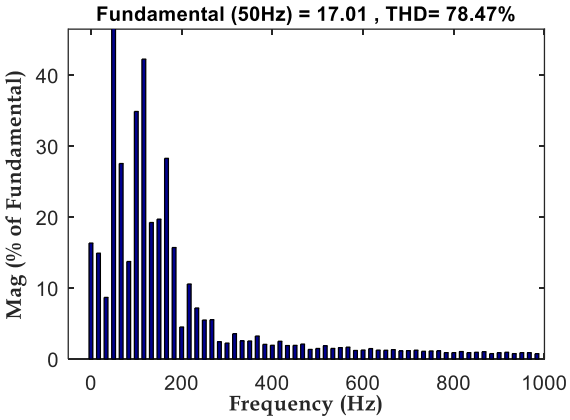

Fig. 13. THD of Stator current Isa (three cycles during the fault).

VII. CONCLUSION

The study in this paper focuses on the impact of symmetric voltage dips faults on a DFIG (Doubly Fed Induction Generator) driven by a wind system with direct torque control.

The results of our analysis significantly demonstrate the impact of symmetric voltage decrease faults on the performance of a DFIG in a wind system with direct torque control. These faults result in distinct characteristics: considerable peaks in electromagnetic torque, a substantial increase in stator and rotor active powers, an increase in the amplitude and distortion of the waveforms, as well as an increase in the rate of harmonic distortion (THD) of the currents.

These observations highlight the critical importance of understanding and managing symmetrical voltage faults in wind farms. Peaks

in electromagnetic torque could affect generator stability, while changes in active and reactive powers could disrupt the power grid. In addition, increasing the THD of currents can have consequences on the quality of the electricity produced. Consequently, continuous monitoring and appropriate protection mechanisms are essential to mitigate these effects and ensure the proper functioning of the wind energy system.

In a broader context, this study contributes to the advancement of understanding of the complex interactions between wind turbines, voltage faults and the power grid, which is essential for the reliability and sustainability of wind energy. It provides a solid basis for the development of advanced management and control strategies aimed at mitigating the negative effects of voltage faults and improving the overall performance of wind farms.

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