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REACTIVE POWER ENHANCEMENT OF DFIG BASED ON STATCOM FOR GENERATION OF WIND ENERGY

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Abstract

The rising significance of wind energy integration in power systems is attributed to its economic advantages. The utilization of Doubly Fed Induction Generators (DFIG) in wind energy is increasingly prevalent thanks to its inherent advantages. These include the ability to operate at variable speeds and autonomously control both active and reactive power, outperforming traditional generators. However, challenges arise when integrating such wind farms with the grid, manifesting as voltage stability issues and grid disturbances. These stem from DFIG's inadequate terminal voltage and frequency regulation, primarily due to insufficient excitation and resulting reactive power shortages. Therefore, enhancing terminal voltage and frequency generation is imperative. In this study, we aim to boost DFIG's performance by augmenting its reactive power through STATCOM, addressing supply voltage and frequency reductions caused by varying loads. Additionally, a neuro-fuzzy logic controller is employed to regulate generated voltage and frequency within the dynamic DFIG-STATCOM-load model, simulated using MATLAB/SIMULINK.

Keywords: DFIG, FACTS, STATCOM, Neuro-Fuzzy controller, ANFIS, d-q theory

1. INTRODUCTION

Following the fossil fuel crisis three decades ago, wind farms emerged as an alternative energy source. Within a short span, wind energy became the leading champion among renewable energy options. Wind power stands out as a cost-effective means of generating electricity with minimal environmental impact compared to other renewables [1]. It has rapidly gained ground in India as one of the swiftest growing electricity sources [2]. The favourable attributes of wind power have fuelled this growth, leading to the establishment of stringent grid interconnection requirements as wind power becomes increasingly integrated into the energy landscape. Presently, wind power plants utilize Variable Speed Wind Turbines (VSWT), specifically the Double Fed Induction Generator (DFIG) and Permanent Magnetic Synchronous Generator (PMSG), both employing back-to-back frequency converters to feed energy into the grid [3]. The PMSG has demonstrated the ability to provide capacitance compensation and low voltage ride-through capabilities in practical applications [4]. However, as wind power expands, new challenges arise, one of which is Sub-Synchronous Controller Interaction (SSCI) [5]. This phenomenon occurs when power electronics controllers, such as those in DFIG wind generators, interact with a series-compensated network. This is strictly an electrical issue, as it does not involve the mechanical aspects of the turbines. When the turbine system interacts with adjacent power electronics controllers, it leads to Sub-Synchronous Torsional Interaction, resulting in decreased frequency and terminal voltage [6]. To address this, a solution involving STATCOM (Static Synchronous Compensator) is implemented to mitigate the frequency and voltage fluctuations. Reactive power regulation becomes a critical technical concern due to the varying power output of wind farms at various wind speeds [7]. To bolster the capacity for regulating reactive power and bolster voltage stability within wind farms, it is advisable to implement a dynamic reactive power management system alongside intelligent reactive power compensation. Emerging technologies such as Flexible Alternating Current Transmission Systems controllers (FACTS) provide utility for electric companies with potent solutions to tackle these challenges. FACTS controllers have the capability to adjust network parameters like the impedance of the line, buses voltage at connected point and the angle of bus voltage (load angle), thus improving the electrical grid's steady-state and transient (dynamic) performance. Furthermore, advancements in power electronic devices, particularly Voltage Source

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Inverters (VSIs) employing Pulse Width Modulation (PWM) are employed as STATCOMs to deliver the necessary reactive power [8]. In the context of shunt compensation, Static Compensators (STATCOMs) are applied to virtually offset transmission line impedance by introducing controllable voltage in parallel with the system. Various techniques proposed by researchers aim to alleviate reactive power compensation challenges [9]. In summary, wind power has evolved into a dominant renewable energy source, but it faces electrical challenges such as Sub-Synchronous Controller Interaction. These challenges are being addressed through advanced technologies like FACTS controllers and innovative reactive power compensation methods, including ANFIS-based STATCOMs, to ensure stable and reliable wind power generation even under varying conditions and loads [10]. Many works have been suggested for reactive power enhancement of DFIG. Reactive power enhanced of DFIG based on SVC (Static VAR Compensator) presented in [11]. Whereas [12] presents mathematical model and control structure of the DFIG based capacitors for improving the reactive power support capability during the fault period. In [13] presents a dynamic coordination control strategy to enhance the reactive power capability of DFIG, the computed reference value is directly applied to the outer control of the rotor side converter (RSC) to regulate reactive power generation of the stator circuit using PI controller. The use of capacitors and SVC have delay time in response and the capacitors proportion with many factors like heat resonance and periodically maintenance. Also the traditional PI controller have many drawbacks of needs tuning to any operating point change. The new design of reactive power enhancing based on STATCOM is a high-speed response and used for the implementation of intelligent electronic devices and high computational time with any passive elements like capacitors, also the use of intelligent controller Neuro-Fuzzy make the system flexible and more adaptively to any change in the system. The new design offer high speed for response of about less than one cycle compared with the literature [11, 12] and [13], also the discrimination utilized adaptive control ANFIS added advantage to STATCOM for reactive power compensation.

2. MATHEMATICAL DESCRIPTION OF THE DOUBLY FED INDUCTION GENERATOR

The stationary frame representation of the DFIG's d-q equivalent circuit is depicted in Figure 1. In the realm of wind turbines, the DFIG with a back-to-back converter configuration is a widely adopted system [14]. While conventional wind turbines operate at fixed rotational speeds, the DFIG offers a broader spectrum of speed control. Approximately one-third of the power within a DFIG converter unit flow through power semiconductors in both directions [15]. Infineon's IGBTs deliver exceptional performance even within the operational boundaries of the converter. Notably, Infineon's advanced module features a low voltage ride-through (LVRT) capability, enabling the wind power converter to handle stringent grid requirements while operating at a shallow output frequency at the generator side. The DFIG is represented in a synchronized reference frame, enabling autonomous management for active and reactive power (d-q) [16]. The widely employed technique for describing the DFIG for control and simulation purposes is the Park transformation model. This model aligns all electrical variables with the stator reference frame [17]. In the context of the DFIG's operation under steady magnetic circuits, a set of equations characterizes its behavior. It's important to note that the oscillatory modes remain unaffected by the generator's mechanical dynamics and power converters; however, the Phase-Locked Loop (PLL) and rotor current dynamics play a crucial role in oscillation analysis [18].

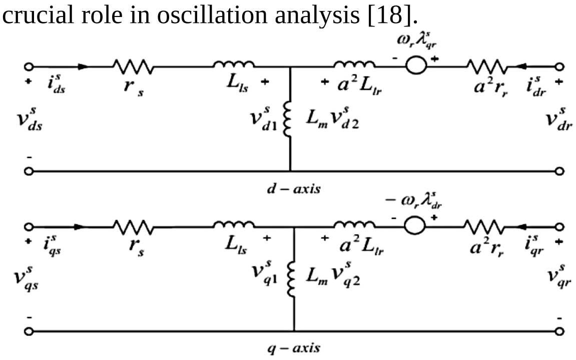


Fig. 1. The transformation of the d-q equivalent circuit of DFIG into a stationary reference frame

The fixed reference outline can be utilised to address the DFIG model by using the logarithmic condition shown below.

$$\begin{cases} \vec{v}_s = \Omega_s \vec{i}_s + \vec{\varphi}_s + jf_s\vec{\varphi}_s \\ \vec{v}_r = \Omega_r \vec{i}_r + \vec{\varphi}_r + j(f_s - f_g)\vec{\varphi}_r \end{cases} \quad (1)$$

$$\begin{cases} \vec{\varphi}_s = L_s \vec{i}_s + L_m \vec{i}_r \\ \vec{\varphi}_r = L_r \vec{i}_r + L_m \vec{i}_s \end{cases} \quad (2)$$

$$T_e = \frac{3x_p}{2} Re(j\vec{\varphi}_s \vec{i}_s) \quad (3)$$

Where:

$\vec{v}_s = v_{\alpha s} + jv_{\beta s}, \vec{v}_r = v_{\alpha r} + jv_{\beta r}$

are the stator and rotor voltage vectors and:

$\vec{i}_s = i_{\alpha s} + ji_{\beta s}, \vec{i}_r = i_{\alpha r} + ji_{\beta r}$

are the vectors representing the stator and rotor currents.

$\vec{\varphi}_s = \varphi_{\alpha s} + j\varphi_{\beta s}, \vec{\varphi}_r = \varphi_{\alpha r} + j\varphi_{\beta r}$

are the vectors corresponding to the stator and rotor fluxes, respectively.

L_s, L_r and L_m correspond to the stator, the rotor, and the magnetising inductances. Ω_s and Ω_r represent the resistance of the stator and rotor.

f_s is the grid frequency, while x_p is the generator's pole pair. T_e denotes the electromagnetic torque.

Power losses caused by stator resistances can be ignored when calculating active or reactive power.

$$P_{sp} = \frac{3}{2}\left(V_{sd} i_{sd} + V_{sq} i_{sq}\right) \tag{4}$$

$$Q_{sp} = \frac{3}{2}\left(V_{sq} i_{sq} - V_{sd} i_{sq}\right) \tag{5}$$

The added d and q stand for the d- and q-pivot components, whereas the suffix 's' indicate the stator amounts, respectively.

3. MODELING AND CONTROL OF STATCOM

The STATCOM functions by introducing an almost sinusoidal voltage with an adjustable magnitude. Its central component is a basically voltage source inverter (VSI) powered via a DC voltage supply [19]. Figure 2 provides an illustration of the basic configuration of a STATCOM when coupled with a DFIG. A capacitive reactance effect parallel to the line impedance is simulated in this scenario if the injected corrected voltage leads the current flow, increasing the line current and the active power flow control in the line. In contrast, an inductive reactance effect parallel to the impedance line is replicated if the injected corrected voltage lags behind the current flow. This results in a decrease in both the active power flow and the current flow in the line.

It is possible for the adaptive controller to quickly modify the injected controlled voltage's phase angle and magnitude. Therefore, the bus voltage (V) and transmitted active power (P) are determined by the characteristics of the injected voltage [20]. Thus, by changing the polarity of the inserted AC output of VSI, the controlled power can be increased or decreased. In the event of a voltage reversal (a 180° phase shift), it directly contributes to the reactive element that results in drop voltage along the transmission system, effectively enhancing the reactive element in the impedance of transmission system. In addition, when the compensated voltage surpasses the voltage present in the uncompensated transmission system when both sending and receiving voltages are taken into account (|Vcomp| > |Vs-Vr|), the active power can be switched around. This enables both positive and negative power flow directions to maintain a stable state for the transmission system. Notably, the STATCOM exhibits an exceptional response time, often within a sub-cycle. Additionally, the power flow transition from positive to negative (increase or decrease) passes through zero voltage compensation smoothly and consistently. Figure 3 provides a visual representation of a typical control scenario for active and reactive power flow utilizing a STATCOM.

4. MEASUREMENT OF LOAD VOLTAGE

The dq theory is utilized for active power and voltage at the load measurement. This methodology, grounded in time-domain analysis, remains applicable in both steady-state and transient scenarios, accommodating diverse voltage and current waveforms commonly encountered in power systems. This theory's computational simplicity, which comes from using algebraic calculations instead of complicated calculations to distinguish between the average and alternating values of estimated power components, is one of its key features.

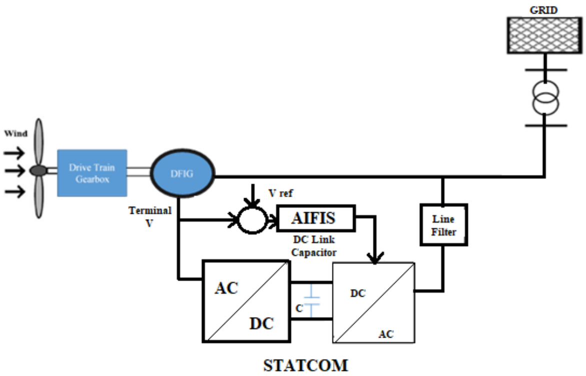


Fig. 2. Basic Setup of STATCOM in Conjunction with DFIG

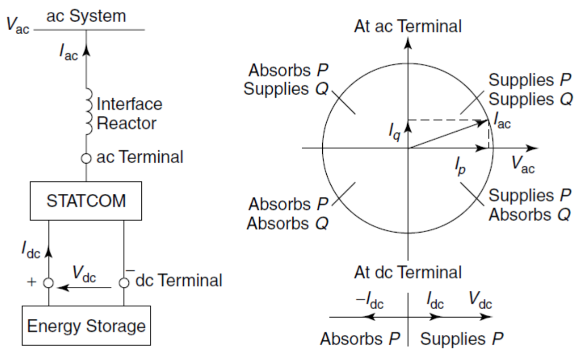


Fig. 3. The AC System's and STATCOM's Power Interaction

The 'Park transformation' which transforms a fixed reference coordinate system (abc) into rotating d-q coordinates, is the fundamental tool used by the dq theory [21]. This transformation can be expressed as follows and is used for time-domain voltage measurements in the natural framework (v_a, v_b, and v_c).

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{7}$$

$$\emptyset = (\omega t + \theta) \tag{8}$$

The phase difference between the stationary and rotating coordinate systems at any given time instant is represented by the angle ∅, while the phase shift associated with the voltage is indicated by the angle θ. Equations (4) and (5) yield the corrected values for the active power and load voltage as follows:

$$p = V_d I_d + V_q I_q \tag{9}$$

$$q = V_d I_q - V_q I_d \tag{10}$$

$$V = \sqrt{{V_d}^2 + {V_q}^2} \tag{11}$$

The block diagram of the Static Synchronous Compensator (SSC) control system is shown in Figure 4. Equation (11) is used to compute the load voltage (V). V serves as the closed-loop control system's feedback. As explained below, error signals ($Error_V$) are produced when the required reference voltage (V_{ref}) and the actual load voltage (V) are compared:

$$Erorr_V = V_{ref} - V \tag{12}$$

Also the error signal ($Erorr_p$) are produced when actual power compared with reference power:

$$Erorr_p = p_{ref} - p \tag{13}$$

To align the compensation in phase with the reference or 180 degrees out of phase, one could alter the phase degree associated with the injected voltage.

$$\delta = \emptyset \pm \gamma \tag{14}$$

Equation (14) allows for the adjustment of the parameter γ according to the sign of the value of the calculation error. The corrected signals $Erorr_p$ and $Erorr_v$ are inputs to ANFIS controller as shown in Figure 4.

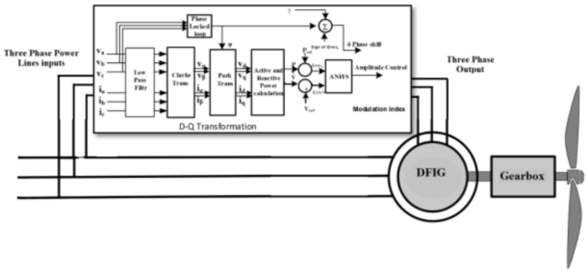


Fig. 4. STATCOM Block schematic with DFIG

5. DESIGNING THE DFIG CONTROL

Fuzzy controller systems are effective for managing approximate reasoning or uncertainty, particularly in situations where mathematical modelling of complex systems is challenging [22]. In this study, we have employed various mechanisms of fuzzy inference within fuzzy logic, and we have selected the Takagi-Sugeno (TS) method. We used an Artificial Neural Network (ANN) to optimize the TS-fuzzy-like-PI controller's membership functions (MF). The TS-fuzzy controller employs an adjustable irregular gain controller, which can lead to significant variations in controller gain. However, random selection of these parameters often leads to either a stable system response or an unstable behaviour [23]. For better performance of our system, we have used a Neuro-Fuzzy to adapt the fuzzing rules and parameters using ANN learning algorithms [24]. The output and input membership function parameters are identified during the training stage as well. Our designed fuzzy control has 7-layers each of which can be composed by either fixed nodes with no tuning requirements or the nodes that need to adjust during the training phase. The yield of these 7-layers depicts the different stages towards designing the fuzzy system and is given in [18]. The main idea of the learning method is to specify the parameters for membership functions as well as make sure that Fuzzy output has a better match with the training data compared to other approaches [25]. In our search for network parameters, we used a hybrid learning technique based on Gradient Descent (GD) and Least Squares Estimate (LSE). In this work, we have divided the input signal universe for conversation into nine membership functions having a triangular shape with a 50% overlap. Consequently, for two inputs, the choosing of triangular shape of membership for matching the smooth change in input signals and then the output relation. Figure 5 depicts the process of determining 81 control rules and their corresponding linear functions. We generated 2 sets of data to fine-tune the Neuro-Fuzzy TS rules. The data that is input consists of a vector including $Error_p$, $Error_v$, and the output (m), that serves as the modulation index. Figure 6 depicts a verification method for our Fuzzy logic system Figure 6a the Rules between two inputs and output, Figure 6b the membership functions of inputs.

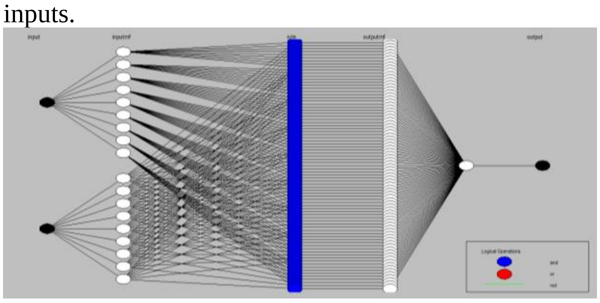
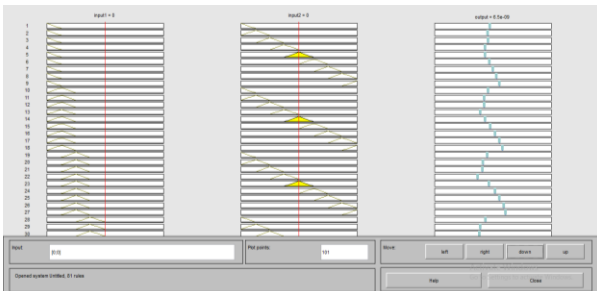
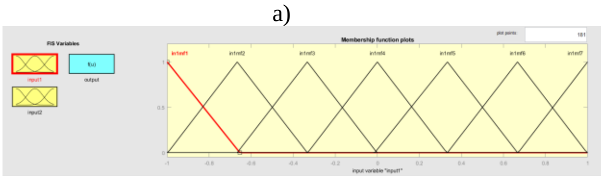


Fig. 5. Fuzzy control scheme



a)



b)

Fig. 6. Design Fuzzy system a) The Rules, b) Membership functions

Figure 7 depicts the output visualization of the STATCOM control design. This technique is carried out using the Neuro-Fuzzy file's Graphical User Interface (GUI), which is integrated into MATLAB/Fuzzy Logic Toolkit. Importantly, it should be noted that the proposed controller demonstrates a considerably reduced computation time when compared to traditional Mamdani-type fuzzy controllers. The system analyzed in this study involves a single machine connected to an endless bus bar. The range of $Error_p$ are between +ve and –ve range ±1 (forward and reverse power respectively).

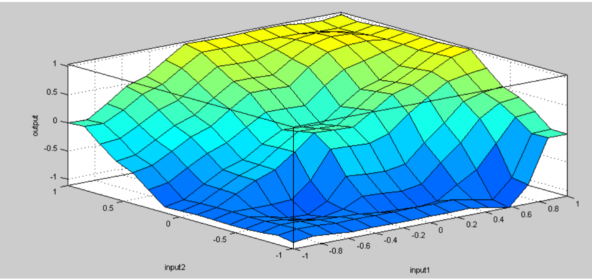


Fig. 7. Control surface of the Neuro-fuzzy controller based on STATCOM

6. ANALYSIS THROUGH SIMULATION

The power system configuration featuring a Doubly Fed Induction Generator (DFIG) along with a Static Synchronous Compensator (STATCOM) controller has been replicated using MATLAB/Simulink. The simulated configuration used to evaluate the performance of the proposed intelligent controller in the event of a step change in load conditions is shown in Figure 8. This evaluation is conducted to illustrate the DFIG's behavior both prior to and following the injection of the required power by the STATCOM. The torque-output power characteristic of the turbine is visualized in Figure 9. The system comprises a cluster of DFIG units serving as wind energy sources, connected to the grid in an on-grid configuration with two supply branches and a variable inductive load. A DC-voltage link source built within the compensator allows for the system to interchange active and reactive power. Upon the occurrence of an abrupt load voltage step change at t=0.6 seconds, the response of the DFIG system in the absence of the connected STATCOM is illustrated in Figures 10 and Figure 10, 12, 14 and 16 respectively without STATCOM. These figures provide insights into various parameters, including the three-phase voltage of the regulated bus, transmission flow current, electromagnetic torque, DC voltage, rotor speed, active power and reactive power. After adding STATCOM, which injects controlled voltage, the performance of the DFIG improves significantly, as shown in Figures 11. 13. 15 and 17 respectively. Notably, the line voltage returns to its nominal value, and both active power and electromagnetic torque are restored to their nominal levels. The findings show that without the STATCOM, the line voltage drops below 0.5 pu leading to an ineffective wind energy system. The grid feeding effectiveness increases the load current and also reduces active power supply and electromagnetic torque. The implementation of the STATCOM helps to solve this great problem, matters, returning the voltage, active power and also torque to their standard values. The simulation findings validate the STATCOM's capacity to correct for load voltage, active power, and torque, hence enhancing DFIG performance. In addition, the ANFIS controller's usefulness in tuning STATCOM functionality is demonstrated. Finally, Figures 18-19 show THD of load voltage and current with STATCOM's injected voltage. The line voltage THD is 2.41 percent, whereas the line current THD value is only 0.21%. These findings highlight the compensating nature of a STATCOM to handle active power flow and line current control, especially during capacitive operation. Collectively, the step change responses and simulated results then prove that STATCOM positively contributes to the stabilization of DFIG-based wind energy system voltage profile as wells as achieves an efficient operation under different type loads.

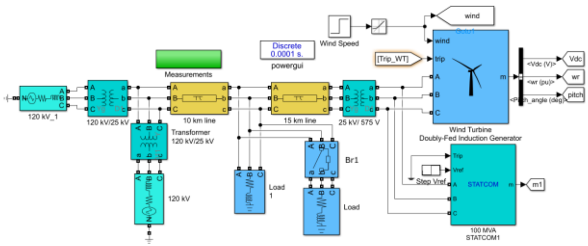


Fig. 8. A simulation system model

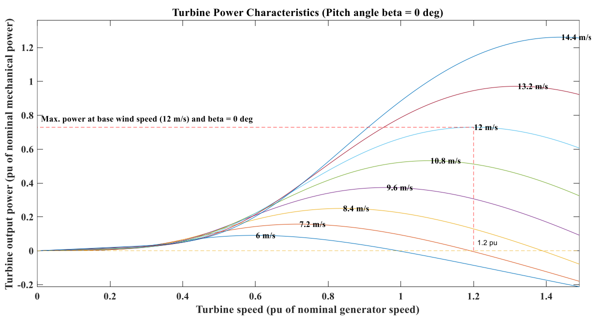


Fig. 9. The turbine-speed characteristics

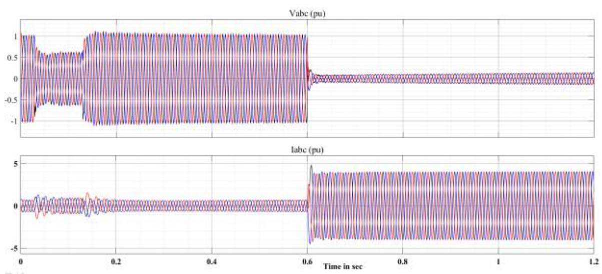


Fig. 10. Line voltage and the line current without a STATCOM

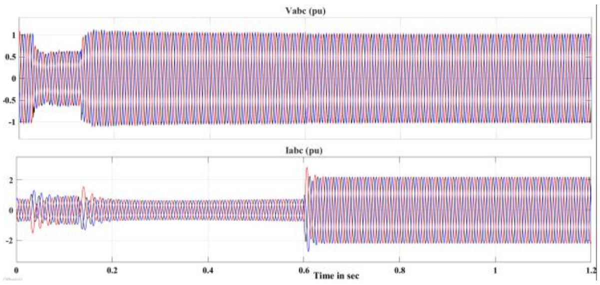


Fig. 11. The line voltage and current when the STATCOM is operational

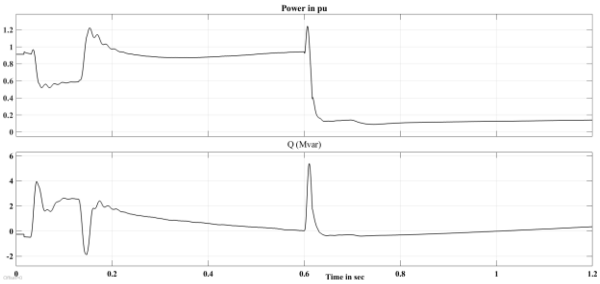


Fig. 12. The active and reactive power in the absence of the STATCOM

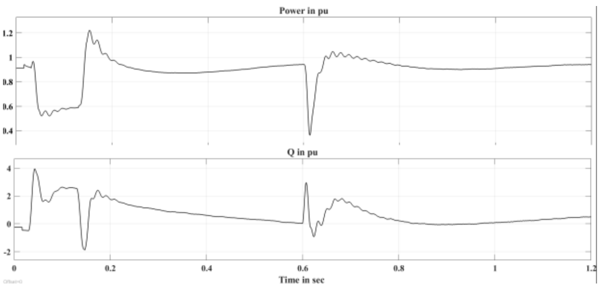


Fig. 13. The active and reactive power with STATCOM

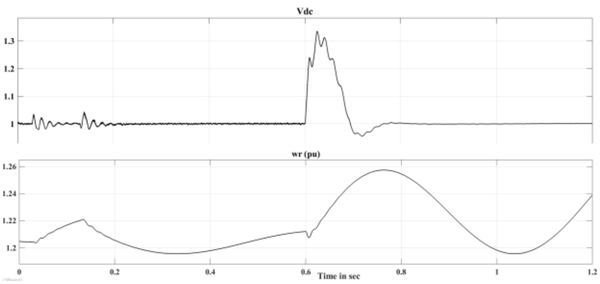


Fig. 14. DC voltage output and turbine speed without STATCOM

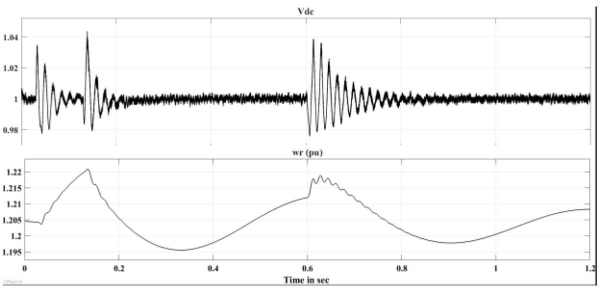


Fig. 15. The DC voltage and turbine speed with STATCOM

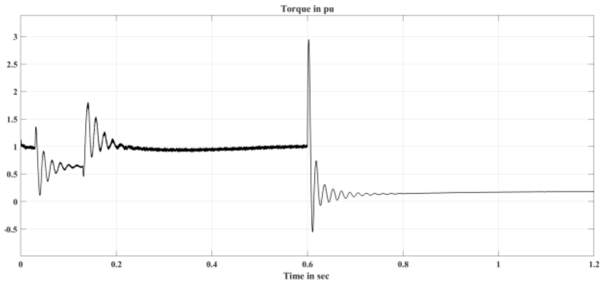


Fig. 16. The torque of the turbine without STATCOM

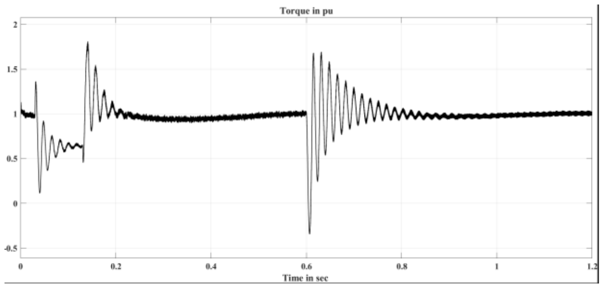


Fig. 17. The torque of the turbine with STATCOM

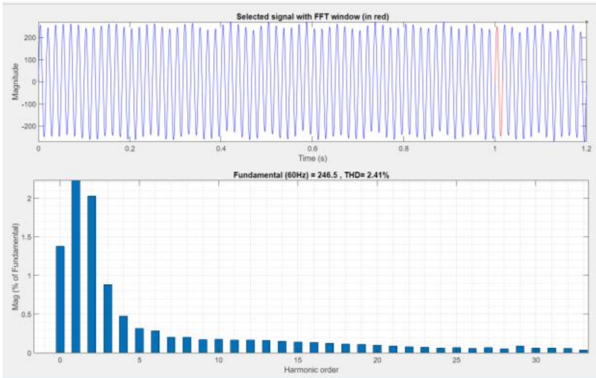


Fig. 18. The THD bus voltage with STATCOM

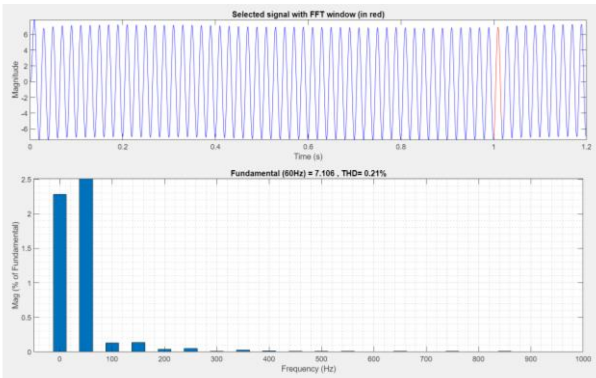


Fig. 19. THD of the line current with STATCOM

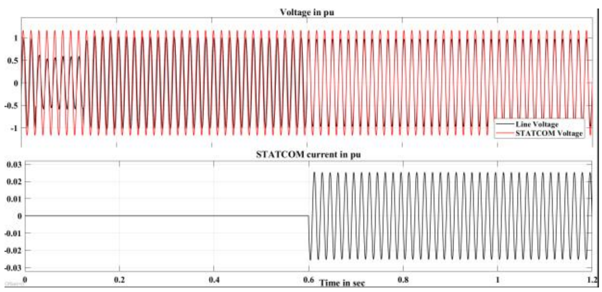


Fig. 20. The voltages and current injection of STATCOM

7. CONCLUSION

This study has employed the Adaptive Neuro-Fuzzy Inference System controller (ANFIS) algorithm for govern STATCOM alongside the DFIG. The tuning process, conducted offline, follows the principles of Neuro-Fuzzy Systems. Utilizing the Takagi-Sugeno fuzzy logic system, the controller attains remarkably swift computational performance, rendering it suitable for real-time deployment. Also from the results, it is clear that the Fuzzy controller has a smoother in response and reaches the steady state faster.

The introduced controller has been effectively utilized for regulating bus voltage and controlling the line current flow in the transmission line before loading, thereby enhancing performance of DFIG's capacity to continuously supply a substantial load. Simulation results unequivocally illustrate the commendable performance of the proposed controller in managing STATCOM operations, underscoring its practical viability.

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Declaration of competing interest: *The authors of this paper declares no conflict of interest.*

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