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Enhanced Power and Current Limiting Control in PMSG based Wind Turbine under Unbalanced Grid Voltage using ANFIS Controller

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ABSTRACT

This paper proposes an innovative approach to enhance the performance of wind turbine systems with permanent magnet synchronous generators (PMSG) during unbalanced grid voltage conditions. The proposed approach involves using an adaptive neuro-fuzzy inference system (ANFIS) controller to regulate the voltage and frequency of the PMSG system, thereby improving its efficiency and stability. Simulations were conducted using MATLAB/Simulink to evaluate the performance of the proposed ANFIS controller under various unbalanced grid voltage scenarios. The results demonstrated that the ANFIS controller was effective in maintaining the voltage and frequency of the PMSG system within acceptable limits, even under severe unbalanced grid voltage conditions. The controller was also found to improve the power output and reduce the system losses.

Keywords : wind turbine, PMSG, ANFIS controller, unbalanced grid voltage, voltage regulation, frequency regulation, efficiency, stability, renewable energy.

I. INTRODUCTION

The requirements for wind-driven generators (WGs) with regard to fault ride through (FRT) and power quality improvement at the grid interface are the two most critical factors to take into account while managing the current power system. Because power converters used for interface and power control totally disconnect them from the grid, PMSG-based WGs are more likely to make attaining FRT easy [1-3].

Power converter-related controllers may be employed to meet the FRT specifications of PMSG-based WGs. The effectiveness of these controllers in meeting FRT criteria is analyzed in the literature on a periodic basis. An imbalance in the active power flow between the grid integration and capture processes occurs from grid breakdowns because they lower grid voltage, which in turn lowers grid power injection rate. Based on PMSG [4] from 2, this leads to significant issues like overcurrent or overvoltage concerns at the intermediate grid-tied WG stages.

The reliability and stability of the energy system are at fault as wind power is increasingly included into the grid. Grid operators have proposed grid codes to standardize the characteristics of the wind energy conversion system (WECS) in order to overcome this problem. The WECS must remain connected and inject the anticipated reactive current to support the grid in the event of a grid fault, according to the LVRT (Low Voltage Ride Through) code, one of the codes. The necessary reactive current as well as the typical LVRT profile. The WECS should supply reactive currents during the fault period. For voltage sags less than 50%, reactive currents should be applied at double the proportion. When a severe failure occurs and the voltage drops by more than 50%, 100% reactive currents are required [5].

Every WT generator has the option of a fixed speed or a variable speed. For instance, squirrel cage induction generators (SCIGs) can be used in both fixed-speed and variable-speed wind turbines, whereas synchronous generators (SGs) and doubly-fed induction generators (DFIGs) are frequently employed in variable-speed wind turbines (VSWTs) (VSWTs). In addition to comparisons, a summary of potential wind generator technologies is provided. Despite being straightforward, reliable, and affordable, a fixed-speed SCIG-based WECS. The disadvantages of exclusively mechanical systems include high mechanical stress, reactive power load on the power grid, severe power fluctuations, and severely constrained FRT (fault-ridethrough) capabilities.

Comparatively to FSWT, which reduces the mechanical stress on WT by absorbing the variations in wind-power, VSWT can optimize wind power at various wind speeds. By generating more power than its fixed-speed operation does, the WT's variable-speed operation maximizes its aerodynamic efficiency [6]. Due to developments in semiconductor switching devices as well as increased dependability and efficiency, the utilization of wind turbines based on PMSG technology is also growing considerably. Recently, many businesses all around the world started making 2MW wind turbines based on PMSG. The failures on the grid side and their effects on the wind farm generators, as was previously discussed, are one of the significant challenges in wind farms that needs to be addressed. The wind farm will face a voltage sag condition if the grid fault causes a decreased supply voltage. This circumstance could cause damage or have a negative impact on the grid once the fault is addressed. Due to the high penetration level of wind farms, the new grid codes, in contrast to the old grid codes, no longer permit disconnecting wind farms from the grid when a grid fault occurs [7].

In-depth modelling and exact simulation are necessary to comprehend the consequences of PMSG-WT operation on the power grid and the PMSG-WT control system. The PMSG WT system with dual PWM controllers has only been thoroughly modelled and analyses in a small number of studies using the PSCAD/EMTDC software. Some publications place a strong emphasis on the PMSG-WT converter control methods without modelling the mechanical component. Others have also simplified the grid-side converter model for the relevant PMSG analysis using an uncontrolled diode rectifier. The PMSG-WT system's Low Voltage Ride Thru (LVRT) Capabilities has also been the subject of extensive investigation. As a safeguard against overvoltage on the DC-link, a chopper is used [8].

A braking chopper (BC) with low-cost benefits and simple control performance has been used for the LVRT in PMSG wind turbine systems. Since the BC can only distribute the power, it is challenging to improve the power quality at the wind turbine systems' output. Moreover, the STATCOM has been used to maintain the grid connection of the wind turbine system during grid disturbances. This technique considerably enhances voltage regulation in both the transient and steady states [9].

Due to the significant penetration of wind energy, power smoothing makes it challenging to stabilize grid operation when the WECS is cut off from the grid due to a line failure. It takes a lot of time and effort to make up for lost supply capacity. The divided WECS zones will join the grid after it has recovered. Also, under failing circumstances, the DC-link circuit of the WECS with AC-DC-AC converter system experiences overvoltage. Hence, the grid and WECS must operate properly [10].

However, an IGBT inverter is followed by a passive rectifier in contemporary commercial PMSG technology. The wind power industry has not yet made use of the PMSG wind turbine, which employs a full voltage-source IGBT converter design and extremely effective vector-controlled technology [11]. A control strategy for output maximization is supplied to the generator-side converter of a small wind turbine built on the PMSG. To extract the greatest power possible from the wind, the switch-mode rectifier on the generator side is carefully regulated. The technology uses an insulated gate bipolar transistor (IGBT), which is utilized to maximize power, as the only active switching component. For a small wind turbine, it is an easy and economical solution.

This work investigates the ANFIS control strategy to regulate the active and reactive electricity provided into the grid through three-phase voltage source inverter to improve power quality and boost performance under dynamic conditions. The researched system is modelled and simulated in MATLAB/SIMULINK. The suggested control ensures that the dc bus voltage is constant without the aid of any external devices and that the three-phase peak currents are within safe ranges. Based on the degree of grid voltage sag, reactive power assistance is provided for the electrical grid in the interim. In this configuration, the MSC controller alters electromagnetic power in accordance with the power that the GSC transmits to the grid and converts the unbalanced power on the dc-link into the kinetic energy of the rotor. The output power and dc bus voltage variations can be reduced by the GSC controller.

This paper is organized as follows: Section- I will be dealing with the introduction of the generators adopting wind energy to generate along with the framing of problem statement and objectives of this novel work being proposed, with reference to various issues; Section-II will be giving the system description that includes the modeling of wind turbine, PMSG, as well as Grid; Section-III will be briefing about the devised novel ANFIS-based controller; Section-IV will describe about the simulation-based results and discussion using PI as well as the ANFIS Controllers; and Section-V will exhibit the conclusion for devised controlling strategy along with the possible future scope of work.

II. SYSTEM DESCRIPTION

The majority of the model of a wind power system based on PMSG consists of the GSC, PMSG, MSC, grid, and wind turbine. In Figure 1, it is shown.

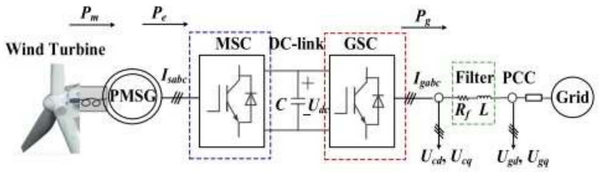


Fig 1 : Proposed System

A. Wind Turbine Modelling

By snatching wind, a wind turbine can generate mechanical power, which is expressed as follows:

$$P_m = \frac{1}{2}\pi\rho R^2 C_p(\beta,\lambda) v^3 \tag{1}$$

Here ρ = Density of air, R = Radius of blade, β = Pitch angle, λ = Tip-speed ratio, v = Speed of wind

Wind energy utilization coefficient denoted as C_p is calculated by the following formula:

$$\begin{cases} C_p = 0.58(116\lambda_m - 0.4\beta - 5)e^{-21\lambda_m} \\ \frac{1}{\lambda_m} = \frac{1}{\lambda+0.008\beta} - \frac{0.0035}{\beta^3+1} \\ \lambda = \frac{R\omega_m}{v} \end{cases}$$

Where the mechanical angular velocity is denoted by

ω_m.

The expression for calculating the mechanical torque

(2)

experienced by the wind turbine is given below:

$$T_m = \frac{1}{2} = \pi\rho R$$

$$\omega P \frac{m}{}{}_m{}^3 C_p(\beta,\lambda)V^2/\lambda$$

(3)

B. PMSG Modelling

The two-phase rotating d-q coordinate system's voltage equation for the PMSG can be written as [12]:

$$L_{sd}\frac{dI_{sd}}{dt} = -R_sI_{sd} + \omega_eL_{sq}I_{sq} + U_{sd}$$

$$\{ \frac{dI_{sq}}{}$$

$$L_{sq} \quad dt = -R_sI_{sq} - \omega_eL_{sd}I_{sd} - \omega_e\psi + U_{sq}$$

(4)

Where U_{sd},U_{sq}, I_{sq}, I_{sd}, and I_{sq} are the stator voltage's and current's respective d-q components in the rotor flux-oriented d-q frame. The stator resistance is denoted byR_s. L_{sd} and L_{sq} Represent the surface-mounted PMSG's equal stator d and q-axis inductances. The electrical angular speed and the permanent magnet chain are represented by electrical angular speed.

The PMSG electromagnetic torque is expressed as [12]:

$$T_e = 1.5n_p[(L_{sd} - L_{sq})I_{sd}I_{sq} + \psi I_{sq}]$$

(7)

Here U^+ = Voltage amplitude of positive sequence element

θ^+ = Initial phase of the positive sequence element

U^- = Voltage amplitude of negative sequence

element θ^- = Initial phase of the negative

sequence element ω = Grid voltage's angle

frequency

Through the use of the Clark transformation,

which is expressed as, the three-phase voltages

can

be transformed into a

stationary coordinate system.

$$U \quad \frac{1}{} \quad -\frac{1}{2} \quad U_{ga} \quad U \ \alpha \quad 2 \quad 1 \quad -{}_2 \quad \sqrt{3} \quad \left]\left[\ gb \ \right]\right.$$

$$U^+\sin(\omega t+\theta^+)+U^-\sin(\omega t+\theta^-)$$

$$[\, U_+\sin(120_0+\theta_+)+U_-\sin(\omega t+120_0+\theta_-)\,]$$

$$U_+\sin(\omega t+120_0+\theta_+)+U_-\sin(\omega t-120_0+\theta_-)$$

$$\left[U^{g}\right] = -\Bigg[\quad \sqrt{3} \quad {}_{g\beta} \quad 3 \quad 0 \quad —$$

$$-\frac{}{2} \quad U_{gc}$$

$$^{+} \ U_{g\alpha} + U^-g_\beta{}^{2}$$

$$= \Big[\ + \qquad - \ \Big]$$

$$U_{g\beta} + U \ {}_{g\beta}$$

(8)

$$-U$$

$$[UUUU_{+-+gggg\alpha\alpha\beta\beta}\ ]^{=} \quad UU_{-+-+}\text{cossinsin}^{\cos} \quad (((\ \omega\omega(\omega^{\omega}ttt^{t}+++^{+}\theta\theta\theta^{\theta}{}_{+-_-+})))^{)} \ ]$$

$$- \qquad [U$$

(9)

According to [5], the mechanical characteristics of the system that employs the dynamic one-mass model are as follows:

$$T_m = J\frac{d\omega_m}{dt} + B\omega_m + T_e \quad (6)$$

Here J = Transmission system's moment of inertia

B = Transmission system's self-damping coefficient

C. Grid Modeling

In a three-phase, three-wire system, the zero-sequence component is not taken into account because there is no path for its circulation. Using the DSC (Delayed Signal Cancellation) approach, the three-phase unbalanced voltages can be separated into positive sequence and negative sequence voltage parts [13]. The imbalanced voltages could be expressed as

$$[U_{ga} \quad U_{gb} \quad U_{gc}]^T = \quad (5)$$

Where $U_{+g\alpha}$, $U_{+g\beta}$, and $U_{-g\alpha}$,$U_{-g\beta}$ represent, respectively, the positive and negative sequence voltage elements.

Following are the active and reactive power outputs according to instantaneous power theory.

$$\begin{bmatrix}P_g\\ Q_g\end{bmatrix} = \frac{3}{2}\begin{bmatrix}U_{g\alpha} & U_{g\beta}\\ U_{g\beta} & -U_{g\alpha}\end{bmatrix}\begin{bmatrix}I_\alpha\\ I_\beta\end{bmatrix} \quad (10)$$

III. PROPOSED ANFIS-BASED CONTROLLER

To create the innovative controller, an ANFIS—Adaptive Neuro-Fuzzy Inference Structure on Takagi-Surgeon fuzzy inference system and artificial neural network technology. Because it incorporates both of these ideas, it has the ability to combine the benefits of neural networks and fuzzy logic in a single framework and perform effectively by managing both current and power even in the case of an imbalanced grid voltage.

Its inference system is based on a set of fuzzy IF-THEN rules that can learn and approximatively represent non-linear functions. ANFIS is regarded as a universal estimator as a result. To use the ANFIS more efficiently and effectively, the best parameters can be found by a genetic algorithm.

The IF-THEN-ELSE rule and the use of linguistic concepts make fuzzy rule bases easy to comprehend. Fuzzy logic, unlike neural networks, cannot learn on its own. Neural networks can learn from data. Understanding the knowledge that neural networks have collected has proved difficult. The ANFIS neural network methodology is a data-driven strategy. A clustered training set of numerical samples forms the basis of the ANFIS synthesis technique. To start the ANFIS learning process, a training data set with the desired input/output data pairs for the target systems to be modelled is required. The number of data pairs, the training and verifying data sets, fuzzy inference systems, and the learning outcomes that must be confirmed after mentioning the step size are all required design criteria for ANFIS controllers. The global command of ANFIS The framework for operating any plant is made up of a collection of components arranged into five interconnected network levels, as shown in the fig-2. The elements of the positive and negative sequences of voltage should be represented, accordingly. According to instantaneous power theory, the outputs of active and reactive power are listed below.

$$CU_{dc}\frac{dU_{dc}}{dt} = P_e - P_s \tag{11}$$

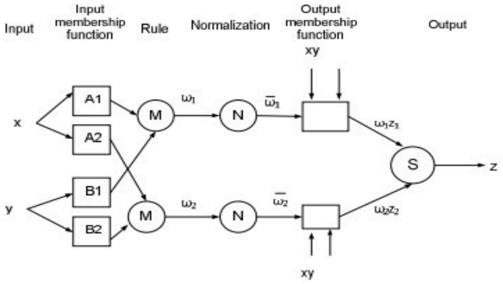
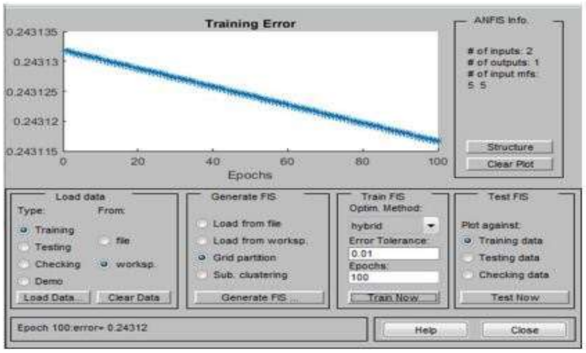


Fig 2 : ANFIS structure

IV. SIMULATION & RESULTS

The researched system is modelled and simulated in MATLAB/ SIMULINK. The simulation results for the suggested controlling schema are shown here. Simulation screenshots of novel controller design

The ANFIS controller simulation was carried out using MATLAB/Simulink, whose screenshots are displayed in the following figure 3:

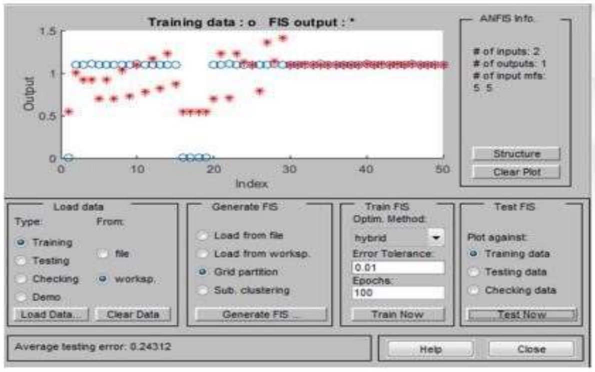


# of inputs: 2
# of outputs: 1
# of input mfs:
5 5

Optim. Method: hybrid
Error Tolerance: 0.01
Epochs: 100

Epoch 100:error= 0.24312

a) Depiction of Training error

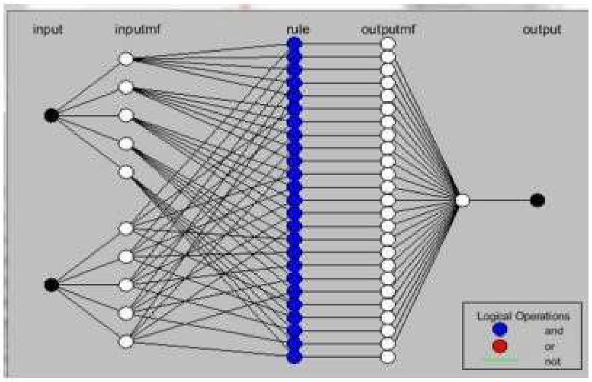


# of inputs: 2
# of outputs: 1
# of input mfs:
5 5

Optim. Method: hybrid
Error Tolerance: 0.01
Epochs: 100

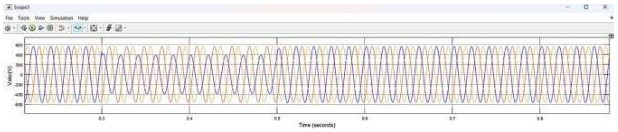
Average testing error: 0.24312

b) Depiction of Training data

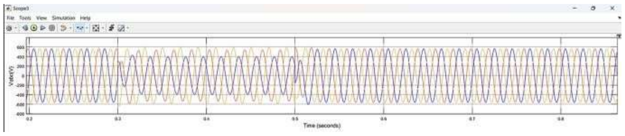


c) Depiction of logical operations via simulation Fig 3 : Simulation screenshots of our novel controller design to tackle Unbalanced Grid Voltage scenarios

A. Simulation results by using ANFIS controller



(a) case I



(b) case II

Fig 11: 3-Phase voltages of unbalanced condition

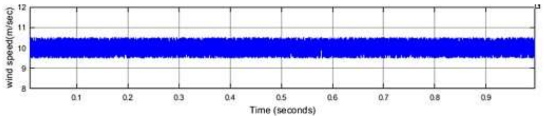


Fig 12: Depiction of Uniform speed of Wind

The above figure 11 and 12 show three-phase unbalanced voltages and wind speed under 30% of voltage sag during the period from 0.3 to 0.5sec, the wind speed is constant during this condition by using ANFIS controller.

Fig 13(a)

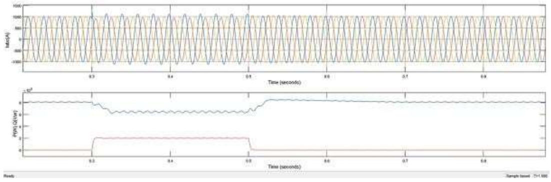
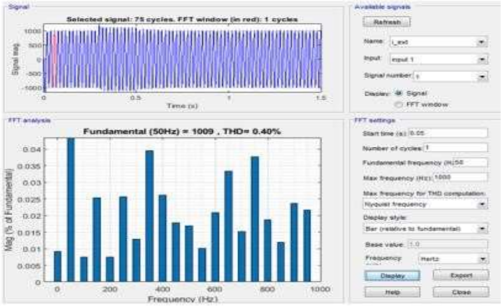


Fig 13(b)



Name: i_ext
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.05
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency: Hertz

Fig 13(c)

Fig 13: Analysis of performance of Control imparted for case 1

The above figure 13 shows control results using control schemes under case 1. The control scheme design does not fully account for the impact of voltage sag. As a result, there are no large fluctuations in both the output power and dc bus voltage by using ANFIS controller.

Fig 14(a)

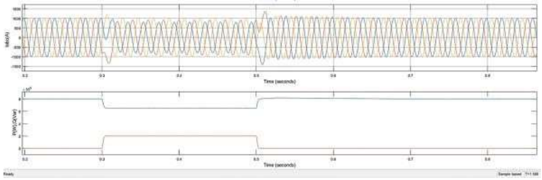
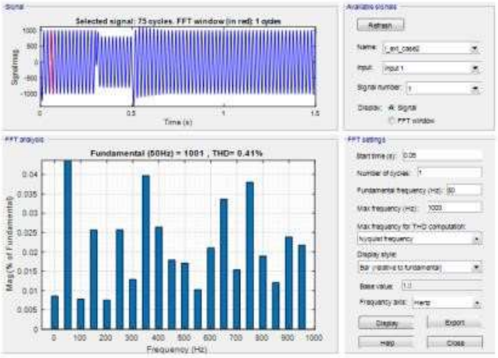


Fig 14(b)



Name: i_ext_case2
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.05
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig 14(c)

Fig 14 : Investigations of performance of Control imparted by ANFIS Controller for case 2

The above figure 14 shows results for control scheme of voltage of dc link, reactive and active power, and three phase currents when inductance changes by using ANFIS controller.

Investigation of control effect with altering of wind speed step

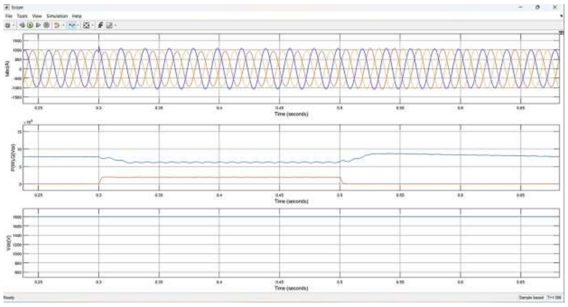


Fig 15(a) under case I

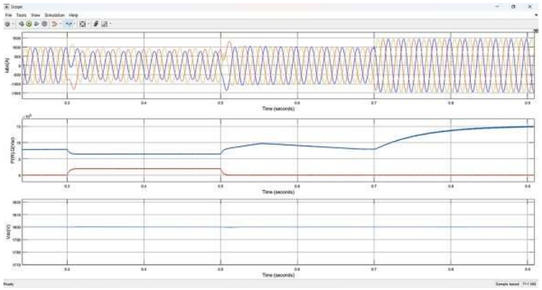
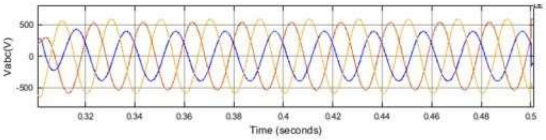


Fig 15(b) under case II

Fig 15 : Investigation of control effect with altering of wind speed step with regards to two fault iterations by ANFIS controller

The control outcomes under 2 faults in the separate asymmetrical grid are shown in figure 15 to demonstrate the system's capacity to react dynamically to variations in wind speed. The power of the system increases from 0.8 MW to 1.5 MW as the wind speed increases from 10 m/s to 12 m/s in 0.7 seconds. Contrarily, the dc bus voltage is always steady, and the bus voltage variation range during the transient process is no more than 0.05%. Furthermore, it is important to take into account the system variables' ability to quickly settle and respond to step changes in wind speed while utilizing the ANFIS controller.

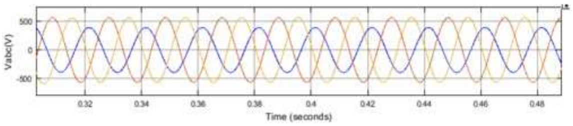
Investigation of 3-Phase Voltage in the Grid



(b) under case II

Fig 16: Investigation of 3-Phase Voltage in the Grid with regards to two fault iterations by ANFIS controller

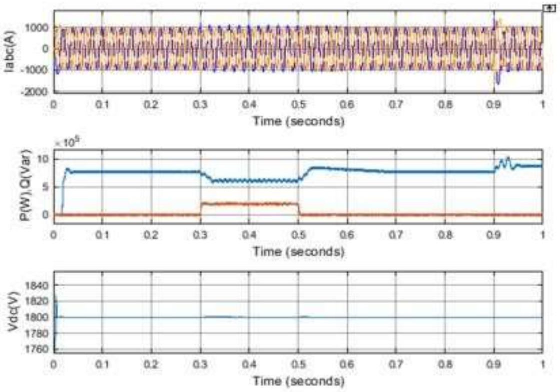
The control outcomes of friendly grid support using the suggested control strategy are shown in GURE 8



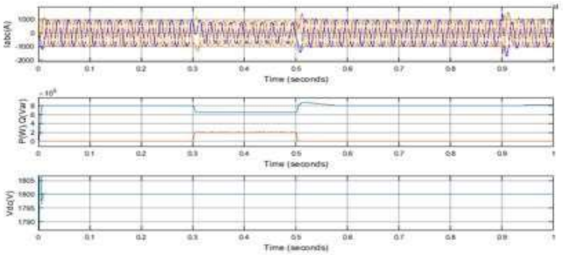
(a) under case I

for unbalanced grid voltage, which have been shown in the above figure 16.

Investigation of control effect during the altering of inductance



(a) under case I



(b) under case II

Fig 17 : Investigation of control effect during the altering of inductance with regards to two fault iterations by ANFIS controller

The above figure 17 shows results for control scheme of voltage of dc link, reactive and active power, and three phase currents when inductance changes by using ANFIS controller.

V. CONCLUSION

In this paper, an innovative ANFIS controller was proposed and evaluated for enhancing the performance of wind turbine systems with PMSG during unbalanced grid voltage conditions. The ANFIS controller was found to effectively regulate the voltage and frequency of the PMSG system, leading to improved efficiency and stability. The simulation results demonstrated that the proposed ANFIS controller was capable of maintaining the PMSG system within acceptable limits under various unbalanced grid voltage scenarios. The controller was also found to enhance the power output and reduce system losses, indicating its potential for practical applications in the renewable energy sector.

Overall, the findings of this paper highlight the potential of ANFIS controllers as an innovative solution for improving the performance of wind turbine PMSG systems during unbalanced grid voltage conditions. Further research and development could build on this work, with the goal of making ANFIS controllers an integral part of wind turbine systems for enhanced efficiency and stability.

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