Improvement of Dynamic Performance in SEIG WECS by Using ANFIS Controller

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***Abstract*: A new hybrid controller for the Self-Excited Induction Generator (SEIG) driven by the Wind Energy Conversion Scheme (WECS) was proposed in this paper. The dynamic stability of the control grid is essential for both user protection and system performance. There must be a full grasp of the effects of power system volatility to research and govern power systems. The suggested control systems were examined using frequency-domain approaches that focused on the nonlinear design of a device that is subjected to severe faults on a related bus, which was tested using time-domain strategies. In this paper, a novel 3-level inverter is designed and controlled by the ANFIS control for the Dynamic Response of the system at the load side. The ANFIS approach can be used to regulate a self-excited induction generator in this study. The design incorporates wind power to give on-grid electricity access. SEIGs are used to power wind turbines in this project, which generates alternating current (AC) for the grid. The system model uses a rotor reference frame and dynamic vector control for the machine reference model. Wind power voltage and active power are controlled by an ANFIS controller in the converter. The ANFIS controller's performance is evaluated in all abnormal scenarios, including the worst-case scenario. System modeling and simulation in Simulink-Matlab allow it to be used in SEIG configurations. Wind power system quality and stability are both improved by the ANFIS control unit, according to simulation results.**

Keywords: Self-excited induction generator "SEIG", wind energy conversion scheme "WECS," Adaptive Neuro-Fuzzy(ANFIS), Frequency, Dynamic Performance.

I. Introduction

This work introduces a new hybrid controller for the self-excited induction generator (SEIG) driven by the wind energy conversion scheme (WECS). The stability of the control grid is essential for both user protection and system performance. There must be a full grasp of the effects of power system volatility to research and govern power systems. The suggested control systems were examined using frequency-domain approaches that focused on the nonlinear design of the device that is subjected to unadorned faults on the related bus, which was tested using time-domain strategies. The ANFIS approach can be used to regulate a self-excited induction generator in this study. The design incorporates wind power to give on-grid electricity access. SEIGs are used to power wind turbines in this project, which generates alternating current (AC) for the grid. The system model uses a rotor frame and the dynamic vector control for the machine model. Wind power voltage and active power are controlled by an ANFIS controller in the converter. The ANFIS controller's performance is evaluated in all abnormal scenarios, including the worst-case scenario. System modeling and simulation in Simulink-Matlab allow it to be used in SEIG configurations. Wind power system quality and stability are both improved by the ANFIS control unit, according to simulation results.

As wind turbine technology and the way turbines are controlled have progressed over the past two decades, the widespread use of wind power has become more prevalent. One of the major often used in wind generators contains an induction generator with a slip ring, power electronic converter, common DC-link capacitor, and 3level 3 phase multilevel inverter. The use of SEIG for wind energy conversion devices is becoming more popular in these scenarios. This is a major advantage of such generators. A vector control-enabled induction generator is ideal for high-performance variable-speed drives and generators. [10]-[11].Modeling wind energy systems in their whole is necessary to better understand their impact and to better operate wind power plants as wind-derived power becomes increasingly prevalent in linked power systems.

It is possible to fine tune the frequency of the stator. This can be achieved by adjusting the wind turbine's pitch angle. During this project, the suggested WECS controller will be constructed in two loops. Wind turbine dynamic performance can be improved by decoupling PI management of output active power and reactive power. Because of this uncertainty and other factors (such as weather conditions and unexpected wind speed), PI parameters need to be tweaked frequently in this control strategy. There has been an increase in the use of artificial intelligence (AI) by researchers [15]. In this study, the ANFIS controller in Simulink Matlab is used to represent a variable-speed self-excited induction generator wind power. Using an AI technology called ANFIS, a system can be governed." Numerous factors are examined in both normal and sick conditions using adaptive neuro-fuzzy control.

According to ref. [9], the adaptive neural control approach and analysis, and nonlinear optimal regulation of multi-machine power networks, were examined. Also includes a comparison of damping outputs with and without a standard power system stabilizer (PSS). When it comes to transient stability and reliability, the neural controller being researched has a greater ability than other controllers. A SEIG-dependent flywheel energy storage device was examined in ref. [10] for transient stability augmentation of a grid-integrated wind farm. An adaptive network fuzzy inference system (ANFIS) controller is used to an IGBT frequency converter in order to improve grid-integrated wind farm's transient stability. With ANFIS and PID controllers, the device's transient efficiency can be evaluated by comparing ANFIS with PID controllers based on black-box optimization.

II. MATHEMATICAL ANALYSIS OF SEIG-BASED WIND FARM

The wind rotor induction generator displayed in Fig2 is used in conjunction with a wind turbine in SEIG wind turbine. With its two-way power converter, this generator provides power for the rotor through two IGBT bridge–voltage source converters. The power converter's capacity to dynamically adjust grid and rotor frequencies allows for variable turbine speed. The turbine rotor's blade angle can be modified to reduce power and rotational speed in the event of severe winds.

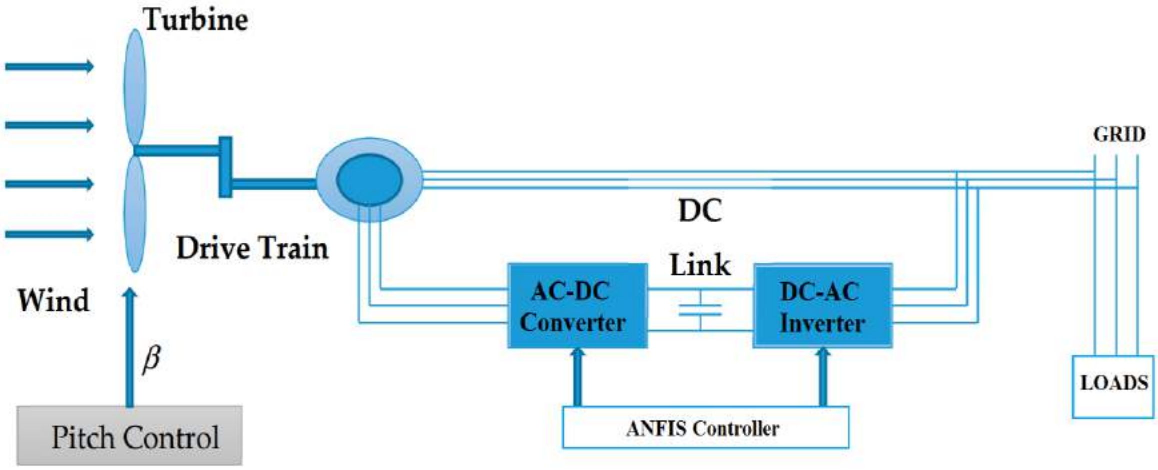


Fig. 1. Wind Turbine and SEIG Modeling

Mechanical power generation from wind turbines (WTs) is cited:

$$P_m = \frac{1}{2}\rho A c_p(\lambda,\beta)\vartheta_{wind}^3 \quad (1)$$

Performance coefficient c_p is given by the formula.

$$c_p = \frac{P_m}{P_{wind}} \quad (2)$$

The TSR (tip speed ratio)

$$\lambda = \frac{\omega_r}{\vartheta_{wind}} \quad (3)$$

The coefficient of performance is expressed as a percentage.

$$c_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_x} - c_3\beta - c_4\right)e^{-\left(\frac{c_5}{\lambda_i}\right)} + c_6\lambda \quad (4)$$

$$\frac{1}{\lambda_x} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \quad (5)$$

A = blade impact area; r = synchronous speed;

V_{wind} = anticipated wind speed; =blade pitch angle.

The WT's drop-in, estimated, and pull-out wind speeds are 4,9,12 km/s, respectively. A similar gearbox is employed for the wind turbine's two-inertia reduced-order mass-spring-damper configuration and wind SEIG's rotor shaft. Ref. [14] can be used to the equations of motion per unit (pu).

Low Voltages in Induction generator, while the SEIG rotor windings are connected to the same side by a SEIG converter with dc-link voltage and Grid Side inverter. SEIG stator windings (GSI). The system of induction generator (SEIG) circuit schematic is identical to that of SEIG. Following these steps, you can use the SEIG model:

$$\frac{X_s' di_{ds}}{\omega_s d_r} = v_{ds} - \left[R_s + \frac{1}{\omega_s T_0'}(X_s - X_s')\right] x i_{ds} - (1 - s_r)E_d' - \frac{L_m}{Lrr}v_{dr} + \frac{1}{\omega_s T_0'}E_q' + X_s' i_{qs} \quad (6)$$

$$\frac{X_s' di_{qs}}{\omega_s d_t} = v_{qs} - \left[R_s + \frac{1}{\omega_s T_0'}(X_s - X_s')\right] x i_{qs} - (1 - s_r)E_q' - \frac{L_m}{Lrr}v_{qr} + \frac{1}{\omega_s T_0'}E_q' + X_s' i_{qs} \quad (7)$$

$$\frac{dE_d'}{dt} = -s_r\omega_s E_d' + \omega_s\frac{L_m}{Lrr}v_{dr} - \frac{1}{T_0'}X\left[E_d' + [(X_s - X_s')]x i_{qs}\right] \quad (8)$$

$$\frac{dE_q'}{dt} = -s_r\omega_s E_d' + \omega_s\frac{L_m}{L_{rr}}v_{dr} - \frac{1}{T_o'}\times\left[E_q' - (X_s - X_s')i_{ds}\right] \quad (9)$$

DC connection equation can be found here:

$$C_{vdc}\frac{dv_{DC}}{dt} = v_{dg}i_{dg} + v_{qg}i_{qg} - \left(V_{dr}i_{dr} + V_{qr}i_{qr}\right) \quad (10)$$

a stator side inductance of Lss, and a rotor side inductance of Lrr Rs is resistance on a rotor side, and Lm is mutual inductance. Xs is the stator reactance; X 0 s is transient reactance of stator side. A transient reactance is defined as an electric field with amplitude that is proportional to the square of the transient reactance. As you can see, there are two sets of numbers: one for the stator voltage on the d side and the other for the stator voltage on the Q side. The ids and iqs numbers reflect the stator current on each of these two axes. A condenser current is iDC, the DC link voltage; idg and iqg are the grid and grid-side currents, respectively; iDC is the condenser current; iqg is the rotor-side q-axis current.

The converter's rotor component regulates power output and keeps track of voltage changes at the output terminals. Fig2. Shows the control block schematics. According to [15], the following are the control equations:

$$\frac{dx_2}{dt} = i_{qr\_ref} - i_{qr} = K_{pi}\left(P_{ref} + P_s\right) + K_{i1}x_1 - i_{qr} \text{ and } \frac{dx_3}{dt} = v_{sref} - v_s \quad (11)$$

$$i_{qr\_ref} = K_{p3}(v_{sref} - v_s) + K_{i3}x_3 \quad (12)$$

$$\frac{dx_4}{dt} = i_{qr\_ref} - i_{dr} = K_{p3}(v_{sref} - v_s) + K_{i3}x_3 - i_{qr} \quad (13)$$

$$v_{qr} = K_{p2}(K_{p1}\Delta p + K_{i1}x_1 - i_{qr}) + K_{i2}x_2 + s_r\omega_s L_m i_{ds} + s_r\omega_s L_{rr} i_{qr} \quad (14)$$

$$v_{qr} = K_{p3}(K_{p3}\Delta v + K_{i3}x_3 - i_{dr}) + K_{i2}x_4 - s_r\omega_s L_m i_{qs} - s_r\omega_s L_{rr} i_{qr} \quad (15)$$

Proportional K_{pi}, integrating (K_{i1}), power regulator gain rotor side converter gain K_{p2}, GSC gain K_{i3},and GSC gain (K_{p4}) are all included in this equation. For example, the GSI's current control component idr ref, while the turbine side operator's current control component is iqr ref.

III. SEIG Wind Turbine Dynamic Model

Equations (14)–(19) can be used to write the dynamic model of a SEIG-based wind turbine in a compact form.

$$x = f(x, y, z) \quad (16)$$

$$z = g(x, u) \quad (17)$$

x represents the state variables of the SEIG, z represents output variables, u represents the input variables. The SEIG model can be summarised using the following equations:

$$z = [v_{dr}, v_{qr}, v_{dg}, v_{qg}]^T \; u = [v_{ds}, v_{qs}, v_{dg}, v_{qg}]^T \quad (18)$$

$$x = [\omega, \beta, \theta_{tw}, s, i_{ds}, i_{qs}, x_1, x_2, x_3, x_4, E'_d, E'_q, V_{DC}]^T \quad (19)$$

IV. Voltage Control Via Switching Capacitor Bank Technique

A. Switching

In the past, capacitor switching has been ruled out because of transient voltage and current transients. The '$\frac{di}{dt}$' value of a given semiconductor switch, has been suggested to be justified in surpassing its maximum current rating by current "spikes." The only technique of this problem is to design a converter/inverter (power electronic device) that can withstand the transient value at the switching instant! The similar circuit in the Fig. 2, explains this condition with the switching capacitor bank by showing how it came about because of the duty cycle. Refer [6] for more information on this circuit.

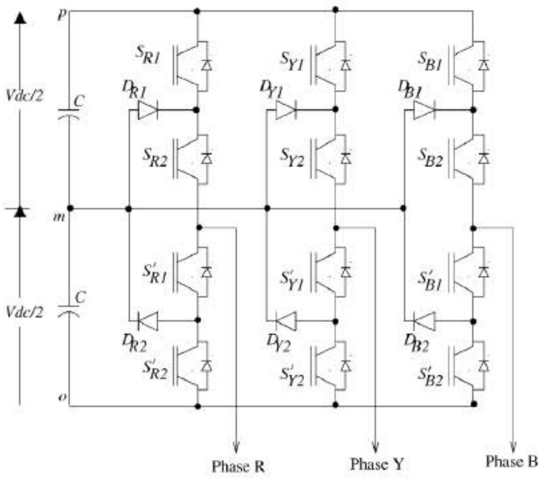


Fig. 2. 3level 3 phase multi-inverter.

TABLE I.

Switch status	State	Pole voltage
$S_{R1} = ON, S_{R2} = ON,$ $S'_{R1} = OFF, S'_{R2} = OFF,$ $D_{R1} = OFF, D_{R2} = OFF$	+1	$V_{Rm} = \frac{V_{dc}}{2}$
$S_{R1} = OFF, S_{R2} = ON,$ $S'_{R1} = ON, S'_{R2} = OFF,$ D_{R1} or D_{R2} will conduct depending on the polarity of the load current	0	$V_{Rm} = 0V$
$S_{R1} = OFF, S_{R2} = OFF,$ $S'_{R1} = ON, S'_{R2} = ON,$ $D_{R1} = OFF, D_{R2} = OFF$	−1	$V_{Rm} = -\frac{V_{dc}}{2}$

Figure 1 illustrates the controller receives the voltage error and then generates a duty cycle. It is utilized as input to converter or inverter switches so that charge of the capacitor bank can be altered to match the needs of the effective excitation, which is what the switches perform. This is how it's done since changing the self-excitation and controlling the terminal voltage may be accomplished automatically by switching the capacitor bank.

B. Frequency Control

To change the system's frequency, the pitch angle of turbine blades is changed to a new number. This way, the SEIG can keep the stator frequency the same while also reducing the effects of speed disturbances. The wind turbine's WECS power coefficient (Cp) determines the angle at which the blades will point at the wind. A formula in Appendix C called Equation (12) shows how to figure out the pitch angle value. This value is then used to figure out how high the plane is (Cp). Finally, optimizing the pitch angle value leads to better mechanical power control and better system frequency adaption, so it's a good idea to do this. Accordingly, frequency control is used to keep the wind turbine's mechanical power in check.

V. ANFIS Method

The algorithm of adaptive neuro-fuzzy inference system (ANFIS) is becoming more and more popular in the field of control. In this part, we give a quick summary of the ANFIS principles that have been explained in [23]. As a whole, this type of fuzzy inference system has a model that connects input features to input membership functions(MFs). This model can be thought of as the system's "core." then it moves the input mf to a set of rules, and the rules to a set of output characteristics by using a mapping function to move them between them. Maps output features to MFs, and the MFs is linked to either a single-valued output or a decision that goes with the output, then There are only fixed MFs, which were chosen at random, that have been taken into account in this case. The neuro-adaptive learning method works in a similar way to neural networks when it comes to how it learns new things. Several optimization techniques can be used to the gradient vector once it has been found in order to change the parameters so that some of the error measurements are less (performance index). Error metrics are often defined as the sum of squared differences between what happened and what they should have been. To figure out the parameters of a MFs, ANFIS uses a combination of least squares estimation and back propagation techniques, like the one shown in the figure.

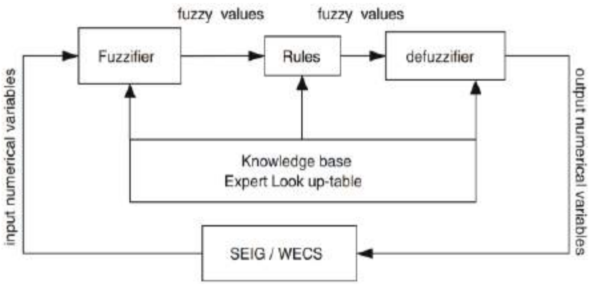


Fig. 3. Controller ANFIS Block diagram

As far as I know, this is the first ANFIS that has been proposed:

The end result is a Sugeno-style system of zeroth order, like the one from the movie.

Defuzzifying with a weighted average gives you one single result. This is how it works: The output Mfs are the same for each of them

It has its own rules. Each rule must have the same number of output Mfs in order for different rules to have the same output Mfs.

The weight of each rule is the same.

Fuzzy logic model: Fig. 3 shows Sugeno's fuzzy logic model, while Fig. 4 shows ANFIS structure, which has four layers: input, fuzzification, and defuzzification. The network can be shown with the N neurons in the input layer and F*N neurons in the fuzz layer.

One neuron is in the output layer. The FN rules have FN neurons in the inference and defuzzification layers, as well as a single neuron at the end. There are two inputs (xandy) and one output, z, in the fuzzy inference system shown in Fig2. This makes it easier for people to see. In the case of a zero-order Sugeno fuzzy model, there are two fuzzy if-then rules that are used most often:

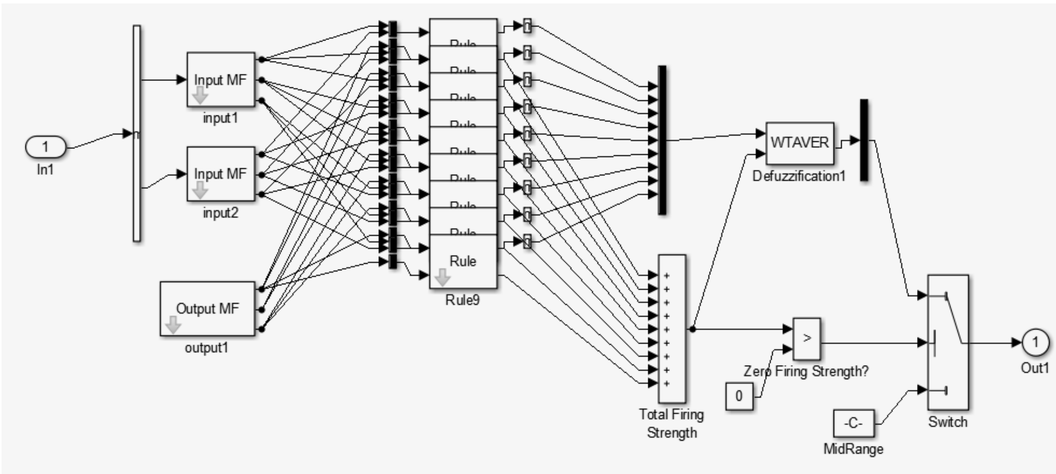


Fig. 4. ANFIS controller block diagram

$$Rule1: If\ 'x'\ is\ A_1\ and\ y\ is\ B_1, Then\ f_1 = r_1$$

$$Rule\ 2: If\ 'x'\ is\ A_2\ and\ y\ is\ B_2, Then\ f_2 = r_2$$

$$Rule\ n: If\ 'x'\ is\ A_n\ and\ y\ is\ B_n, Then\ f_n = r_n \quad (20)$$

VI. RESULTS

Self-Excited induction generator: Wind turbines use an AC/DC PWM converter and an induction generator that has a winding on the outside to make it work. A variable-frequency power source is provided to the rotor and stator by the DC/AC converter, because of how it's made. At low wind speeds, the SEIG technology makes it possible to get the most energy out of the wind by adjusting how quickly the turbine moves and reducing the strain on the turbine when there are strong gusts of wind. SEIG technology does this. This means there's no need to put in capacitor banks. It will be used to set the terminal voltage (Vref= 1 pu), the voltage droop (Xs= 0.02 pu), and the voltage source voltage.

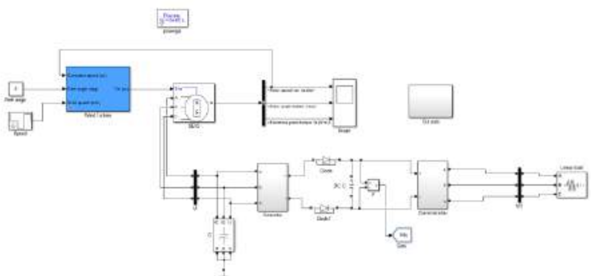


Fig. 5. Simulation diagram of the SEIG wind Turbine.

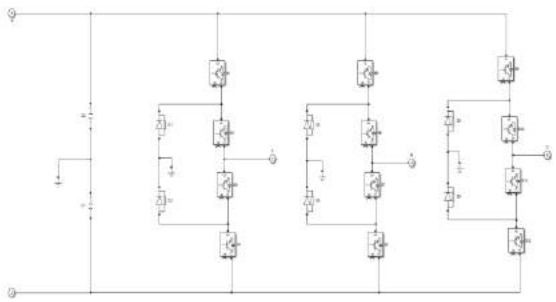
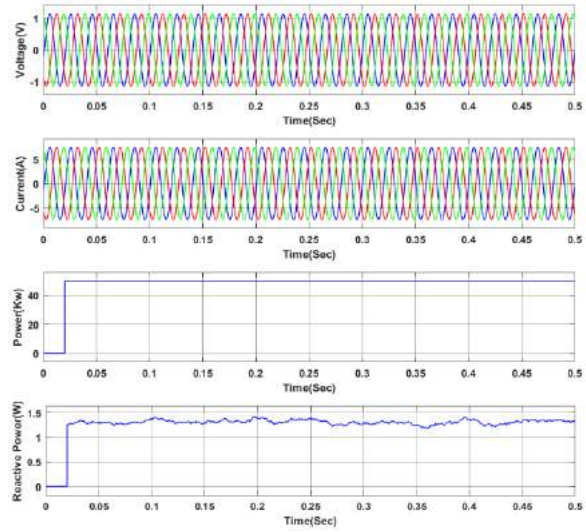
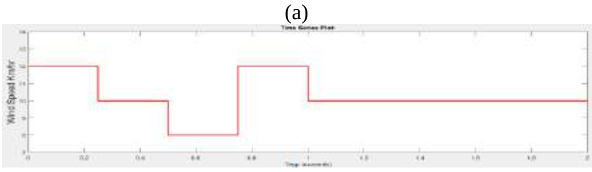


Fig. 6. Proposed 3- level 3-Phase inverter in SEIG WTs.



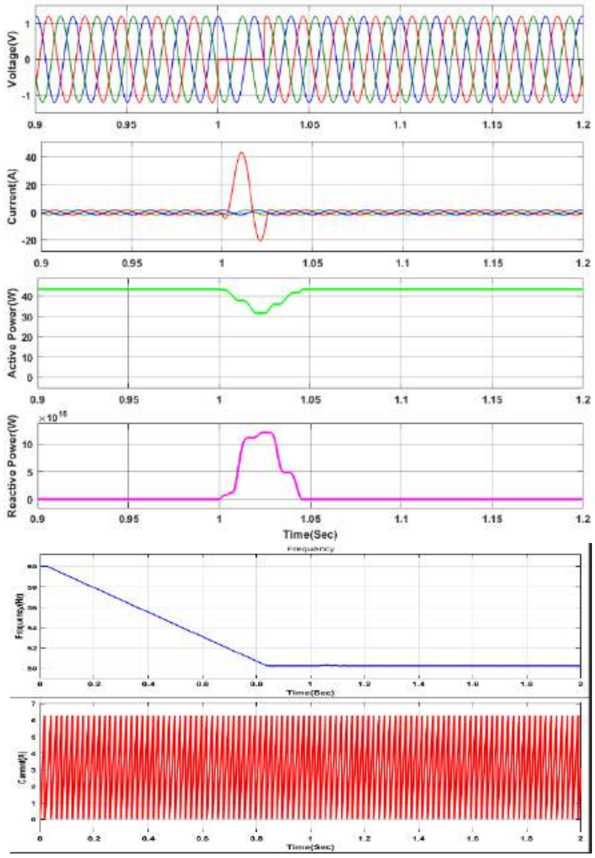
(a)



(b)

Fig. 7. (a) Voltages, Current ,Active &Reactive power (b) Wind speed.

Fig 7. **Dynamic Response on Variation of wind speed** Shows the Voltages, Reactive power, active power, and Wind speed of SEIG at time t=1 a small disturbance occurs in the active power and reactive power due to the loads.



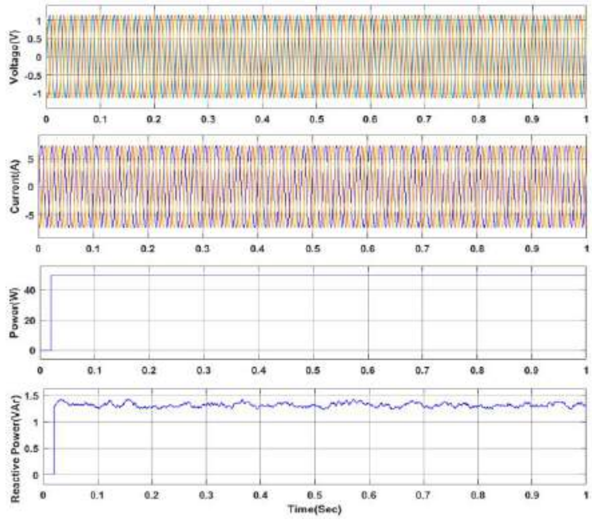


Fig. 8. Source Voltages, Currents, Active power & Reactive power

Fig 8. **Dynamic Response on Variation of Linear Load** Shows the Load Voltages, Load Currents, Inverter voltage, Active power & Reactive power, and Frequency of the linear load at time t=1 a small disturbance occurs in the active power and reactive power due to the loads, and in the fig8(e) frequency is dropped from 60Hz to 50Hz at the time period of 0.9sec. and it was maintained at 50Hz.

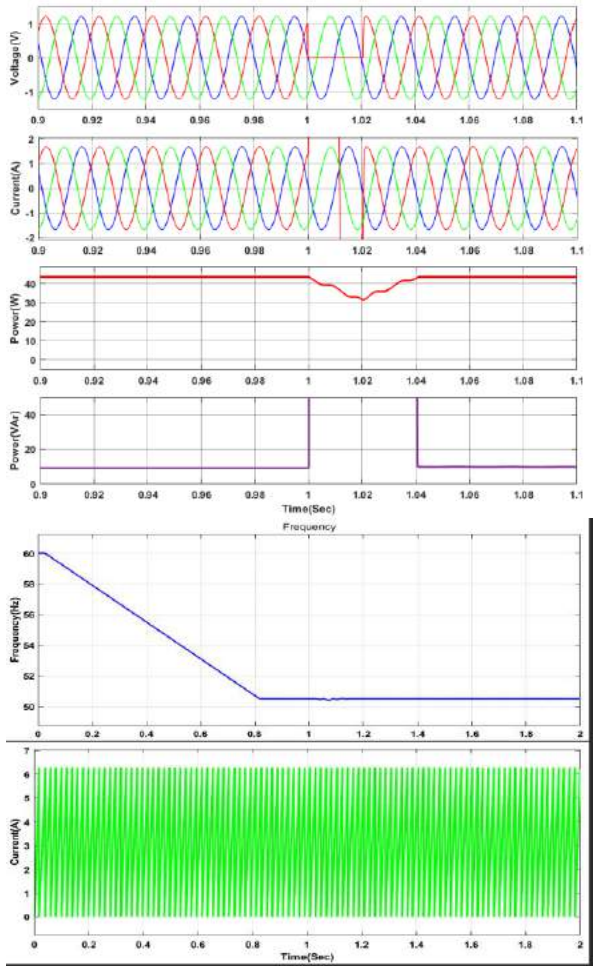


Fig. 9. (a) Load Voltages, Load Currents, Active power & Reactive power (e) Frequency and Inverter current of the nonlinear load.

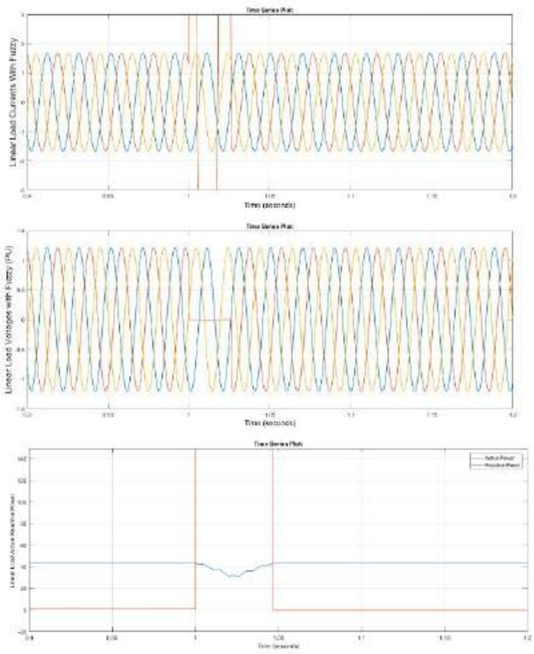
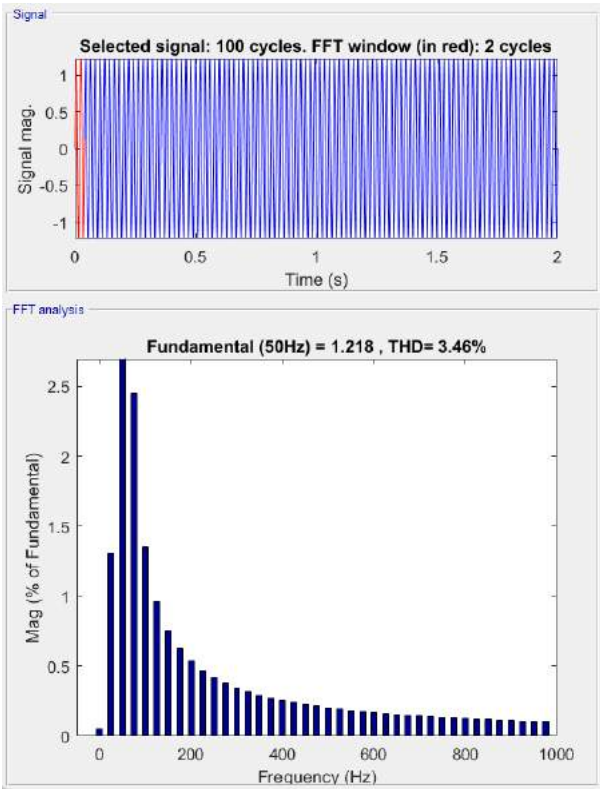


Fig. 10. Linear Load Currents, Voltages and the Active power Reactive power of the Load.



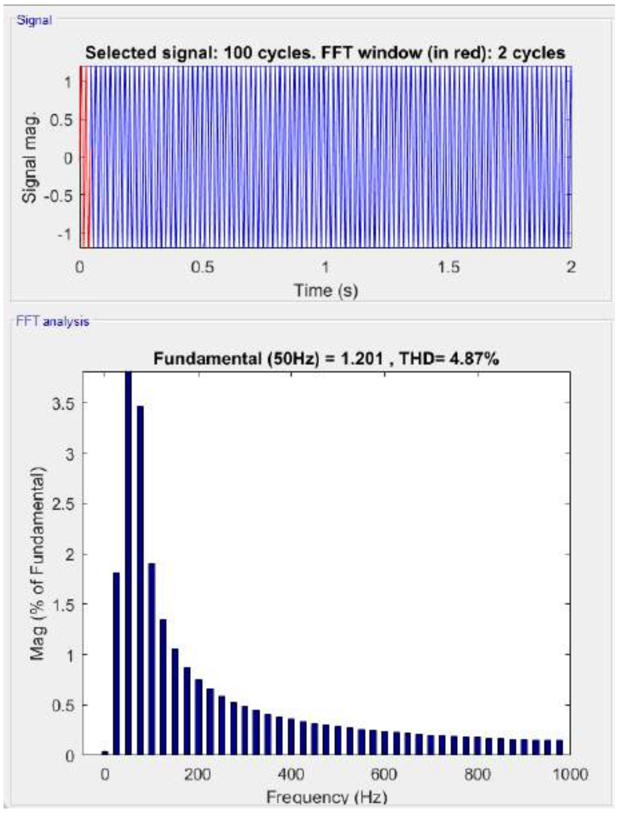


Fig. 11. THD of the linear load (a) FFT analysis of the Wind output voltage THD is 3.46% (b). FFT analysis of the Load THD is 4.87% with the Fuzzy.

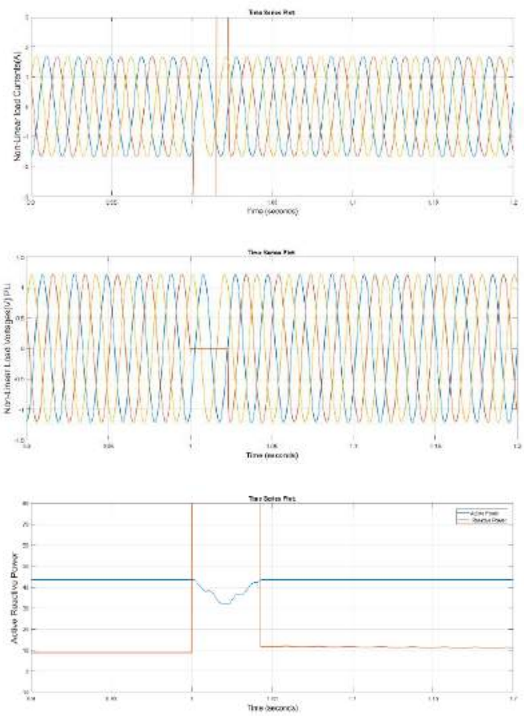


Fig. 12. Non-Linear Load Currents, Voltages and the Active power Reactive power of the Load.

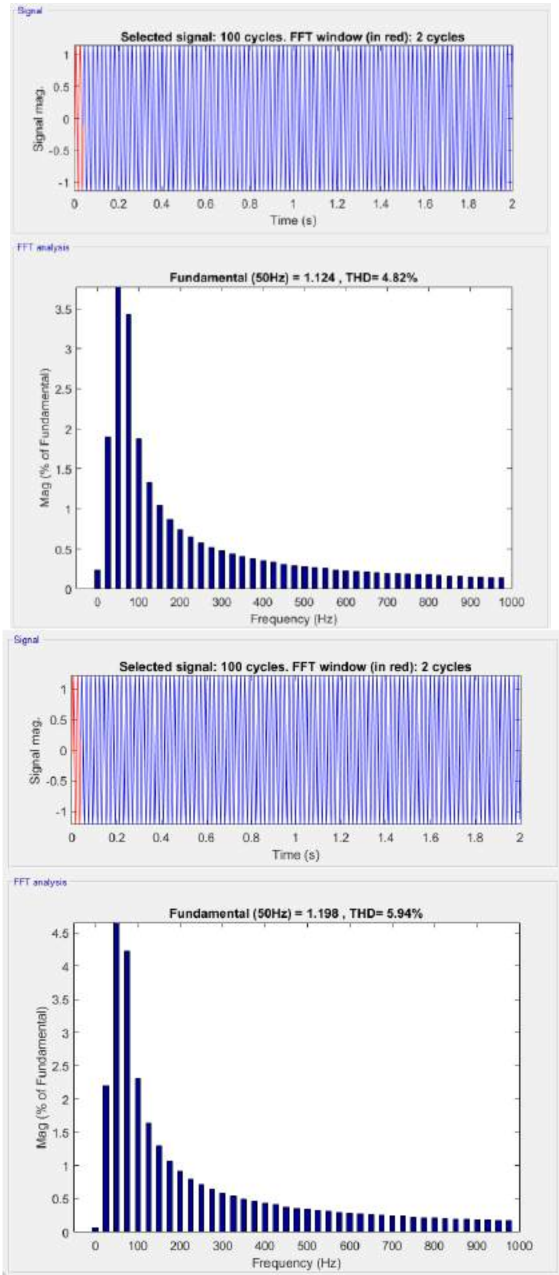
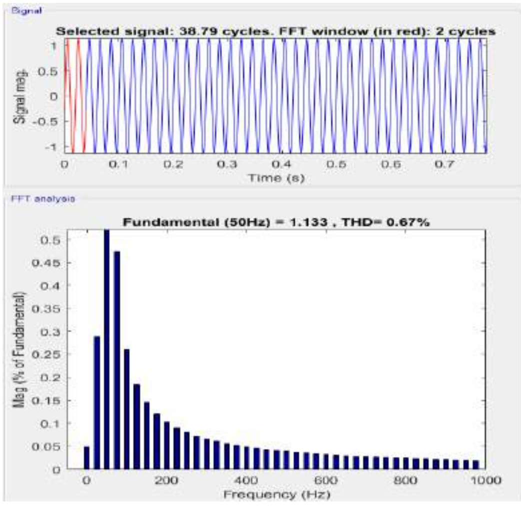
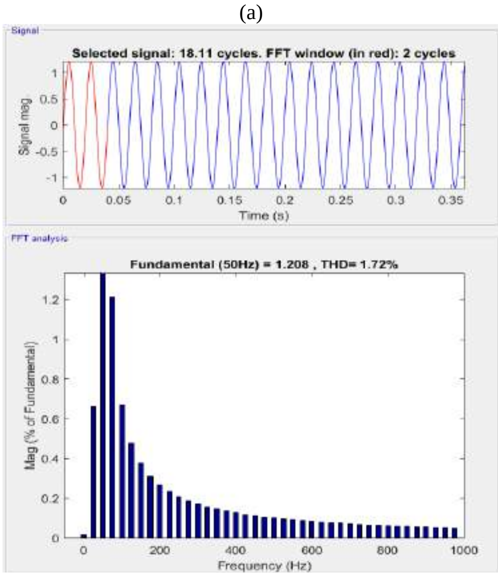


Fig. 13. THD of the Non-linear load (a) FFT analysis of the Wind output voltage THD is 4.82% (b). FFT analysis of the Load THD is 5.94% with the Fuzzy.

Fig 9. **Dynamic Response on Variation of Non-Linear Load** Shows the Load Voltages, Load Currents, Inverter voltage, Active power & Reactive power, and Frequency of the Non- linear load at time t=1 a small disturbance occurs in the active power and reactive power due to the nonlinear loads, and in fig 9(e) frequency is dropped from 60Hz to 50Hz at the time period of 0.9sec, and at time t=1.1 sec a slight deviation occurred in the frequency by the Non-linear load it was maintained at 50Hz.

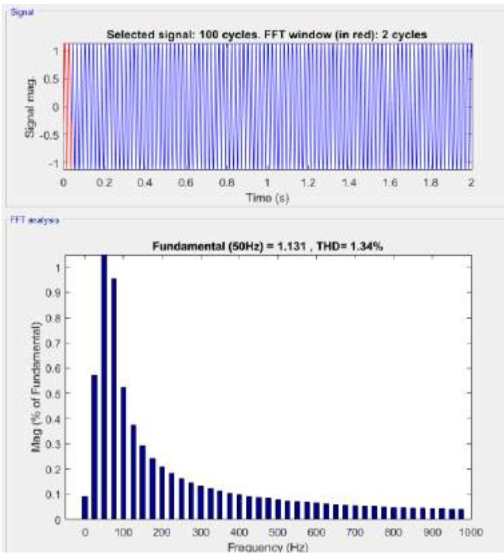


(a)

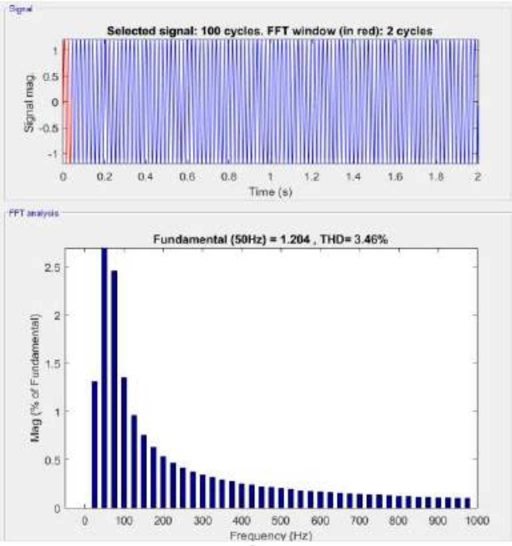


(b)

Fig. 14. THD of the linear load (a) FFT analysis of the Wind output voltage THD is 0.67% (b). FFT analysis of the Load THD is 1.72%.



(a)



(b)

Fig. 15. THD of the Non-linear load (a) FFT analysis of the Wind output voltage THD is 1.34% (b). FFT analysis of the Load THD is 3.46%.

TABLE II. SEIG CONTROLLERS' PERFORMANCE

SEIG	SEIG (IAG) VL(Load Voltage) % Regulation	Frequency control (f-Hz)
Without controller	22.6% Very Poor voltage regulation	40Hz poor frequency, with heavy deviations
With PID	15.6% poor voltage regulation	45Hz poor frequency slight deviations
With Fuzzy	0.8% Good voltage regulation	60-50Hz better frequency deviations with slight oscillations
With ANFIS	0.4% Very Good voltage regulation	60-50Hz without oscillations, and good in dynamic response.

VII. CONCLUSION

A new AI-based controller for a self-excited induction generator (SEIG) has been proposed to improve the SEIG's dynamic performance when it is driven by a WECS. This will make the SEIG more stable. It can be easier to control the system's frequency and voltage by using the ANFIS controller that has been proposed. AC To get the electricity from the SEIG, an AC wind turbine is used. Rotor reference frames and dynamic vectors are used in the model of the machine to show how the machine works. Mathematical software called Simulink is used to model the entire power system, as well as the adaptive neuro-fuzzy controller. The controller is tested in a variety of bad situations, including the worst-case scenario, to see how well it works. Wind turbine power quality and stability improve when the ANFIS control unit is used. The wind turbine's stator frequency can be changed by using ANFIS to change the blade angle. The system dynamics are better when an ANFIS controller is used instead of a variable PI controller with an FLC. Another simulation was run to look at how well the system worked when the wind suddenly changed speed. A nonlinear device called ANFIS can help the system work at different points. The dynamic vector method is used in this model to simulate SEIG. The rotor reference frame is used in this model. Simulated in Matlab Simulink software is all the parts of the power system, as well as the adaptive neuro-fuzzy controller. The controller is tested in a variety of bad situations, including the worst-case scenario, to see how well it works. Wind turbine power quality and stability are better when the ANFIS control unit is used.

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