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Design of an Optimal Tip Speed Ratio Control MPPT Algorithm for Standalone WECS

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Abstract: ***This paper presents a design of an optimal tip speed ratio (OTSR) control maximum power point tracking (MPPT) algorithm for standalone wind energy conversion system. The system consists of a wind turbine, permanent magnet synchronous generator, diode bridge rectifier, boost converter and fuzzy logic controller (FLC). The wind turbine model details the mechanism of three bladed fixed pitch variable speed operation of the turbine. The generator model is established in the dq–synchronous rotating reference frame. Controlling the generator to achieve maximum power point can be done by diode bridge rectifier connected to a boost converter. Fuzzy logic controller is used to control the duty cycle of the boost converter. In order to verify the presented model simulations with MATLAB/Simulink software have been conducted. Simulation results prove the validity of the model. Moreover, the concept of the MPPT has been presented in terms of the adjustment of the generator rotor speed to maintain the optimal tip Speed ratio according to instantaneous wind speed.***
Keywords: Wind turbine, PMSG, Diode Bridge Rectifier, boost converter, Fuzzy logic controller.

I. INTRODUCTION

Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Including the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, bio fuels and hydrogen derived from renewable resources. In modern renewable energy generation technologies, wind turbines have been focused as an attractive solution. These generation wind turbines are suitable for both off-grid electric requirements and grid-connected applications. Wind turbines give many advantages like less environment impact, Improve the energy security via distributed generation etc. The main design requirements in small wind turbine are Low cost, Improved reliability, Low noise level, High energy yield (especially at low and above rated wind speeds) etc. To fulfil these requirements, optimum wind turbine control system designs are essential. The wind turbines are allowed to operate only a specified range of wind speeds. The power characteristics of a wind turbine are defined by the power curve, which relates the performance that is guaranteed by the manufacturer. A typical power curve is characterized by three wind speeds: cut-in wind speed, rated wind speed and cut-out wind speed as described in Fig.1. The wind turbine starts to capture power at the cut-in wind speed. The power captured by the blades is a cubic function of wind speed until the wind speed reaches its rated value. To deliver captured power to the load at different wind speeds, the wind generator should be properly controlled with variable speed operation. As the wind speed increases beyond the rated speed, aerodynamic power control of blades is required to keep the power at the rated value. This task is performed by three main techniques: passive-stall, active-stall, and pitch control. The wind turbine should stop generating power and be shut down when the speed is higher than the cut-out wind speed.

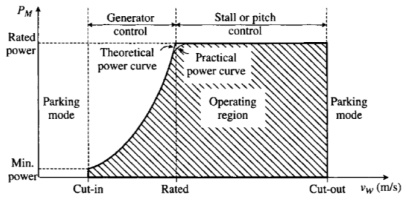


Fig.1 A typical power curve of a wind turbine

In variable speed wind energy conversion system, the previous control techniques are allowed to extract maximum energy from cut in speed to rated wind speed. But, the present system allowed to extracting maximum energy from cut in wind speed to cut out wind speed. Different types of variable speed generators are available for wind energy conversion system. In this work PMSG is used due to its gearless construction, less weight, low speed operation, high efficiency, and self-excitation features. Controlling the Generator to achieve maximum power point can be done by a three phase diode rectifier and boost converter. By changing the duty cycle of the boost converter, the generator shaft speed and output voltage can be adjusted. The block diagram of wind energy conversion system is shown in fig 2.The system supplies a resistive load and consists of a wind turbine, PMSG,

diode rectifier, dc-dc (boost) converter and fuzzy logic controller. Wind turbine converts the kinetic energy in wind into mechanical power that runs a generator to produce clean electricity. Today's turbines are versatile modular sources of electricity. Their blades are aerodynamically designed to capture the maximum energy from the wind. The wind turns the blades, which spin a shaft connected to a generator that makes electricity. The diode bridge rectifier converts the generator output ac power to dc power and it's connected to the boost converter to implement generator side control to obtain the maximum power point.

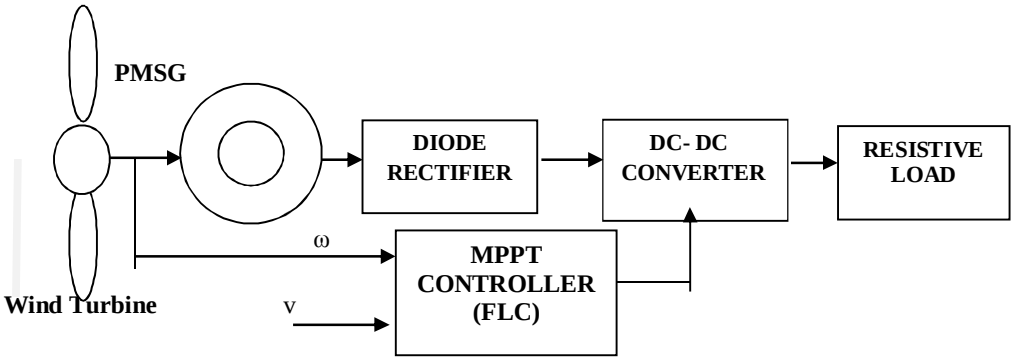


Fig.2. Block diagram of Proposed WECS

When the wind speed is below the specified limit, the maximum power point tracking (MPPT) of the system is essential to maximize the use of wind energy. The MPPT is realized by controlling the boost converter which is connected to the generator through diode bridge rectifier. The various types of MPPT methods, namely Tip Speed Ratio (TSR) control, Optimum Torque (OT) control, Power Signal Feedback (PSF) control, Hill Climb Searching (HCS) control. The TSR method changes the generator speed to maintain the reference tip speed ratio. The reference TSR can be determined experimentally or theoretically and stored as a reference. This method is very simple to understand but it requires wind speed measurement and wind turbine characteristics. The principle of OT control method is to adjust the generator torque according to a maximum power reference torque of the wind turbine at a given wind speed. It is simple, fast, and efficient but efficiency is lower compared to that of TSR control method. In PSF control method the reference optimum power versus shaft speed is stored in look up table. So reference optimum power curve of the wind turbine should be obtained first from the experimental results. Memory and knowledge of the wind turbine is required for this method. While implementing the PSF control the power loss should be considered in order to determine the accurate given maximum power. It makes difficult to determine the maximum power point accurately. HCS control method is a mathematical optimization technique used to search for the local optimum point of a given function. This method does not require prior knowledge of the wind turbine's characteristics curve; it is independent, simple, and flexible. However, it fails to reach the maximum power points under rapid wind variations if used for large and medium inertia wind turbines. To overcome these drawbacks of the TSR method, some different data's are used in this paper. The proposed MPPT method is based on the two time periods according to wind speed and shaft speed. If both time periods are equal, the tip speed ratio is maintained at constant value and the system is operated in maximum power point. In TSR method one reference and one real time parameters are used, but the present system two real time parameters are used, which improves the system performance. Fuzzy logic controller is used to implement the proposed MPPT technique. Duty cycle of the boost converter is changed by fuzzy logic controller with instantaneous wind speed to adjust the shaft speed to maintain the two time periods are equal. The proposed model is implemented in MATLAB/SIMULINK environment and the simulation results are presented to verify the performance of the system.

II. WIND TURBINE MODEL

Wind energy systems convert the kinetic energy of the wind into the electrical energy. The kinetic energy produced by a moving object is expressed as

$$E = \frac{1}{2} m v^2 \quad \rightarrow (1)$$

In this case, *m* is the mass of air and *v* is the wind velocity. The mass *m* could be derived from

$$m = \rho A v \quad \rightarrow (2)$$

Where, ρ is the air density in (Kg/m^3)

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$A = \pi R^2$, is the swept area of the rotor blade

v is the wind velocity in (m/s)

R is the rotor radius in (m)

The mechanical power of the wind turbine (P_w) is defined is the kinetic energy over the time (t), thus P_w is expressed as

$$P_w = E = \frac{1}{2}mv^2 = \frac{1}{2}\rho\pi R^2 v^3 \quad \rightarrow(3)$$

This equation tells us that maximum power available depends on rotor diameter. The power expressed by Eq. (3) is the ideal power captured by the wind turbine. The actual power of the wind turbine depends on the efficiency of the turbine represented by C_p (λ, β) which is the function of the tip speed ratio (λ) and pitch angle (β). The tip speed ratio (λ) is defined to be the ratio between the turbine speed and the wind speed, and is given by

$$\lambda = \frac{\omega R}{v} \quad \rightarrow(4)$$

Where, ω is the rotor tip speed.

Therefore, the actual power captured by the wind turbine is given by

$$Pm = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda, \beta) \quad \rightarrow(5)$$

Where, Pm is the mechanical power that extracts from the wind.

The power coefficient C_p (Betz coefficient) reaches maximum value =0.594. In practice, values of obtainable power coefficient's are in the range of 45% which depends of the tip speed ratio λ of the wind turbine and angle of the blades β.

The turbine power coefficient is a nonlinear function and expressed by a generic function

$$c_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_1} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda i}} + c_6\lambda \quad \rightarrow(6)$$

$$\frac{1}{\lambda_i} = \left[\frac{1}{\lambda+0.089} - \frac{0.035}{\beta^2+1}\right] \quad \rightarrow(7)$$

In this paper, the angle (β) is set to zero due to the assumption of fixed pitch wind turbine. Hence, the power coefficient mainly depends on the tip speed ratio. Fig.3 shows the characteristic of C_p as a function of λ. Based on that curve, there is only one optimal operating point, denoted by $\lambda_{optimal}$, where Cp is maximum. To obtain the maximum power from the available wind the wind turbine should be operated at this point. Fig.4 presents the optimal operating point for various wind speeds.

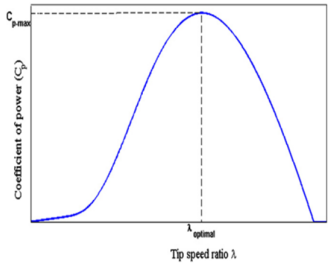


Fig. 3 The characteristic of the power coefficient as a function of tip speed ratio

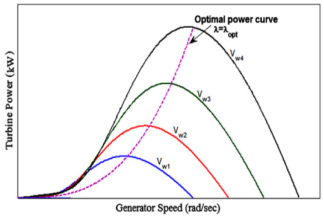


Fig.4.The characteristic of turbine power versus generator speed for various values of wind speed

The amount of aerodynamic torque is obtained from the Pm.

$$T_m = \frac{Pm}{\omega} \quad \rightarrow(8)$$

Where, T_m is the mechanical power in N-m.

ω is the generator shaft speed in rad/sec.

III. PMSG MODEL

In order to design the PM machine in Matlab/Simulink is necessary to develop the mathematical model of the machine that is derived from the space vector form of the stator voltage equation.

$$V_{abc}=R_s I_{abc}+\frac{d}{dt}\varphi_{abc} \quad \rightarrow(9)$$

Where Rs is the stator winding resistance per phase, I_{abc} is the stator phase current, V_{abc} is the stator phase voltage and φ_{abc} is the flux linkage.

The dynamic model is derived in dq reference frame were q axis is rotating with 90^o ahead to the d axis with respect to the direction of rotation. Based on the reference frame theory, stator voltage equations in dq synchronous reference frame are presented:

$$v_d = R_s i_d + \frac{d}{dt}\varphi_d - \omega_e\varphi_q \quad \rightarrow(10)$$

$$v_q = R_s i_q + \frac{d}{dt}\varphi_q + \omega_e\varphi_d \quad \rightarrow(11)$$

Where v_d, v_q are the dq axis stator voltage, i_d, i_q are the dq axis stator current, φ_d, φ_q are the dq axis flux linkages, R_s stator resistances and ω_e is the electrical speed in rad/s. Flux linkage equations are expressed as $\varphi_d = L_d i_d + \varphi_m$, $\varphi_q = L_q i_q$. With $L_d=L_q=L_s$ dq axis inductances and φ_m permanent magnet flux linkage. With the help of flux linkage equations, stator voltage equations in dq reference frame have the fallowing form:

$$\frac{di_d}{dt} = \frac{v_d}{L_s} - \frac{R_s i_d}{L_s} + \omega_e i_q \quad \rightarrow(12)$$

$$\frac{di_q}{dt} = \frac{v_q}{L_s} - \frac{R_s i_q}{L_s} - \omega_e\left(i_d + \frac{\varphi_m}{L_s}\right) \quad \rightarrow(13)$$

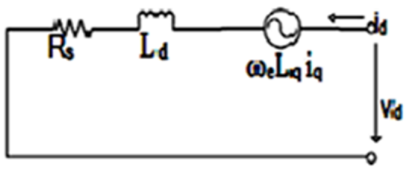


Fig.5 d-axis equivalent circuit

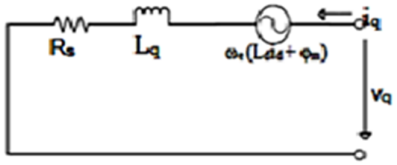


Fig.6. q-axis equivalent circuit

The electromagnetic torque equation is given by

$$T_e = \frac{3}{2}P\left(\varphi_m i_q + (L_d - L_q)\, i_q i_d\right) \quad \rightarrow(14)$$

As the inductances on the d- and q-axis are equal, the electromagnetic torque can be regulated by i_q as

$$T_e = \frac{3}{2}\, p\, \varphi_m i_q \quad \rightarrow (15)$$

The mechanical equation of the machine is express as a function of the electromagnetic torque (T_e), load torque (T_m) and electrical velocity of the machine:

$$T_e = T_m + B\,\omega_m + J\frac{d}{dt}\omega_m \quad \rightarrow(16)$$

Where J is the moment of inertia and B is the viscous friction.

IV. POWER ELECTRONIC CONVERTERS

A. *Three Phase Diode Bridge Rectifier*

Rectification is the process of conversion of alternating input voltage to direct output voltage. A rectifier converts ac power to dc power. In diode based rectifiers, the output voltage cannot be control. For high power applications and where three phase power supply is available, a three phase bridge rectifier should be used. The diode rectifier is the most simple, cheap and rugged topology used in power electronic applications. The disadvantage of this diode rectifier is its disability to work in bi-directional power flow. The average output dc voltage from this rectifier can be obtained from Eq. (17), where the overlap due to the internal inductance of the PMSG is ignored.

$$\text{Average outpu voltage} = \frac{3}{\pi} V_{ml} = \frac{3\sqrt{2}}{\pi} V_l = \frac{3\sqrt{6}}{\pi} V_p \quad \rightarrow(17)$$

Where, V_{ml} = maximum value of line voltage

V_l = rms value of line voltage

V_p = rms value of phase voltage.

B. Boost Converter

A boost converter (step-up converter) is a DC-to-DC power converter with an output voltage greater than its input voltage. It is a class of switched-mode power supply (SMPS) containing at least two semiconductors and at least one energy storage element, a capacitor, inductor, or the two in combination. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple. In this model the boost converter is used to control the generator speed to operate the system at maximum power point by changing its duty cycle.

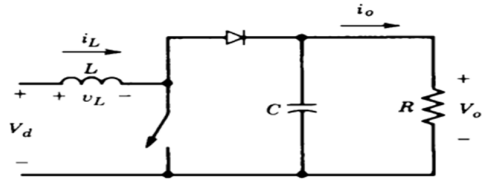


Fig.7. Boost converter schematic

The output voltage of the boost converter in terms of input voltage and duty cycle is given by

$$V_o=\frac{v_i}{1-D} \quad \rightarrow(18)$$

The above expression shows that the output voltage is always higher than the input voltage (as the duty cycle goes from 0 to 1), and that it increases with D, theoretically to infinity as D approaches 1. This is why this converter is sometimes referred to as a *step-up* converter.

V. OTSR MPPT TECHNIQUE (PROPOSED METHOD)

An optimal TSR for maximum power extraction is inferred by relating the time taken for the disturbed wind to re-establish itself to the time required for the next blade to move into the location of the preceding blade. The block diagram of OTSR method is shown in fig. 8.

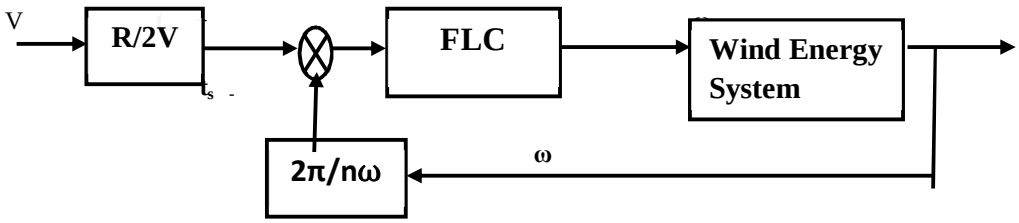


Fig.8. Block diagram of OTSR MPPT technique

For an n bladed rotor, the time period for the blade to move to its predecessor's position is given by

$$t_s=\frac{2\pi}{n\omega} \quad \rightarrow(19)$$

The time taken for the disturbed wind to re-establish itself (t_w) given as:

$$t_w=\frac{R}{2V} \quad \rightarrow(20)$$

If ($t_s > t_w$), then some wind is unaffected. If ($t_w > t_s$), then some wind is not allowed to flow through the rotor. The maximum power extraction occurs when $t_w = t_s$. According to the equations (19), (20) and (4) an optimal tip speed ratio is expressed as

$$\lambda_{opt}=\frac{4\pi}{n} \quad \rightarrow(21)$$

Where, n is the number of blades.

For three bladed wind turbine the optimal tip speed ratio is 4.188. In real time, the optimal tips speed ratio can be calculated by

$$\lambda_{opt}=2\omega t \quad \rightarrow(22)$$

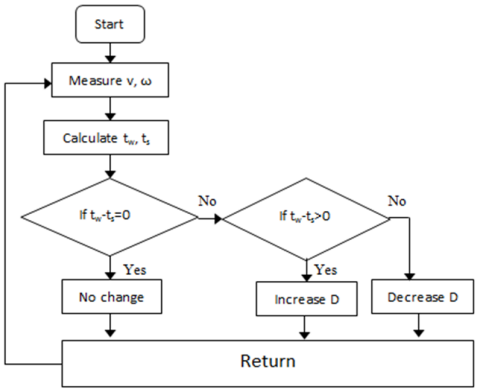


Fig.9. Flowchart for OTSR MPPT technique

The optimal tip speed ratio depends on the number of blades of the wind turbine. The wind turbine is modelled by replacing v by t_w. If the aerofoil is designed with care, the optimal tip speed ratios may be about 25-30% above these optimal values. These highly efficient aerofoil rotor blade designs increase the rotational speed of the blade rotor therefore generating more power.

VI. FUZZY LOGIC CONTROLLER

Fuzzy logic control is a new addition to control theory. Its design philosophy deviates from all the previous methods by accommodating expert knowledge in controller design. FLC is one of the most successful applications of, fuzzy set theory. Its major features are the use of linguistic variables rather than numerical variables .Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and large), may be represented by fuzzy sets. FLC's are an attractive choice when precise mathematical formulations are not possible

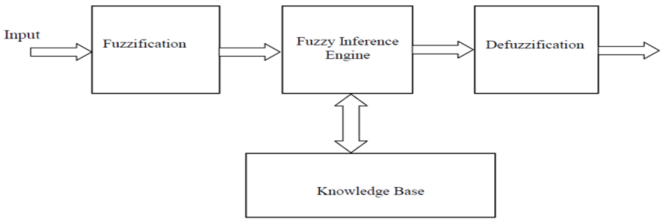


Fig.10. Basic structure of fuzzy logic controller

A. *Fuzzification*

It is a process of transforming a classical set into fuzzy set or it is a process of translating an uncertain event into fuzzy set by assigning a proper membership function or it is a process of transforming a scalar value into a fuzzy value. The membership function values are assigned to the linguistic variables using seven fuzzy subset for input variable and five subset for output variable. The triangular membership function is used for both variables.

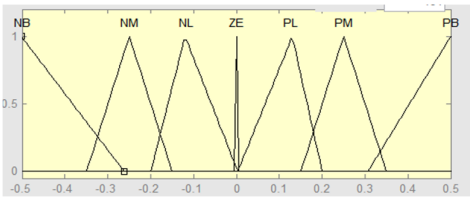


Fig.11. Membership function of input variable

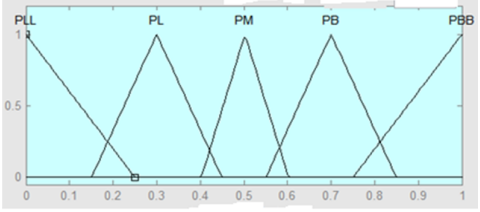


Fig.12. Membership function of output variable

B. *Fuzzy Inference Engine*

These are the types of the method with the rule base so as to obtain the fuzzy values. There are basically two methods, such as Mamdani and Sugeno method. In this work Mamdani's method is used with Max-Min operation fuzzy combination. Fuzzy inference is based on fuzzy rule base system. Rules are framed in inference engine block. The commonly used method is MAX-MIN. The output membership function of each rule is given by MIN (Minimum) operator and MAX (Maximum) operator.

C. *Knowledge Base Or Rule Base*

Fuzzy control rules are obtained from the analysis of the system behaviour. In their formulation it must be considered that using different control laws depending on the operating conditions can greatly improve the converter performances in terms of dynamic response and robustness. The control rules that associate the fuzzy output to the fuzzy inputs are derived from general knowledge of the system behaviour. A typical rule can be written as follows.

If input is NB then output is ZE

To obtain the control decision, the max-min inference method is used. It is based on the minimum function to describe the AND operator present in each control rule and the maximum function to describe the OR operator.

D. *Defuzzification*

The output of fuzzy controller is a fuzzy subset. As the actual system requires a non-fuzzy value of Control, defuzzication is required. Defuzzifier is used to convert the linguistic fuzzy sets back into actual value. There are five methods for defuzzification: Centroid method, Bisector method, Middle of Maximum, Smallest of Maximum, Largest of Maximum. The most commonly used method among all is the centroid method. For symmetrical figure such as triangular, square, centroid lies at the centre. For complex objects the overall centroid is calculated by breaking it into smaller objects using a weighted average (by area).

$$Cx = \frac{\sum CixAi}{\sum Ai}$$

Ci = Centroid of respective figure
Ai = Area of respective figure.

VII. SIMULATION RESULTS

The wind turbine model is implemented by the following equation, which is derived from the equations (5) and (20).

$$P_m = \frac{1}{16}\rho\pi R^5 C_p / (t_w)^3.$$

The Simulation diagram for wind turbine is shown in fig.13. Wind turbine model inputs are rotor radius, wind speed, generator tip speed and output is mechanical torque. The MPPT controller model and the overall simulation diagram of the proposed system are shown in fig.14 and fig.15. The system parameters are listed in table 1.

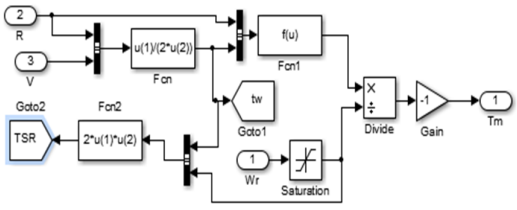


Fig.13. Simulation diagram for wind turbine

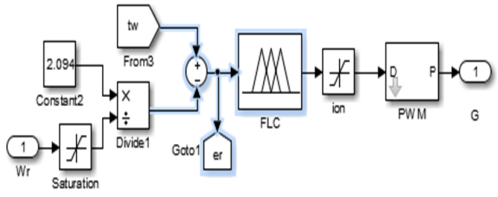


Fig.14. Simulation diagram for MPPT controller

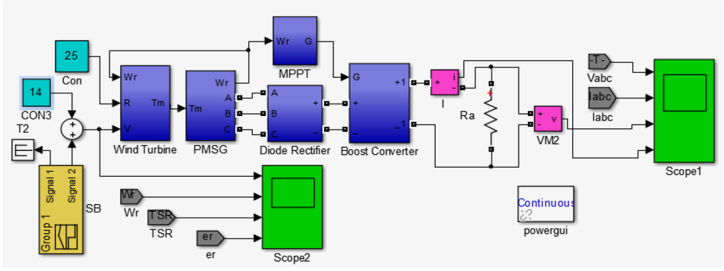


Fig.15.The overall simulation diagram

TABLE 1
THE PROPOSED SYSTEM PARAMETERS

Parameters	Symbol	Value and Units
Rotor radius	R	25m
Cut-in wind speed	V	5m/s
Cut-out wind speed	V	25m/s
Optimal TSR	λ_{opt}	4.188
Power coefficient	C_p	0.45
Air density	ρ	1.237kg/m^3
Stator Resistance	R_s	4.34ohm
Armature Inductance	L_s	0.000515H
Generator Inertia	J	0.00062kg.m^2
Pole Pairs	P	34
Boost converter inductance	L	100Mh
Boost converter capacitance	C	150μF
Load Resistance	R_L	100ohm
Switching frequency	f	5KHZ

The simulation output waveforms of the proposed system are shown in fig.16. When the wind speed is14m/s, the generator tip speed is 2.35rad/sec, tip speed ratio is nearly 4.188 and the error value is maintaining at zero. The generator output voltage is 5500v and the boost converter output voltage is 10KV. The wind speed is increased to 18m/s the tip speed not increased to the exact value to maintain the error value zero when the FLC is not present. If FLC is present the tip speed increased to exact value by changing the boost converter duty cycle. Therefore the error value is maintaining at zero. The generator and boost converter output voltages are increased. The wind speed is decreased to 10m/s the tip speed, generator and boost converter output voltages are decreased. The simulation results are obtained with FLC**.**

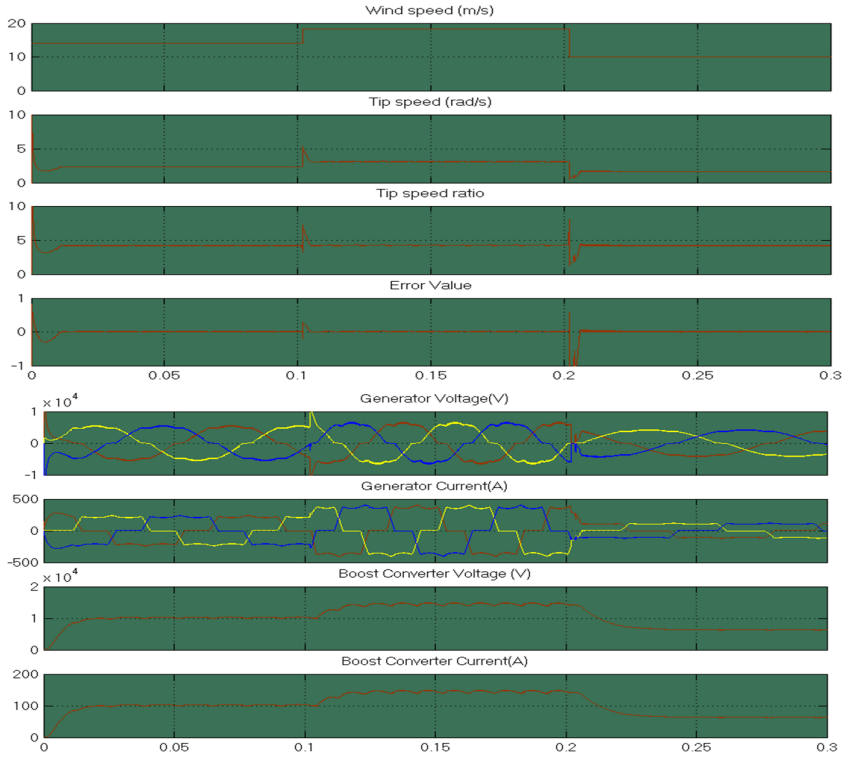


Fig.16. Simulation results of proposed system

VIII. CONCLUSION

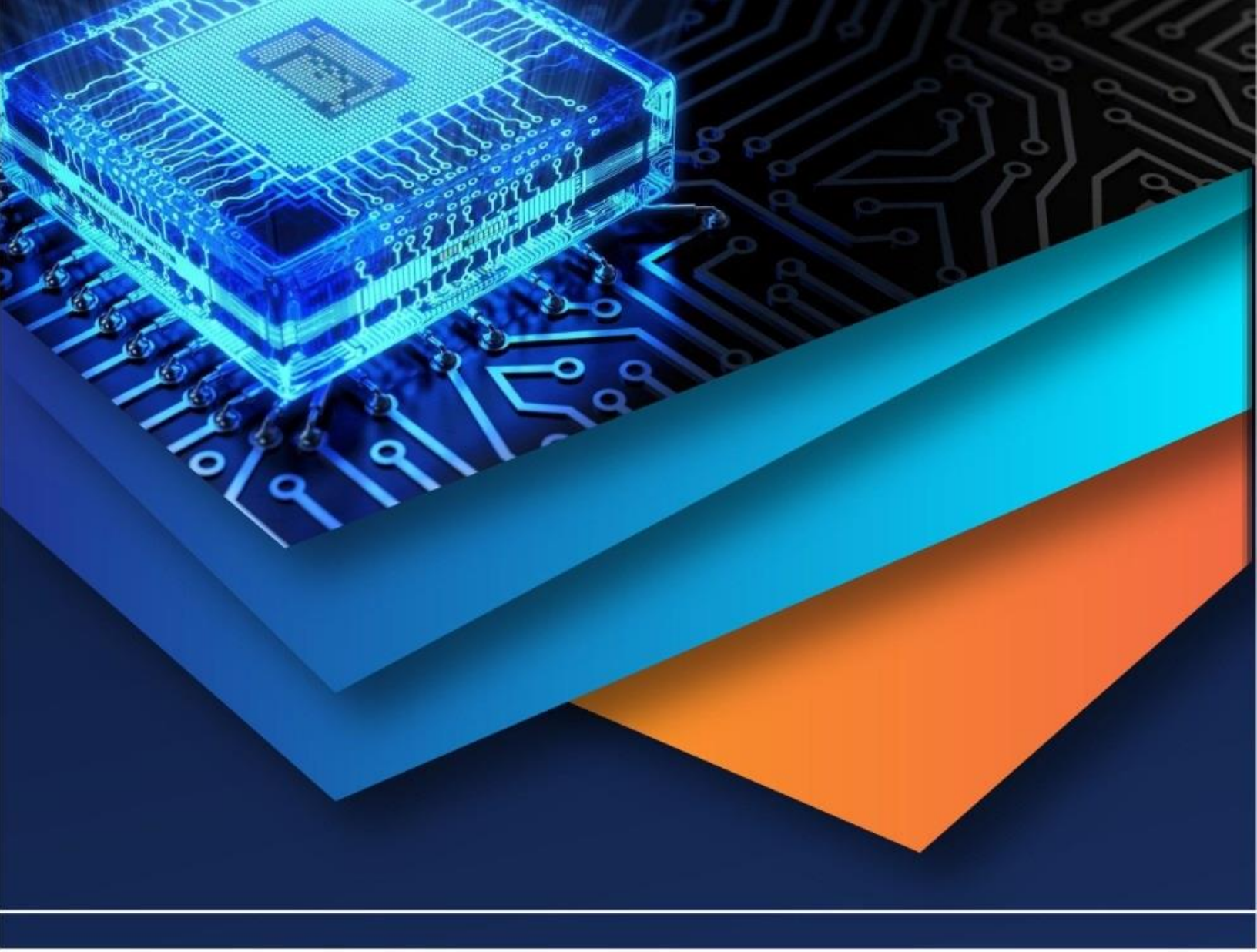
This paper proposed a design of an optimal tip speed ratio control MPPT algorithm for standalone wind energy conversion

system. The system supplies to a resistive load through diode bridge rectifier and boost converter. The proposed wind energy conversion system was designed and simulated in Matlab/Simulink R2013a. The MPPT algorithm is implemented by using the fuzzy logic controller due to its advantages like Very robust, easily modified, use multiple inputs and outputs sources, simpler than its predecessors (linear algebraic equations), very quick and cheaper to implement. The combination of diode bridge rectifier and boost converter increase the system reliability. The simulation results have shown the proposed system performance.

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