

Design of Wind Turbine Energy System Based on Matlab/Simulink

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ABSTRACT

This paper presents modelling and simulation of wind turbine - electrical generation system using Matlab/Simulink software package. This system consists of wind turbine coupled with the Permanent Magnet Synchronous Generator (PMSG). The PMSG is connecting to the load through a three-phase full wave rectifier and a buck converter. Control strategy based on Fuzzy Logic Controller (FLC) is presented to regulate the output voltage of the wind generation system irrespective of variations in the wind speed and load. The wind turbine and FLC are implemented in Matlab/Simulink based on its mathematical model of its equivalent equations. Simulation results show that the controllers can regulate the output voltage of the system under varying wind speed and load conditions.

Keywords: Wind Turbine, PMSG, Rectifier, Chopper, and FLC.

تصميم منظومة قدرة كهربائية لتوربين ريحي باستخدام برنامج

Matlab/Simulink

الخلاصة

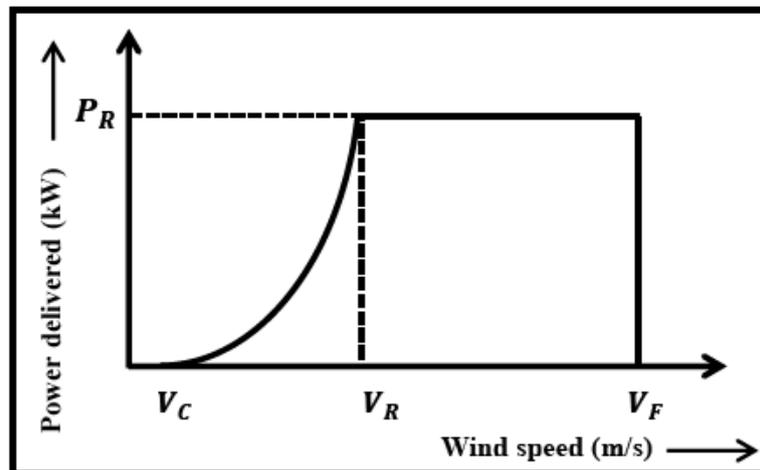
في هذا البحث تم تمثيل ونمذجة منظومة قدرة كهربائية لتوربين ريحي باستخدام برنامج Matlab/Simulink. تتكون المنظومة من توربين ريحي مقترن مع مولد التزامني ذو اقطاب مغناطيسية دائمية. فولتية اخراج المولد التزامني المتناوبة تم تحويلها الى فولتية مستمرة عن طريق مقوم فولتية ثلاثي الأطوار ذو الموجة الكاملة ثم تم تقطيعها بواسطة مقطع من نوع (Buck). تم بناء وحدة سيطرة على مقطع الفولتية بالاعتماد على المنطق المضبب لتنظيم فولتية الإخراج تحت تأثير تغير سرعة الرياح وتيار الحمل. تم بناء وحدة التوربين الريحي ووحدة السيطرة المعتمدة على المنطق المضبب من خلال برنامج Matlab/Simulink بالاعتماد على التمثيل الرياضي

لمعادلات التوربين الريحي والمنطق المضبيب. أظهرت نتائج المحاكاة امكانية السيطرة على فولتية المنظومة عند تغيير سرعة الرياح بقيم مختلفة وكذلك عند تحميل المنظومة بأحمال مختلفة ايضا.

INTRODUCTION

In recent years, wind energy has been regarded as one of the significant renewable energy sources. Among the existing wind power generation systems, their generators can be categorized into four main types [1]: 1) fixed-speed squirrel-cage induction generator; 2) variable-speed wound rotor induction generator that employs variable rotor resistance; 3) variable-speed doubly fed induction generator that employs a frequency converter between the grid and its rotor windings; and 4) variable-speed synchronous generator, which is either a wound rotor synchronous generator or a PMSG. In this paper, gearless multi-pole PMSG is chosen and it is attractive because it offers better performance due to higher efficiency and less maintenance since it does not have rotor current and can be used without a gearbox, which also implies the reduction of the weight of the nacelle, and reduction of costs. It produces electricity from the mechanical energy obtained from the wind [2].

A typical wind turbine power curve is shown in Fig. 1. The wind system starts to generate when wind speed reaches the threshold V_C (cut-in wind speed). This threshold is dependent of many factors of the wind energy system. For higher wind speed values, the generated power of the wind turbine rises until rated wind speed V_R and rated power P_R . V_R depends on system design parameters. For higher wind speeds, the system is regulated at rated power P_R until cut-out wind speed V_F is reached. Then, the wind energy system is automatically put out of production for security reasons. The most frequent methods to control a wind turbine are: a) blade pitch control, b) passive stall control, c) active stall control and d) yaw control [3].



Figure(1) :Typical curve of a wind turbine

Several publications were found where other groups had constructed wind turbine experimental work using similar ideas as ones proposed here, ([4], and [5]). In [4] was studied an electronic circuit for wind energy conversion system. For each converter principle operation, basic equations, and experimental results were

presented. The battery charger converter was tested with a 500W wind-turbine generator with maximum power point tracking controller for optimal performance. For the tests four stationary batteries in series connection of 100Ah and 12V were used. Accordingly to the experimental results, it was verified that the control system performance is satisfactory for the battery bank voltage regulation and maximum power tracking. In [5], the development of a novel Wind Generator (WG) maximum power tracking control system is presented, comprising of a high-efficiency buck-type dc/dc converter and a microcontroller-based control unit

In our paper, a detailed model for the wind turbine unit is implemented using Matlab Simulink based on its basic mathematical equations. The output voltage of the PMSG which is coupled with the wind turbine is fed to uncontrolled rectifier. Finally, with the aid of FLC a controlled buck convertor has been designed and tested for different wind speed and load conditions to maintain the output voltage constant.

MODELLING OF WIND ENERGY SYSTEM

Fig. (2) illustrates the configuration of the proposed wind energy system. The wind turbine coupled with a PMSG. The rectifier is a three phase full wave diode rectifier for converting three phase AC voltage to DC voltage. The buck converter is a DC-DC step down converter where the voltage output is controlled by a pulse signal from the fuzzy control model.

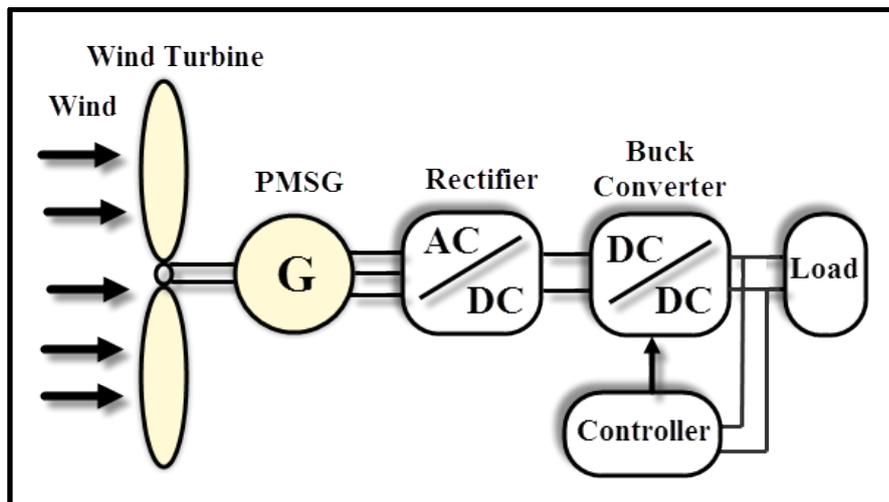


Figure (2): Configuration of wind energy system

A- WIND TURBINE MODEL

Windenergy systems convert the kinetic energy of the wind into the electrical energy. The kinetic energy (E_{kin}) produced by a moving object is expressed as [6, 7]:

$$E_{kin} = \frac{1}{2} m u^2 \quad \dots (1)$$

In this case, m is the mass of air and u is the wind velocity. The mass (m) could be derived from

$$m = \rho_a A_v s \quad \dots (2)$$

Where ρ_a is the air density in kg/m^3 , A_v is the area swept by the blades in m^2 , and s is the distance travelled by the wind in m .

$$A_v = R^2 \pi \quad \dots (3)$$

Where R : is the radius of the wind turbine blade.

The wind supplied power (P_v) can be calculated by derivation of the wind energy.

$$P_v = \frac{dE_{Kin}}{dt} = \frac{1}{2} \frac{dm}{dt} u^2 = \frac{1}{2} \rho_a A_v \frac{ds}{dt} u^2 \quad \dots (4)$$

Where, $\frac{ds}{dt} = u$

$$P_v = \frac{1}{2} \rho_a A_v u^3 \quad \dots (5)$$

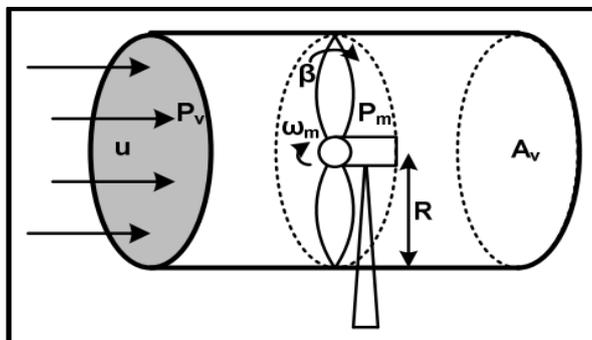
The power expressed in the previous equation is the ideal power captured by the wind turbine. The actual power of the wind turbine (extraction of mechanical power (P_m)) depends on the power coefficient of the turbine represented by $C_p(\lambda, \beta)$ which is the function of the tip speed ratio (λ), blade pitch angle (β) (in degree), number of blades, and blade aerodynamics characteristics [4, 6].

Then the extraction of mechanical power (P_m) is

$$P_m = C_p(\lambda, \beta) \cdot P_v = \frac{1}{2} C_p(\lambda, \beta) \cdot \rho_a \cdot A_v \cdot u^3 \quad \dots (6)$$

For a fixed pitch type the value of blade pitch angle (β) is set to a constant value. Fig. 3 shows the extraction of mechanical power (P_m). The tip speed ratio (λ) is defined to be the ratio between the turbine speed (w_m) and the wind speed (u), and is given by [4, 8]

$$\lambda = \frac{w_m \cdot R}{u} \quad \dots (7)$$



Figure(3): Extraction of mechanical power [4]

The power coefficient of the turbine is given by

$$C_p(\lambda, \beta) = \left(\frac{116}{\lambda_1} - (0.4\beta) - 5 \right) 0.5e^{\frac{-16.5}{\lambda_1}} \quad \dots (8)$$

Where:

$$\lambda_1 = \left(\frac{1}{(\lambda + 0.089\beta)} - \frac{0.035}{(\beta^3 + 1)} \right)^{-1} \quad \dots (9)$$

Then, the mechanical torque (T_m) of the wind turbine could be expressed as

$$T_m = \frac{P_m}{\omega_m} \quad \dots (10)$$

The wind turbine block (model) is simulated in Matlab/Simulink software package according to equations (1 to 10) as shown in Fig. (4).

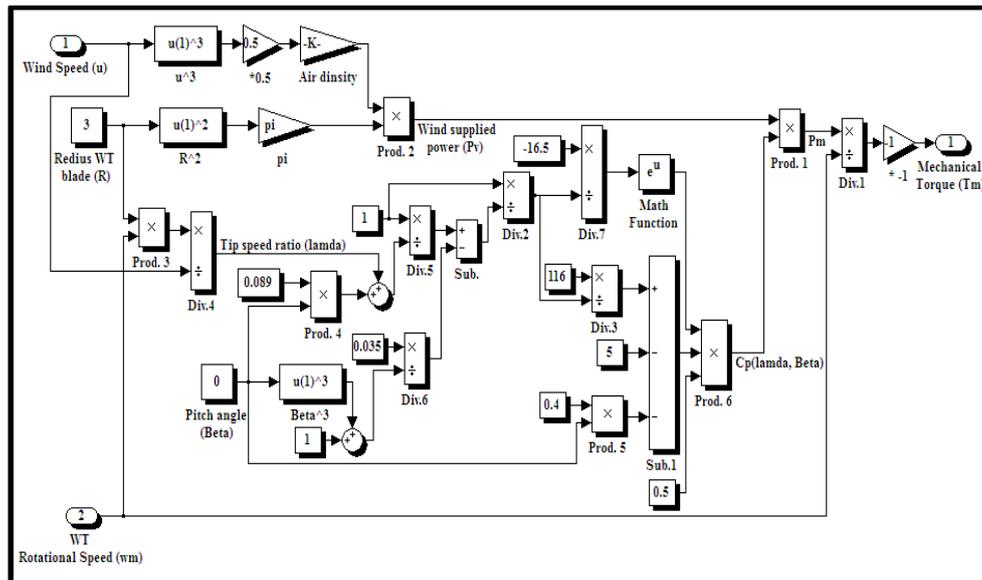


Figure (4): Simulink model of the wind turbine

B- PERMANENT MAGNET SYNCHRONOUS GENERATOR MODEL

A typical Synchronous Generator (SG) makes use of an external excitation circuit, while a PMSG is a self-excitation machine. In the case of PMSG the excitation is produced by the permanent magnets which are placed on the rotor and produce the essential magnetic flux. Note that the magnetic flux is fixed and cannot be varied. Consequently, the magnitude of the output voltage of a PMSG can be controlled only by changing the generator speed. Additionally, the PMSG active power is controlled through the speed. The voltage magnitude of a typical SG can be varied by controlling the current through the excitation circuit. In both generators, the voltage frequency depends on the speed [9].

In PMSG, the relation between torque (T) and induced voltage (E) is as follows [10]:

$$T = K_t I_a \quad \dots (11)$$

$$E = K_e \omega \quad \dots (12)$$

Where: I_a is stator current, K_e is the machine constant, and ω is the angular rotor speed. On the other hand, it is obvious that:

$$E = V_t + I_a(R_a + jX_s) \quad \dots (13)$$

Where: V_t is the terminal phase voltage as shown in the equivalent circuit of the PMSG for one phase in Fig. 5.

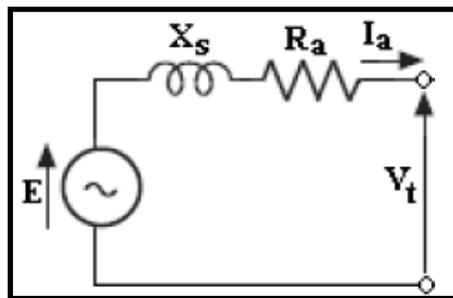


Figure (5): Equivalent circuit of PMSG for one phase

C- THREE-PHASE FULL BRIDGE RECTIFIER MODEL

A three-phase full bridge rectifier shown in Fig. 6 converts the AC generated output voltage from PMSG, which will be varying in magnitude and also in frequency, into DC voltage. The average output voltage ($V_{rect.}$) of the three phase diode rectifier is obtained [8, 11] as follows:

$$V_{rect.} = \frac{3\sqrt{6}}{\pi} V_t \quad \dots (14)$$

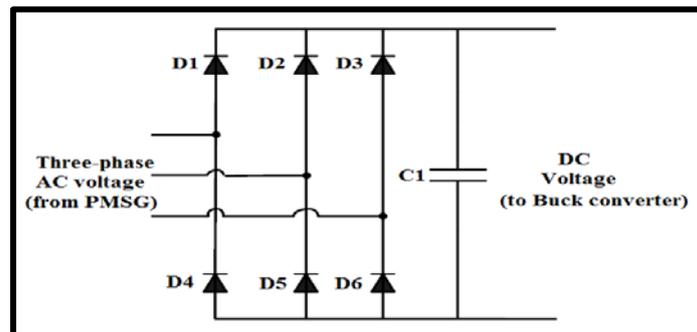


Figure (6): Three-phase full bridge rectifier

A dc link capacitor (rectifier output capacitor) (C_1) is used at the output stage of the rectifier to eliminate significant ripple voltage components [11,12].

$$C_1 = \frac{V_m}{6fRV_{r(pp)}} \quad \dots(15)$$

Where V_m is the peak value of the phase voltage, f is the frequency of the source, R is the load resistance, and $V_{r(pp)}$ is the peak-to-peak ripple voltage.

D- STEP-DOWN (BUCK) CONVERTER MODEL

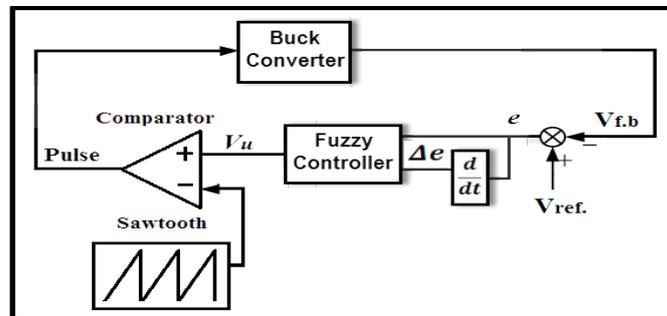
The conversion of rectified DC voltage to any specified DC output voltage can be carried out employing a DC-DC converter or chopper circuit (i.e. convert an unregulated dc voltage to a regulated dc output voltage) [8]. The buck converter output voltage (V_{dc}) is obtained as:

$$V_{dc} = K V_{rect} \quad \dots(16)$$

Where: K duty cycle of the buck converter.

E- FUZZY CONTROL MODEL

The block diagram of fuzzy control model for buck converter is shown in Fig. 7, the conventional single-loop feedback control is realized by to adjust the duty cycle of the buck converter.



Figure(7): Block diagram of the fuzzy control model

Here a FLC of the simplified type is used [13], which consists of a set of linguistic statements composed of two inputs, the voltage error (e), and the rate of the voltage error value (Δe), in order to carry out control actions by using if-then rules. The inputs in the approach are e and Δe , while the output is the control signal (Vu).

$$e(k) = V_{ref}(k) - V_{f.b}(k) \quad \dots (17)$$

$$\Delta e(k) = e(k) - e(k - 1) \quad \dots (18)$$

Where: $V_{ref}(k)$ is the desired voltage; $V_{f.b}(k)$ is the feedback voltage, and k is the sampling time.

Two inputs (error and error rate) both use P (positive), Z (zero), and N (negative). Use Gaussian type function as Membership Function (shown in Fig. 8). Get the solutions of fuzzy by the method of weighted average.

Fuzzy control rules are a summary of expert knowledge and experience accumulated. Fuzzy control rules is expressed by the fuzzy conditional statement,

If $e(k)$ and $\Delta e(k)$ then Vu

All the rules drawn into the table constitutes a fuzzy control rule table. There are 9 fuzzy control rules, shown as Table (1). The linguistic variables used for the output signal Vu ; NB (Negative Big) NS (Negative Small) Z (Zero) PB (Positive Big) and PS (Positive Small).

Table (1): Fuzzy rules

| e \ Δe | N | Z | P |
|----------------|----|----|----|
| N | NB | NS | Z |
| Z | NS | Z | PS |
| P | Z | PS | PB |

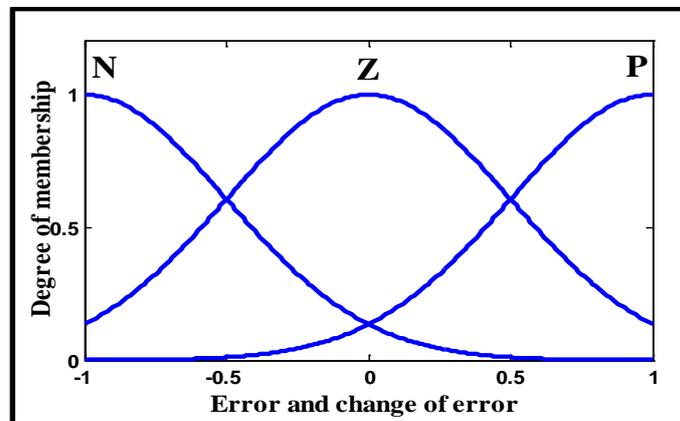


Figure (8): Membership function of error and change of error

MODELLING AND RESULTS DISCUSSION

The model of wind energy system is simulated using Matlab/Simulink software package as shown in Fig. (9). There are six main blocks in the model: the wind turbine block, PMSG block, Three-phase full wave rectifier block, control unit block, buck converter block, and the battery block.

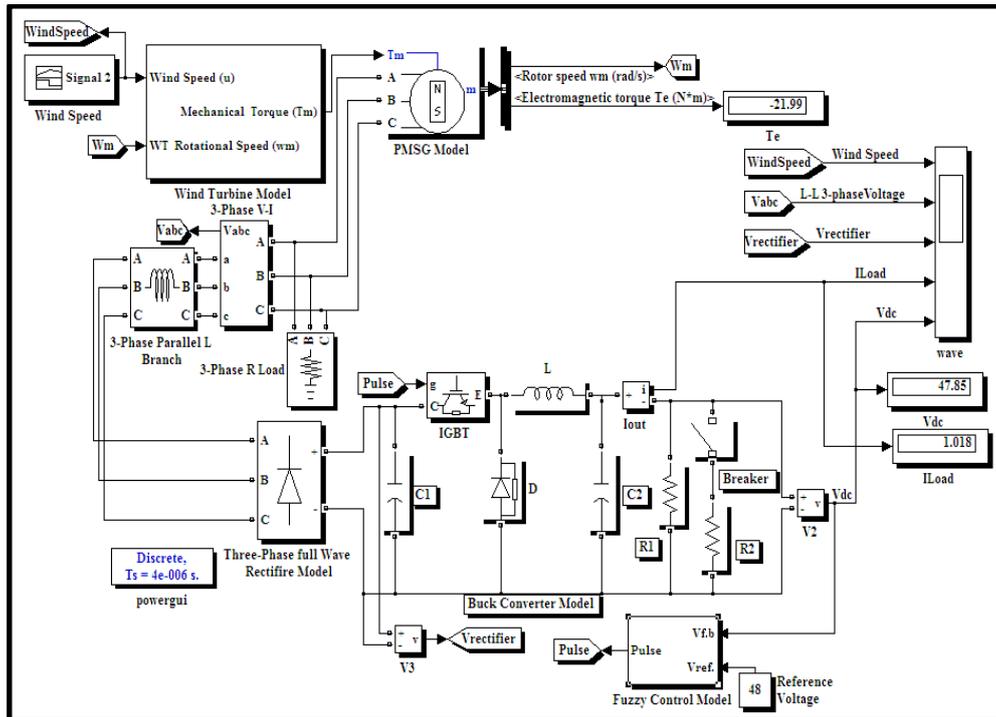


Figure (9): Simulink model of wind energy system

The performance of the proposed wind energy system is tested by considering the variations in wind speed and load see Fig. 10.

- Wind speed is varied between 11 m/s to 20 m/s as mentioned below (Fig. 10 (a)):

For 0 - 0.3 sec., wind speed = 11 m/s

For 0.3 - 0.7 sec., wind speed = 16 m/s

For 0.7 - 1 sec., wind speed = 20 m/s

Fig. 10(b & c) shows the PMSG output voltages and three-phase full bridge rectifier output voltage respectively for different values of wind velocities.

- The variations in the load are given below (Fig. 10 (d)):

For 0- 0.5 sec., load = 1A

For 0.5 -1 sec., load = 2A

Considering the variations in the load and wind speed as mentioned above, response of Buck chopper output voltage V_{dc} is shown in Fig. 10 (e).

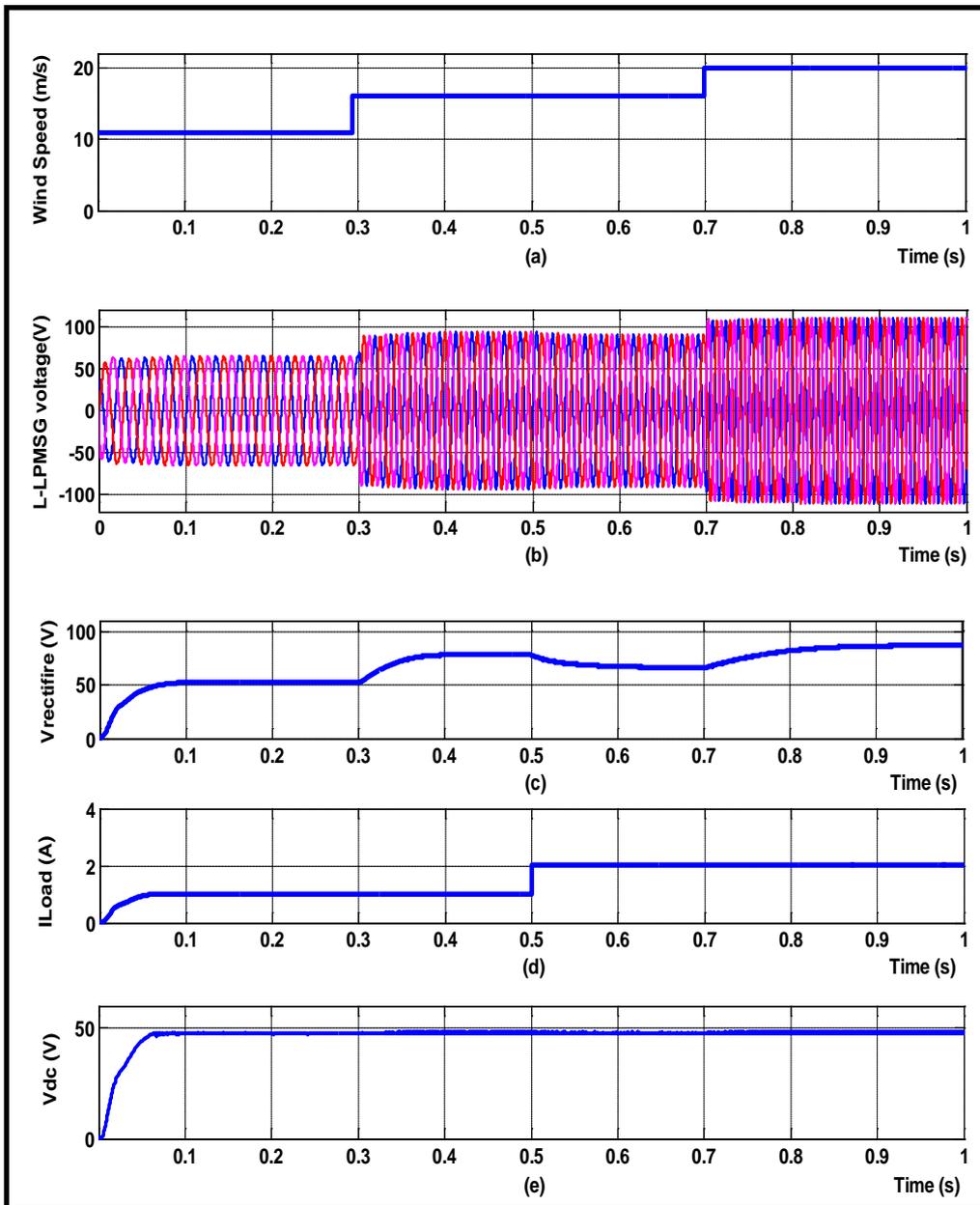


Figure (10): Simulation result of wind energy system: (a) Wind speed, (b) PMSG output voltages, (c) Full bridge rectifier output voltage, (d) Load current, and (e) Buck chopper output voltage

The previous responses of the wind energy system in Fig. 10 (a, b, and c) show the effect of increasing the wind speed on the PMSG output voltage and the rectified voltage, this effect is shown in the following table.

Table (2): Effect of the wind speed variation on the PMSG output and rectified voltage

| Time (sec) | Wind speed (m/s) | PMSG output voltage (V) | Full bridge rectifier output voltage (V) |
|------------|------------------|-------------------------|--|
| 0-0.3 | 11 | 65 | 52.5 |
| 0.3-0.7 | 16 | 90 | 78 |
| 0.7-1 | 20 | 110 | 87 |

When the load current suddenly increased from 1A to 2A at 0.5 sec (see fig. 10(c, d)), the rectified voltage decreased from 78V to 66V.

The fuzzy control action can be observed in the output voltage of the Buck chopper (see Fig. 10 (e)), irrespective of fluctuations in wind speed and load, V_{dc} is maintained constant at its reference value (48V). (Even the load is suddenly changed the rise in voltage is very small).

CONCLUSIONS

The wind energy system is modelled using Matlab/Simulink software package and analysed for various input wind speed and load current. It was shown by the simulation results; as the wind speed varies the output voltage of PMSG also varies, the varying voltage is rectified into DC and is stepped down in a buck chopper controlled by fuzzy logic producing a controllable DC voltage irrespective of wind speeds. The proposed FLC is able to carry out a robust control against the variation of a wind speed and the load current. The DC voltage from the chopper can be injected to rechargeable battery to be charge or they can be inverted in an inverter to obtain an AC output of constant voltage and constant frequency.

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