Voltage Regulation of Stand-Alone Variable Speed Wind Energy System

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***Abstract* - This paper presents simple control of a variable speed stand-alone wind turbine with a permanent magnet synchronous generator (PMSG) to get constant voltage. The system consists of wind turbine, PMSG, un controlled rectifier and voltage source inverter using PI control. The parameters of PI control are calculated by using try and error method. The system is modified by using a switch mode rectifier and a voltage source inverter between the PMSG and a three phase loads. The loads that used are resistive, inductive and capacitive loads. By adjusting the parameters of a buck converter, we get a good result. Results have been done using PSIM/SIMULINK.**

***Index Terms* – stand-alone, wind turbine, PMSG, switch mode rectifier, voltage source inverter and controlled output voltage.**

I. INTRODUCTION

Nowadays, there are difficult problems in the world in using nonrenewable energy due to consumption of fossil fuel and environmental problems, so most countries stated to use renewable energy. Wind energy, is one of renewable energy sources, which is regular, clean and environmental.

Variable speed wind energy systems have several advantages such as yielding maximum output power, improving efficiency, developing low amount of mechanical stress and power quality compared with fixed speed systems [1]. Variable speed system use power electronics devices, where AC–DC converter is used to convert AC voltage with variable at the generator side to DC voltage at the DC-link voltage. The DC voltage is converted again to AC voltage at the load side of the system [2], [3].

The PMSG can be connected directly to the wind turbine, which results in a simple mechanical system. In the variable speed operation, there is a reduction of the drive train noise, reduction in mechanical stresses, and the increased energy capture [14].

There are two types of connection between PMSG and the load. The first is designed as back-to-back PWM converter [4], [5]; the second is a switch mode rectifier and an inverter [6], [7]. The system consists of wind turbine with PMSG connected to three phase loads through un controlled rectifier and voltage source inverter, and then it is modified by using a switch mode rectifier instead of un controlled rectifier to get constant voltage.

In this paper, the modeling and simulation of the system are executed using the PSIM software package.

II. DESCRIPTION AND MODLING OF THE SYSTEM

The system consists of a variable-speed wind turbine and PMSG connected to the loads through un controlled rectifier and voltage source inverter as shown in Fig. 1. A brief description of each element of the system is given below.

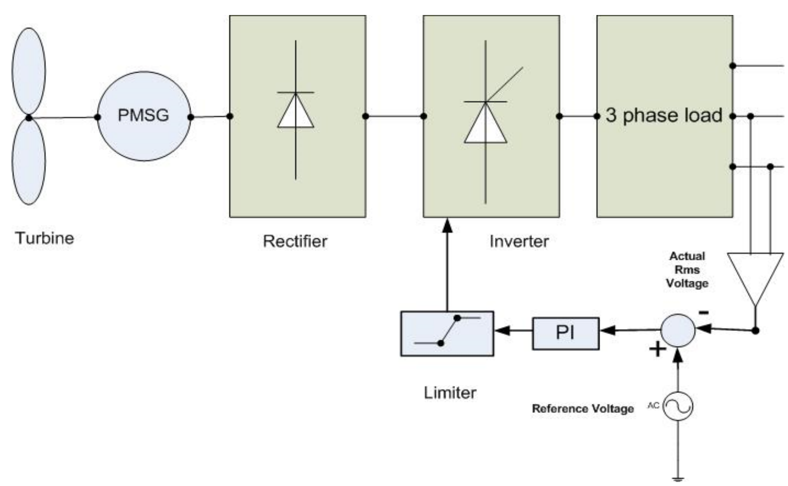

Figure 1. Modeling of the system using voltage source inverter.

A. Wind Turbine

The mechanical power of the wind turbine is given [8] by (1):

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$$Pm = 0.5CpAUw^3 \quad (1)$$

The tip speed ratio λ is given as

$$\lambda = \frac{R\omega_m}{Uw} \quad (2)$$

Where:

Cp is power coefficient,
β is blade angle,
A is area of wind turbine,
U_w is wind speed,
ρ is air density,
R is radius of the rotor and ω_m is the mechanical angular velocity.

In this study The Cp curve for the wind turbine using β =0 [9] is shown in Fig. 2.

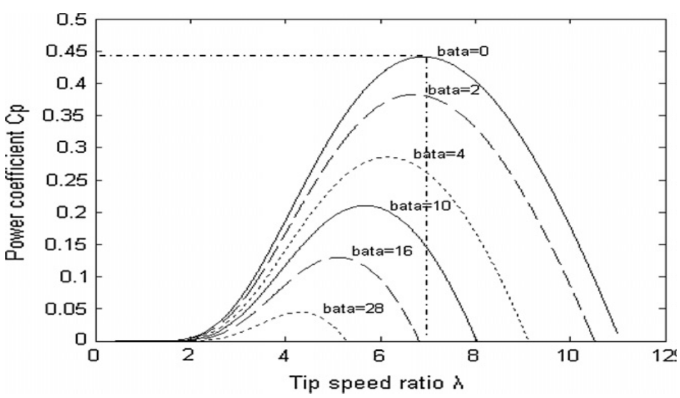

Figure 2. Power coefficient versus tip speed ratio.

B. PMSG Model

Theoretical models for generator producing power from a wind turbine have been developed [10].

$$\upsilon q = -Riq + Lq\frac{diq}{dt} - \omega eLdid + \omega e\lambda m \quad (3)$$

$$\upsilon d = -Rid + Ld\frac{did}{dt} + \omega eLqiq \quad (4)$$

Where:

R and L are the machine resistance and inductance per phase,
υq and υd are the two-axis machine voltages,
iq and id are the two-axis machine currents,
λm is the amplitude of the flux linkages established by the PMSG, and ω_e is the angular frequency.

The expression of electromagnetic torque is given [10] as:

$$Te = 1.5\frac{p}{2}[(Ld - Lq)iqid - \lambda miq] \quad (5)$$

The relationship between ω_e and ω_m is expressed as

$$\omega_e = \frac{p}{2}\omega_m \quad (6)$$

Where:

P is number of poles.

C. Three phase rectifier

Three phase rectifier is used to convert ac voltage from PMSG to dc voltage.

D. voltage source inverter

Voltage source inverter is used to supply three phase loads with constant voltage. In linear region (ma<=1), the fundamental frequency component in the output voltage varies linearly with the amplitude modulation ratio ma. Therefore, the line-to-line rms voltage can be written [12] as:

$$VL.L = 0.612m_aV_d \quad (7)$$

Where:

m_a is modulation index and V_d is input voltage of three phase inverter.

Control algorithm of the system depends on (7). From (7) output voltage depends on dc input voltage of inverter and modulation index. To get constant output voltage, PI control is used with inverter. PI control is designed to adjust modulation index m_a to get a good result.

III. DECRIPTION AND MODELING OF MODIFIED SYSTEM

The system is modified by using a single switch buck rectifier instead of un controlled rectifier as shown in Fig. 3. A brief description of each element of the system is given below.

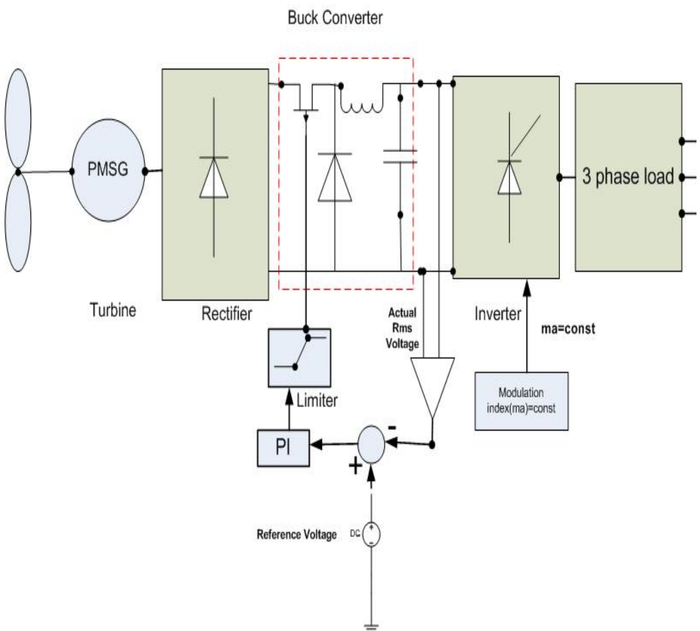

Figure 3. Modified modeling using a switch mode buck rectifier.

A. *Wind Turbine*

Modeling of wind turbine is shown at the beginning of the article.

B. *PMSG Model*

Modeling of PMSG also is shown at the beginning of the article.

C. *Un Controlled Rectifier and a Switch Mode Buck Converter*

PMSG connect with un controlled rectifier and a switch mode buck converter. Fig. 4 shows the equivalent circuit of buck converter. In continuous conduction mode of operation the mathematical equations of the buck converter are given as follows [11]:

$$\frac{V_o}{V_i} = D \tag{8}$$

$$\frac{I_o}{I_i} = \frac{1}{D} \tag{9}$$

Where:

V_i is the input voltage,
V_o is the output voltage,
I_o is the output current,
I_i is the input current and D is the duty cycle.

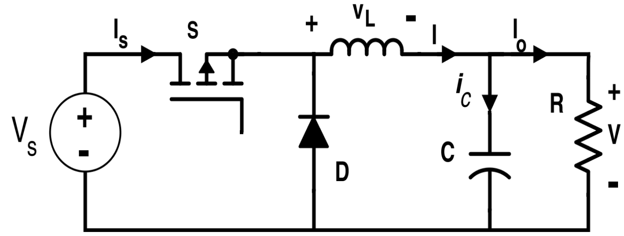

Figure 4. Equivalent circuit of buck converter.

D. *voltage source inverter*

Voltage source inverter is shown at the beginning of the article.

IV. CONTROL ALGORITHM OF MODIFIED SYSTEM

Fig. 3 shows the modified system where a switch mode buck converter is used. From (7) output voltage depends on input voltage of inverter and modulation index. Modulation index m_a is kept constant. Dc input voltage of inverter is kept constant to get constant output voltage by using buck converter. We compare input dc voltage of inverter with constant dc voltage. Error signal sends to PI control to get pulses to a switch of buck converter. Buck converter converts a higher input voltage into a lower output voltage. Design of buck converter depends on the values of the inductor and capacitor.

Value of the inductor required to ensure the converter operating in the continuous conduction mode is calculated from [13]:

$$L \geq \frac{V_i\, D\,(1 - D)}{F_s\, \Delta I_l} \tag{10}$$

The output capacitor value calculated to give the peak-to-peak output voltage ripple 0.1% is [13]:

$$C_o \geq \frac{V_i D\,(1 - D)}{8 L F_s^2 \Delta V_o} \tag{11}$$

Where:

V_i is input voltage,
D- is duty cycle,
F_s is switching frequency,
ΔI_l is peak-to-peak ripple of the inductor current and
ΔV_o is peak-to-peak ripple of the output voltage.

V. SIMULATION RESULTS

The simulink model of proposed system is shown in Fig. 5. The system consists of wind turbine, PMSG, un controlled rectifier and voltage source inverter that uses PI control to adjust constant output voltage. Fig. 6 shows wind speed change with time so the line voltage and power from PMSG are variable.

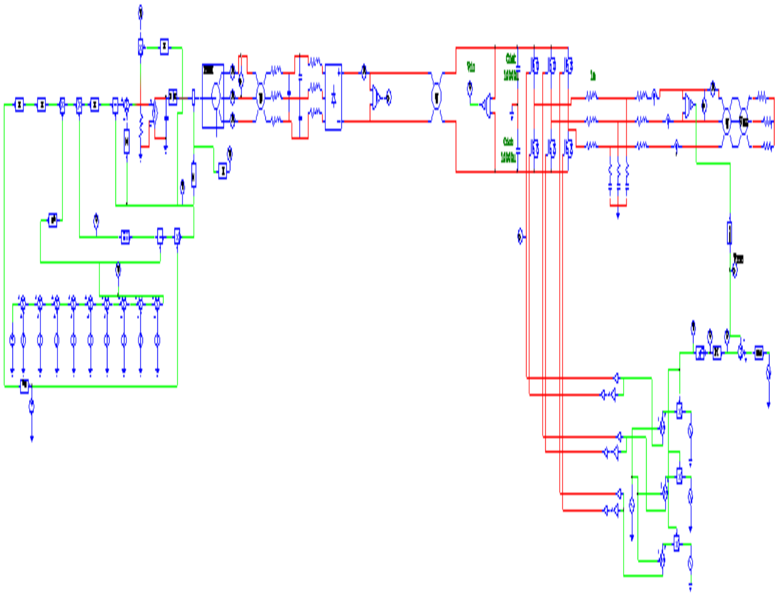

Figure 5. Simulink model of the system.

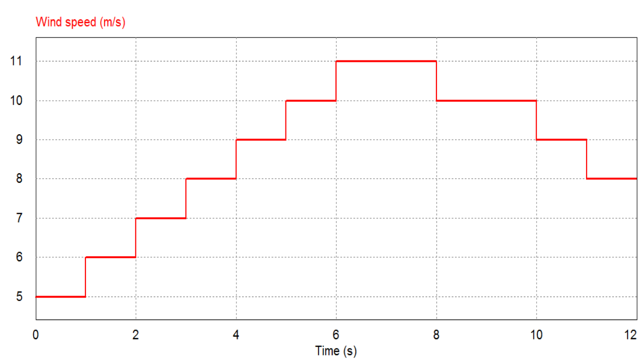

Figure 6. Wind speed change with time.

Figs.7 and 8 show the rms output voltage for resistive loads RL= 100Ω with different values of parameters of PI control. The waveform of Fig. 8 is better than Fig. 7 due to changing the parameters of PI control.

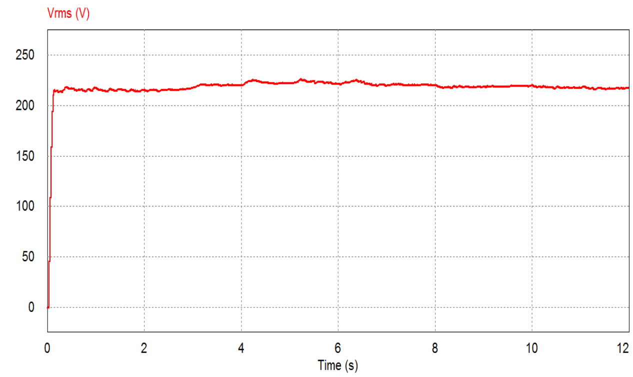

Figure 7. Rms output voltage with Kp=0.0001, Ki=0.003 For resistive loads.

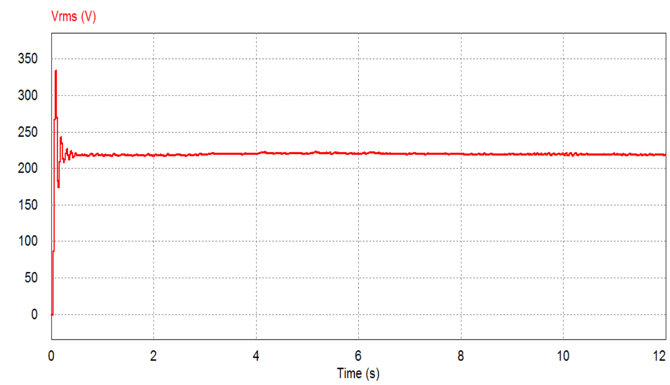

Figure 8. Rms output voltage with Kp=0.0001, Ki=0.001 For resistive loads.

Figs.9 and 10 show the rms output voltage for inductive loads RL= 100Ω, L=10 mH with different values of parameters of PI control. The waveform of Fig. 10 is better than Fig. 9 due to changing the parameters of PI control.

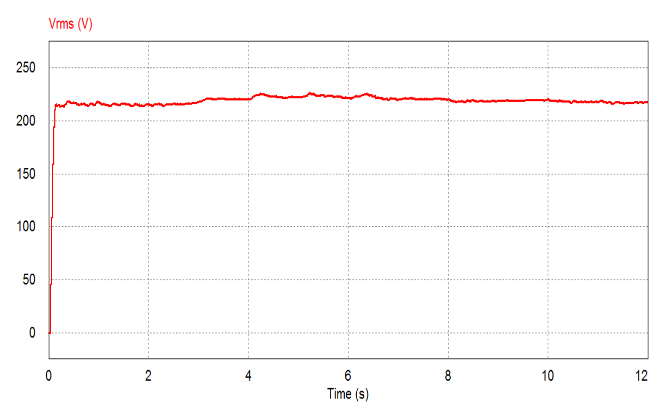

Figure 9. Rms output voltage with Kp=0.0001, Ki=0.003 For inductive loads.

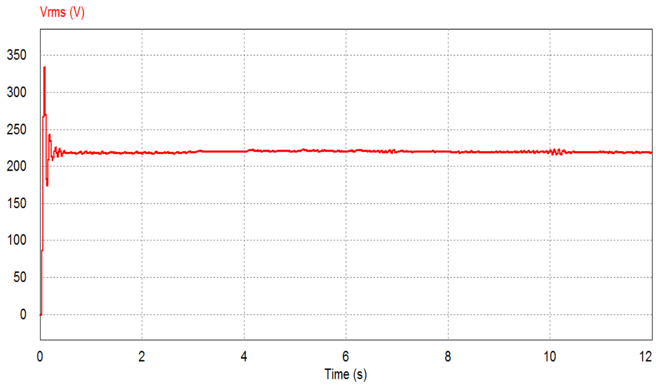

Figure 10. Rms output voltage with Kp=0.0001, Ki=0.001 For inductive loads

Figs.11 and 12 show the rms output voltage for capacitive loads RL= 100Ω, C=50 µF with different values of parameters of PI control. The waveform of Fig. 12 is better than Fig. 11 due to changing the parameters of PI control.

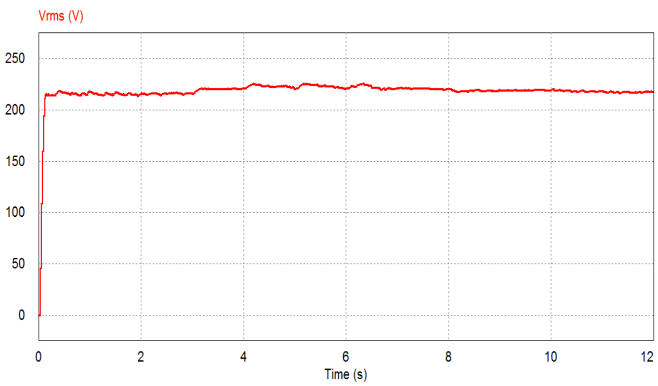

Figure 11. Rms output voltage with Kp=0.0001, Ki=0.003 For capacitive loads.

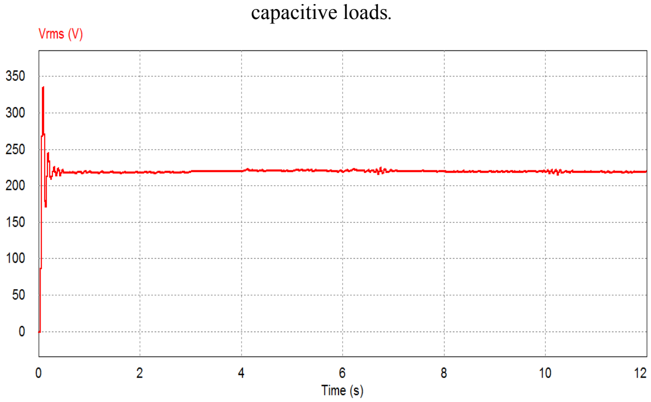

Figure 12. Rms output voltage with Kp=0.0001, Ki=0.001 For capacitive loads.

A modulation index ma change with time to achieve constant output voltage is shown in Fig. 13 where the value of ma is <= 1. Firing angles of inverter for resistive, inductive, capacitive loads respectively are shown in Figs.14, 15 and 16.

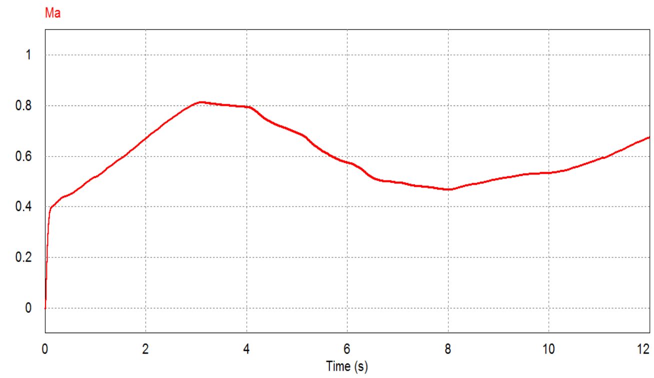

Fig. 13 Modulation index ma with time.

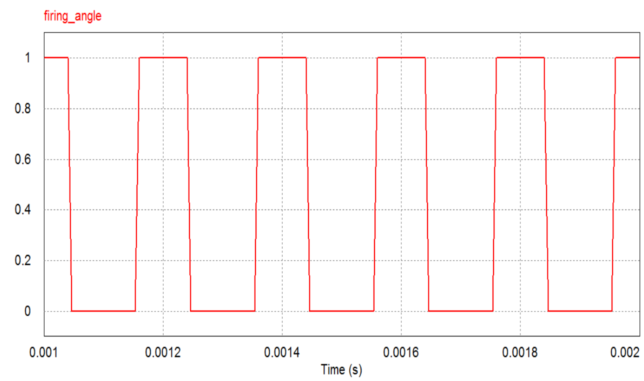

Figure 14. Firing angle of inverter with time for resistive loads.

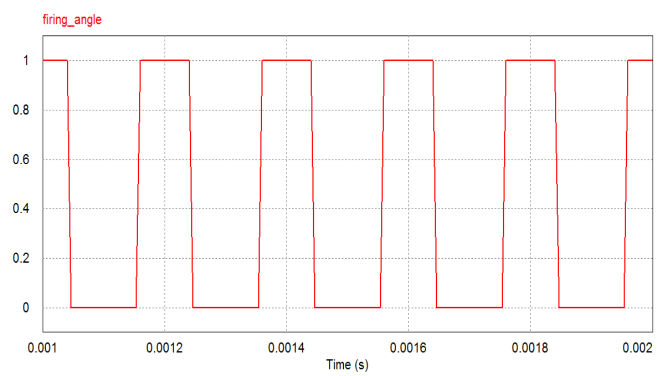

Figure 15. Firing angle of inverter with time for inductive loads.

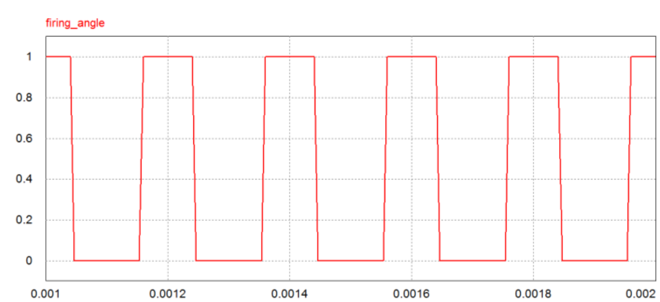

Figure 16. Firing angle of inverter with time for capacitive loads.

The modified system that used a switch mode buck rectifier is shown in Fig. 17.

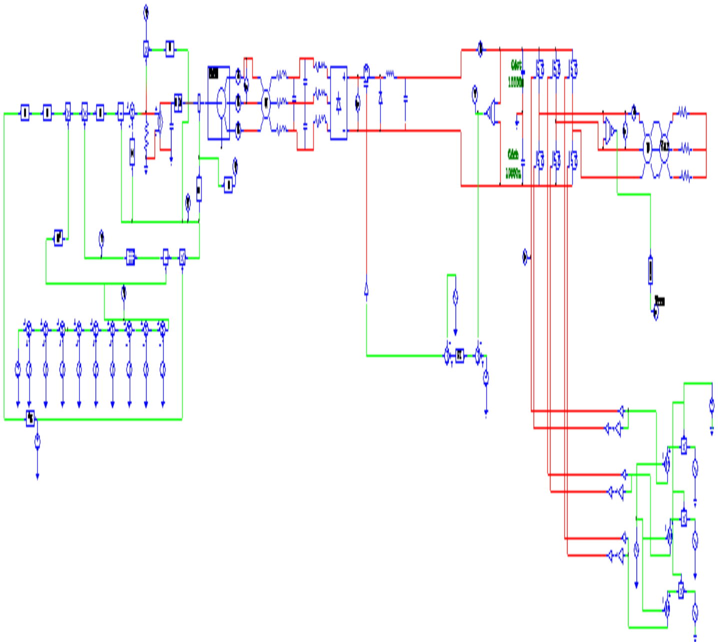

Figure 17. Simulink model of modified system.

Buck converter with PI control adjusts the dc output voltage constant which fed to the inverter. From (7) the rms output voltage of inverter is constant because modulation index m_a and input dc voltage of inverter are kept constant.

Figs. 18 and 19 show rms output voltage for resistive loads with changing the parameters of PI control. The parameters of PI with kp= 1, ki= 0.4 give a good result compare to kp=1, ki=0.1. Rms of output voltage for inductive and capacitive loads with kp = 1, ki =0.4 are shown in Figs.20 and 21 respectively. Disturbance occurs at small time, after that the Rms of output voltage is kept constant.

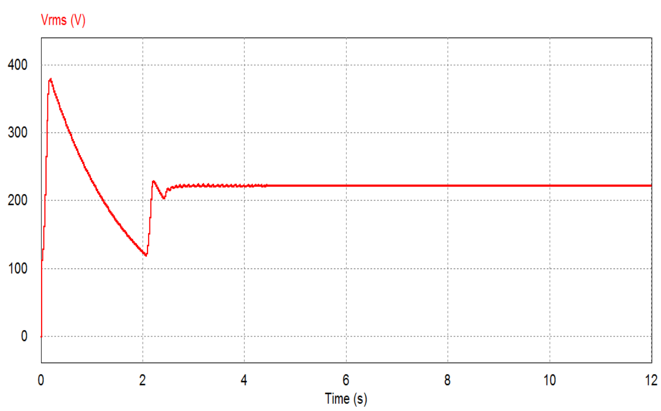

Figure 18. Rms output voltage with kp= 1, ki=0.1 For resistive loads.

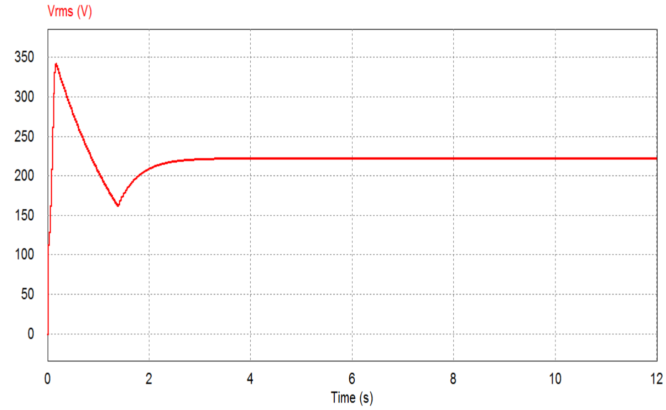

Figure 19. Rms output voltage with kp= 1, ki=0.4 For resistive loads.

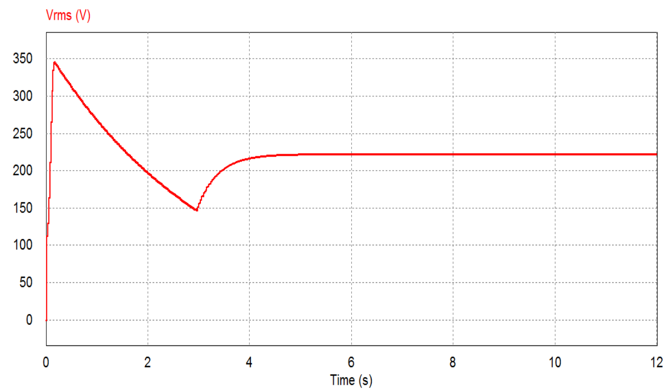

Figure 20. Rms output voltage with kp= 1, ki=0.4 For inductive loads.

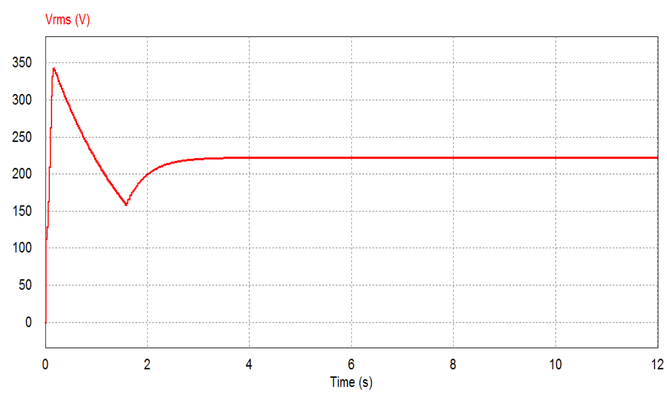

Figure 21. Rms output voltage with kp= 1, ki=0.4 For capacitive loads.

Fig.22 shows the response of rms output voltage of inverter for resistive loads when the parameters of buck converter and PI control change. The response is very bad compare to Figs.18 and 19.

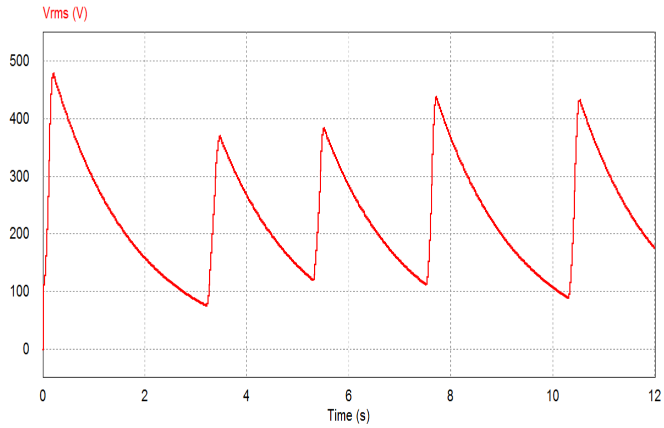

Figure 22. Rms output voltage with Kp=1, Ki=0.008 For resistive loads.

VI. CONCLUSIONS

This paper proposes an accurate model system in Fig. 1 consists of wind turbine, PMSG, un controlled rectifier and voltage source inverter. Wind speed changes with time to take its effects on rms output voltage. The performance of system is a very good by adjusting the parameters of PI control where the parameters of PI control kp=0.0001, ki=0.001 give a good result compare to kp=0.0001, ki=0.003. The loads are used in system resistive, inductive and capacitive loads. The parameters of PI control are calculated by using try and error method. A switch mode buck rectifier is used in modified modeling in Fig. 2. PI control and buck converter are designed to get constant dc output voltage which fed the inverter. From equation (7) Modulation index ma is kept constant to get rms output voltage constant. The parameters of PI control kp=1, ki= 0.4 give a good result compare to kp=1, ki=0.1. When we change the parameters of buck converter and PI control, the response of rms output voltage will be bad as shown in Fig.22.Finally control of modified system is simple comparing to first system.

APPENDIX

1) Permanent magnet synchronous generator:

L_d = 5.24 mH
L_q = 5.24 mH
R_s = 0.432Ω
N_p = 36 poles

2) Wind turbine

P_m = 20 KW
R = 5 m
V_w (rated speed) = 12 m/s
V_w (cut in speed) = 3 m/s

3) Buck converter

L = 1.6 H
$C_o = 5\ \mu F$
F_s = 50 KHz

VII. REFERENCES

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