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Modeling and performance analysis of a small scale direct driven PMSG based wind energy conversion systems

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Abstract

This paper proposes a small scale wind energy conversion system comprising a direct driven PMSG connected to the grid through a power electronic interface. The variable voltage variable frequency output from the wind generator is rectified, boosted and converted in to a fixed voltage fixed frequency output. The boost chopper maintains a constant DC at the inverter terminals. The modulation index of the inverter is adjusted to extract maximum power from the wind. The system components such as wind turbine, PMSG, power electronic interface are modeled in MATLAB/SIMULINK .The power flow analysis of the entire system is carried out for various wind velocities and the effect of duty ratio and modulation index is studied and optimum duty ratio for maximum power extraction at different wind speeds is found out and the simulation results are presented

Keywords: wind energy conversion systems, permanent magnet synchronous generator, direct drive.

1. Introduction

In the recent years, Wind energy conversion systems (WECS) have become a focal point in the research of renewable energy sources. This is due to the rapid advances in the size of wind generators as well as the development of power electronics and their applicability in wind energy extraction. The high installed capacity of today's wind turbines and decreasing plant costs have shown that wind power can be competitive with conventional, more heavily polluting fossil fuels in the long term. The higher target is to achieve 12% of the world's electricity from wind power by 2020[1].

. The induction generators are commonly used for low and medium power generations; in such generation schemes it is found that 25% of overall turbine downtime is due to gear box failures; further the gearbox requires frequent maintenance and it also increases the weight of the nacelle which in turn increases the cost [2].The above drawbacks can be overcome in the direct driven wind energy conversion systems (WECS) by replacing mechanical gearbox systems with power electronic converters[3].By eliminating the need for a gearbox between the turbine and generator, these systems are less expensive and also require less maintenance.

Nowadays Permanent Magnet Synchronous Generators (PMSG's) are more attractive for direct driven wind energy schemes [5], [7] because of its improved performance and decreasing cost. Further the PMSG has several advantages such as

- Higher efficiency and energy yield.
- Additional power supply is not needed for the magnet field excitation.
- Improvement in the thermal characteristics of the PM machine due to the absence of the field losses.
- Higher reliability due to the absence of mechanical components such as slip rings.

The voltage of the direct driven PMSG is variable due to the intermittent nature of the wind energy. Fluctuating voltage and power is of major concern in converter based grid connected wind generation systems. These variable speed generators necessitate AC-DC-AC conversion systems [4].

In this paper, a study of small-scale direct driven PMSG suitable for household and community level power generation is considered. A dynamic model of the wind energy conversion scheme is developed in MATLAB/SIMULINK. The effect of variation in the duty ratio of the chopper and the modulation index of the inverter on the power output of the generator are analyzed for different wind speeds. The grid integration of the Wind Generator and the study of Active power export and RKVAR requirement under various wind velocities are carried out. A reactive VAR compensator for the improvement of reactive power is designed and incorporated in the system

2. Modeling of system components

In the scheme shown in fig 1, the output of the generator varies with wind velocity and the maximum power occurs at a particular rotational speed for a given wind velocity. The optimum speed is achieved by varying the duty ratio of the chopper and the maximum power is fed to the grid at required voltage and frequency using an inverter.

2.1 Wind turbine model

The power, p_{wind} in the air flow is expressed as [8]

$P_{wind} = 1/2\rho\, av^3$ (1)

Where,

A = area swept by the blades [m^2]

P = air density [kg/m^2]

V = wind velocity [m/s]

The mechanical power captured by the wind turbine is

Written as

$P_t = 0.5\rho\, a\, c_p (\lambda, \beta)\, v^3$ (2)

The tip speed ratio is defined as

$\Lambda = \omega r * r/v$ (3)

Where,

R=rotor radius[m]

ωr = angular velocity [rad/s]

C_p=coefficient of power conversion

The power coefficient is a nonlinear function of the tip speed ratio λ and the blade pitch angle β (in degrees). If the swept area of the blade and the air density are constant, the value of c_p is a function of λ and it is maximum at the particular λ_{opt}. Hence, to fully utilize the wind energy, λ should be maintained at λ_{opt} , which is determined from the blade design. Then

$P_{turbine} = 0.5\rho\, A\, c_{pmax} v^3$ (4)

2.2 PMSG model

Dynamic modeling of PMSG can be described in d-q reference system as follows [9], [10],[11]:

$V_{g\,q} = -(R_g + p\, L_q)\, i_q - \omega_e L_d i_d + \omega_e \psi_f$ (5)

$V_{g\,d} = -(R_g + p\, L_d)\, i_d - \omega_e L_q i_q$ (6)

Where, R_g is the stator resistance, L_q and L_d are the inductances of the generator on the d and q axis, ψ_f is the permanent magnetic flux and ω_e is the electrical rotating speed of the generator, defined by ωr $\omega r = p_n \omega_m$ (7)

Where, p_n is the number of pole pairs of the generator and ωm is the mechanical angular speed. In order to complete the mathematical model of the PMSG, the expression for the electromagnetic torque can be described as [10]

$T_e = 3/2\, P_n[(L_d - L_q)\, i_d\, i_q - \psi_f\, i_q]$ (8)

If $i_d = 0$, the electromagnetic torque is expressed as:

$T_e = -\, 3/2\, p_n\, \psi_f\, i_q$ (9)

2.3 Power conditioning system

The overall function of the power conditioning system (PCS) is to convert the variable amplitude and variable frequency three-phase output voltage from the generator to a fixed amplitude and fixed frequency single-phase ac voltage. The power conditioning system used for connecting the individual WTG to the distribution grid requires the flexible, efficient and reliable generation of high quality electric power. The PCS consists of a diode bridge rectifier, a boost chopper and a single phase inverter. Figure 2 shows the circuit diagram of the power conditioning system

. The output from the PMSG is rectified using a three-phase rectifier whose output voltage Vrec is given by

Vrec =1.65Vm (10)

If ignore the losses of diodes, diode rectifier does not change the power. It only uses to convert AC to DC.

The output from the diode bridge rectifier is fed to the boost chopper. Figure 3 shows the circuit diagram of the boost converter used in the PCS. The standard unidirectional topologies of the DC-DC boost converter or chopper in Figure. 3.a consist of a switching-mode power device containing basically two semiconductor switches (a rectifier diode and a power transistor with its corresponding anti-parallel diode) and two energy storage devices (an inductor and a smoothing capacitor) for producing an output DC voltage at a level greater than its input DC voltage. This converter acts as an interface between the full-wave rectifier bridge and the Voltage Source Inverter, by employing pulse-width modulation (PWM) control techniques. Figure 3.b shows control diagram of the boost chopper.

The input to the boost converter is the variable DC voltage output from the PMSG / rectifier circuit. The boost converter controls its output voltage to a fixed dc voltage range as required by the inverter stage. Note that the input voltage used is dictated by the voltage range expected from the generator / rectifier circuit..The power generated by a wind turbine typically varies in Proportion to the cube of its rotational speed. Both the voltage vs. Speed characteristic of the Generator and power vs. Speed characteristic of the turbine are considered when specifying the component values in the boost converter circuit. The boost converter is widely used and has been designed to operate in continuous conduction mode, which results in a simple relationship between the input and output

Voltage:

$$V_{out} = V_{in}/(1\text{-duty ratio}) \quad (11)$$

This equation neglects the resistance of the inductor, and the small voltage drop across the diode and switch, but demonstrates the relationship between the duty ratio and output voltage as the input voltage varies.

The boost converter is also used to implement another important function ,the ability to track the maximum power operating point of the turbine in given wind conditions [12],[13]. This is achieved by adjusting the duty ratio of the boost converter using a perturbation .the effect of duty cycle for various input voltages is shown in the figure 4. From the figure the optimum duty ratio for various input voltages can be found out. The method is based on the observed system power output only with no external measurement of wind speed necessary. If the duty ratio adjustment leads to an increase in output power, then the duty ratio is again adjusted in the same direction (provided the output voltage remains within a pre-specified range). If it leads to a decrease in output power, the duty ratio is adjusted in the opposite direction. Stand alone systems will normally have the fixed dc bus rigidly fixed by the presence of batteries. However, grid connected systems will generally have no battery storage, thus the “fixed” dc bus can vary as the duty cycle is altered. The inverter circuit must compensate for this variation to ensure that the ac voltage output remains at a fixed amplitude and frequency.

Therefore the input to the inverter must be maintained constant irrespective of changes in the input voltage of the boost chopper. So a PI controller is incorporated with this boost chopper circuit to maintain its output constant by tuning it[6]. The values of proportional gain (k_p) and integral gain (k_i) used in the pi controller are:

K_p=0.01

K_i=1.

The constant output of the boost chopper is fed to a single phase Voltage Source Inverter (VSI). In a VSI the input source is a voltage which is stored in DC link capacitor. This inverter chops the input DC voltage and generates an AC voltage with desired magnitude and frequency with respect to pulse patterns and modulation techniques different current and voltage control techniques have been proposed to generate a high voltage high current rectangular waveform based on reference waveforms characteristics[15]

3. Simulation results and discussions

The performance of the proposed method was firstly evaluated by MATLAB/SIMULINK simulation. The wind turbine power characteristics are drawn for various wind velocities and it is found that at the wind velocity of 8 m/s maximum power is extracted by the wind turbine which is shown in figure 5.

Under rated conditions the output voltage , current and torque of the generator are recorded and shown in the figures 7 and 8. It is found that at the rated speed of 400rpm, the out put phase voltage of the generator is 99V , the output current is 15A.

3.1 Dynamic results

The dynamic results of the PCS at different output voltages of the generator are recorded and shown in figures 9, 10, 11. It is found that with the varying wind velocity the output voltage of the generator varies which in turn varies the output voltage of the rectifier,chopper and inverter. But the input voltage of the inverter must be maintained constant so as to send constant voltage to the grid, hence to maintain constant voltage at the input of the inverter a PI controller is incorporated in the boost chopper which maintains constant chopper output voltage irrespective of changes in wind velocity. The dynamic results of the PCS without PI controller and with PI controller are shown in figure 12 and figure 13, it is inferred from the waveform that the PI controller maintains constant chopper output tvoltage even if the wind velocity varies and hence ensures constant power flow to the grid irrespective of variations in wind velocity

3.2 Power flow analysis

The power flow analysis for the entire system is carried out and a switched capacitor compensator is designed for reactive power compensation, since most loads are inductive and consumes lagging reactive power, the compensation required is usually supplied by leading reactive power. The most common form of leading reactive power compensation is by connecting shunt capacitors to the line. The active and reactive power transport at various wind velocities is carried out and the results are presented in the figures 14 and figure 15.

1

2 4. Conclusion

In this paper the dynamic model of a grid connected direct driven PMSG based wind electric generator is presented. A power electronic interface comprising an AC-DC-AC converter is used to maintain the DC bus voltage constant for different wind velocities and to extract maximum power from the wind. The simulation results are presented for various wind velocities and the effect of variations in duty ratio of the chopper is investigated. The optimum duty ratio for various wind velocities is identified and the results are discussed. The power flow analysis for the entire system is carried out and a switched capacitor compensator is designed for the improvement of reactive power.

APPENDIX

Parameters of the turbine

PARAMETERS	RATINGS
Rated power	2KW
Rated wind speed	8m/s
Air density	1.2kg/m^3
No of blades	3
Blade diameter	2m
Gear ratio	1

3

4 Parameters of the generator:

PARAMETERS	RATINGS
Rated power	2KW
Rated speed	400rpm
No of poles	18
Rated voltage	99V
Rated current	15A

5

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Table 1

Supply voltage in volts	**Optimum duty ratio**	**Output voltage of chopper with PI controller**
70	0.6	300
80	0.45	300.7
90	0.35	300.4
100	0.3	300.8
110	0.25	300
120	0.2	300

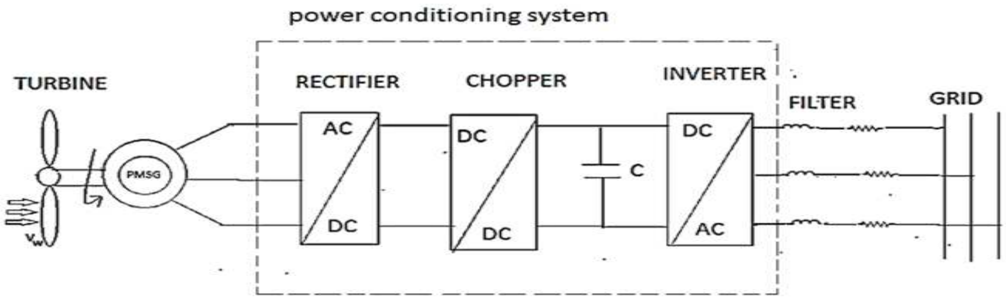


Figure.1. Wind turbine generator with grid

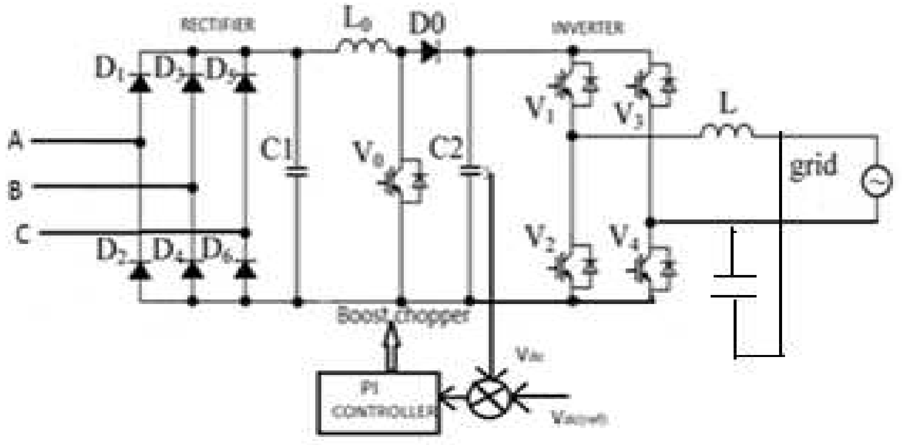


Figure.2.Circuit diagram of the power conditioning system

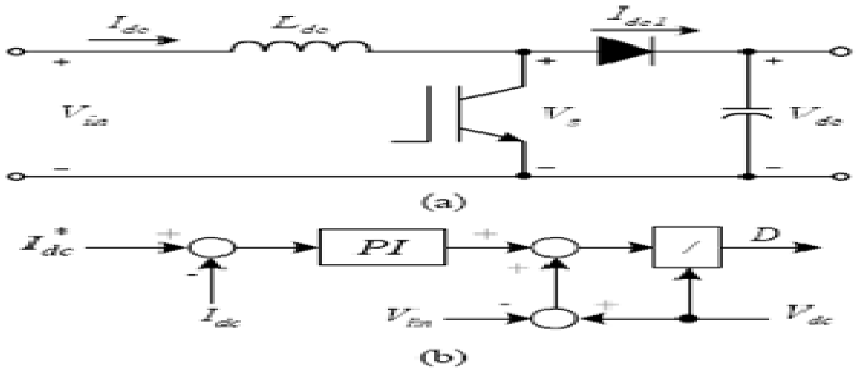


Figure.3.a. Switching-mode power device

Figure3.b Control diagram of the boost chopper.

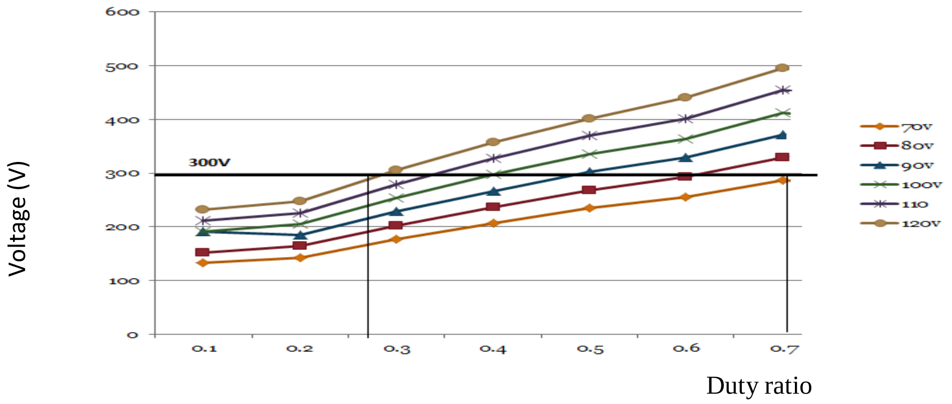


Figure.4.Effect of duty ratio and optimum duty ratio

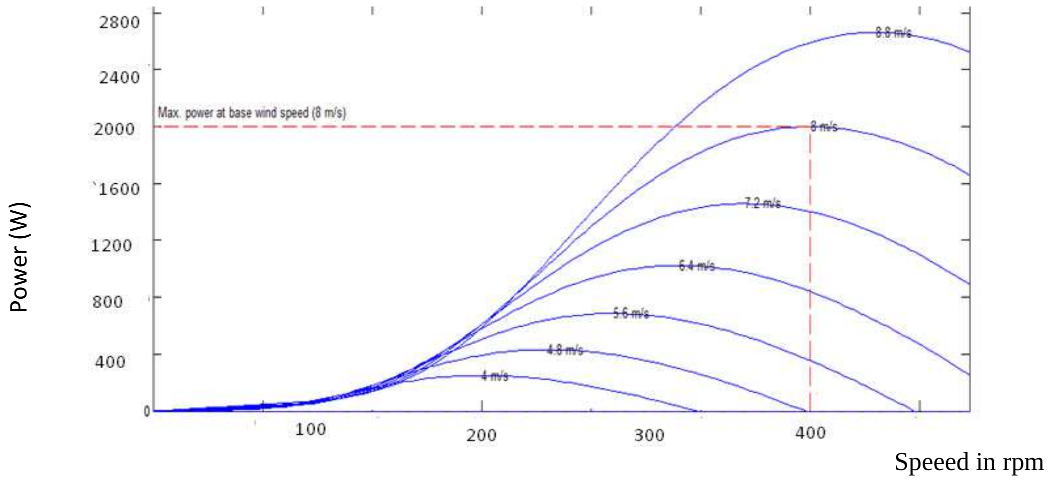


Figure.5.Power characteristics of the wind turbine

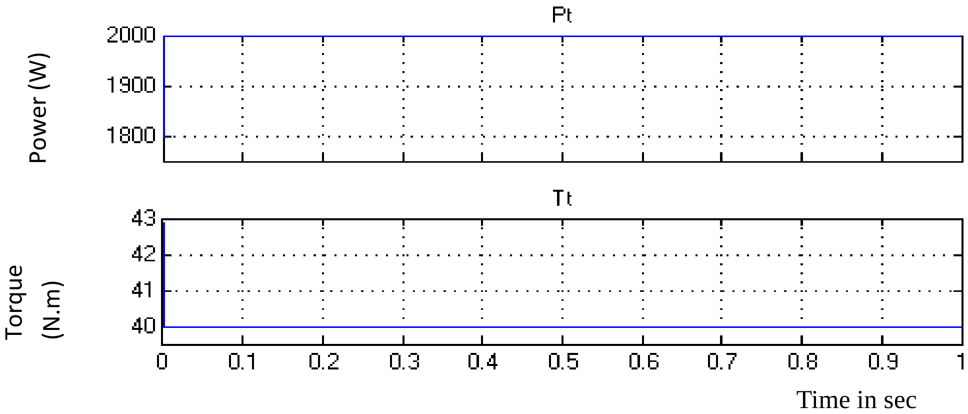


Figure.6. speed and torque of the generator at 400 rpm

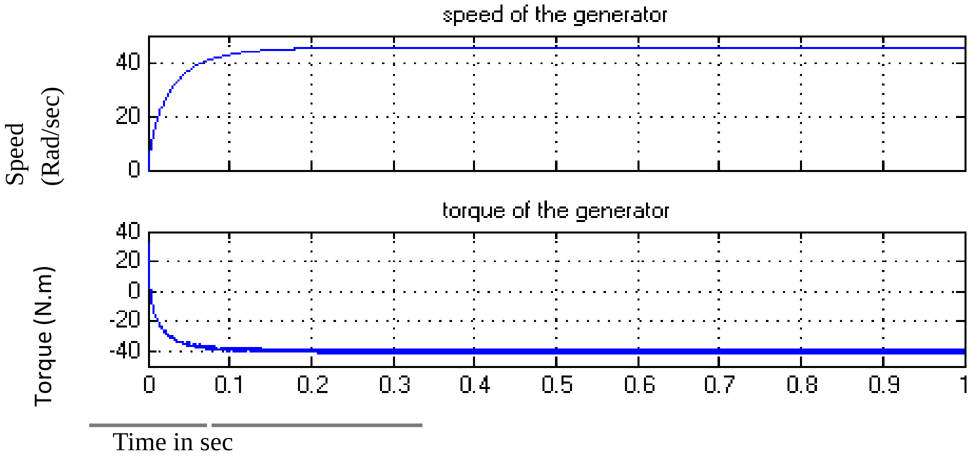
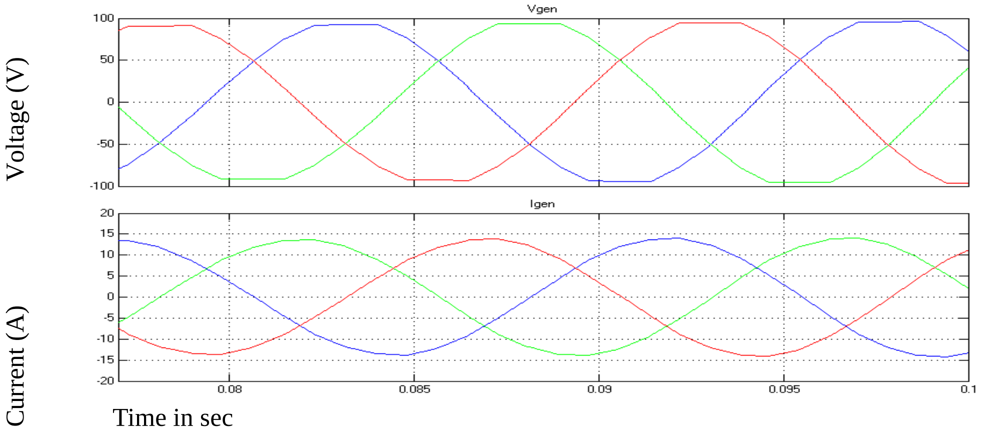
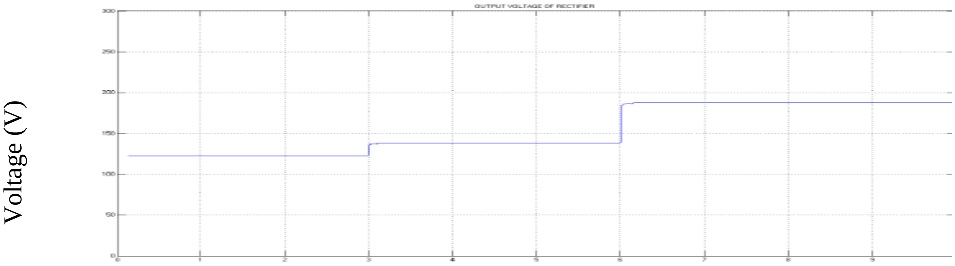


Figure.7. speed and torque of the generator at 400 rpm



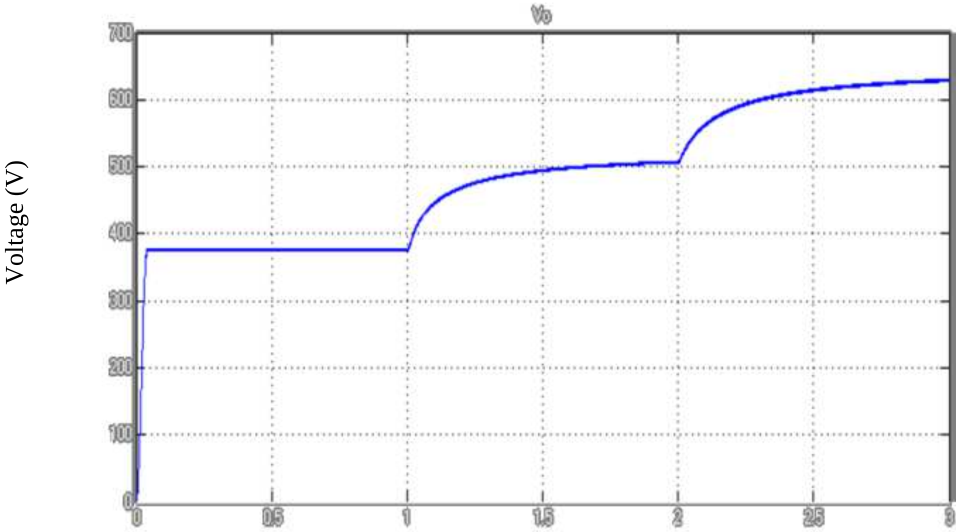
Time in sec

Figure.8. Output voltage and current of the generator at 400 rpm



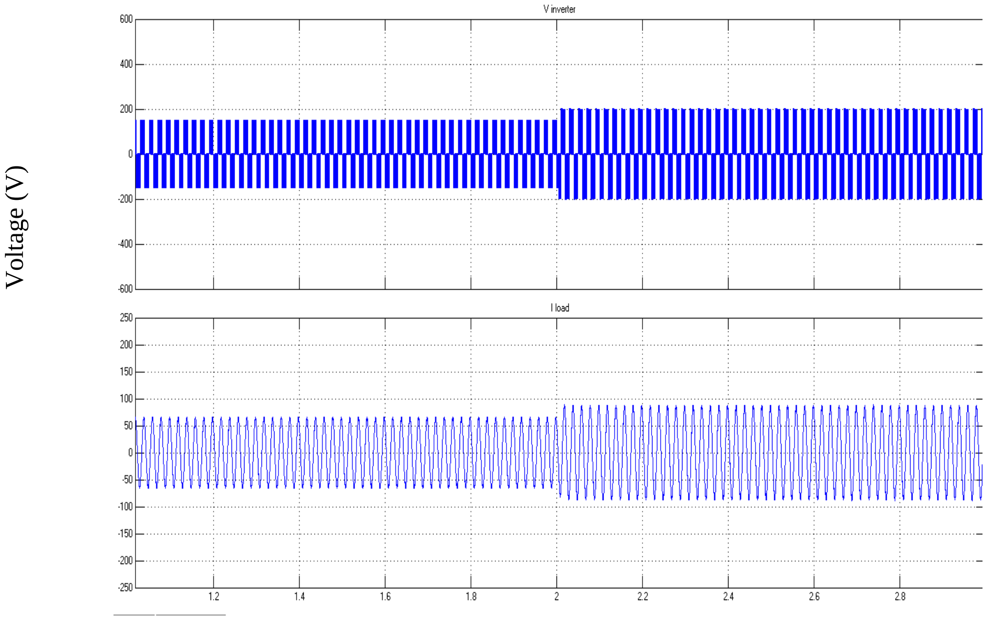
Time in sec

Figure.9. Output voltage of the rectifier for various generator voltages



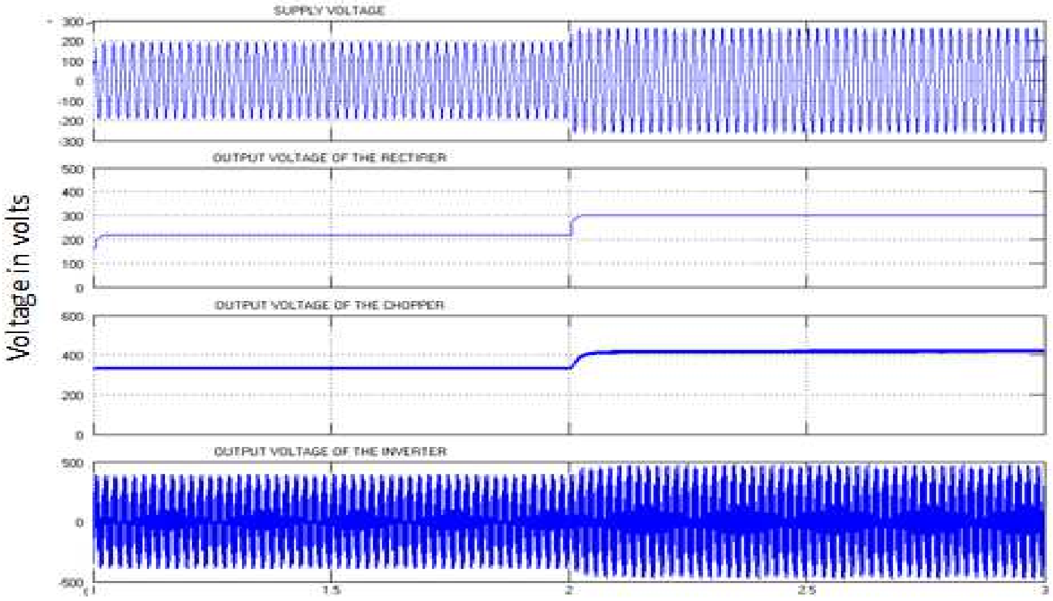
Time in sec

Figure.10. Output voltage of the chopper for various generator voltages



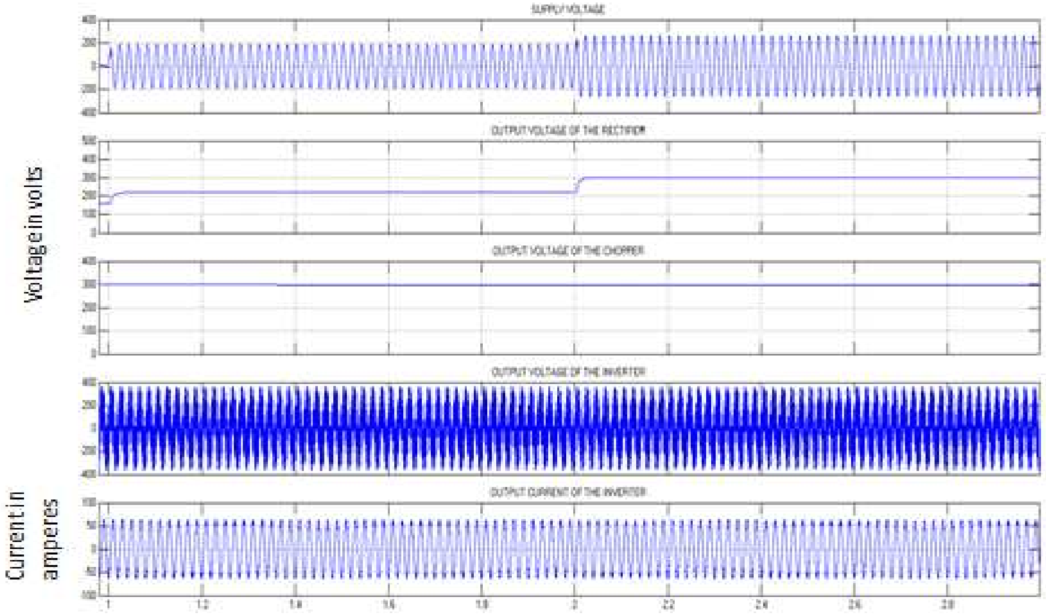
Time in sec

Figure.11. Output voltage of the inverter for various generator voltages



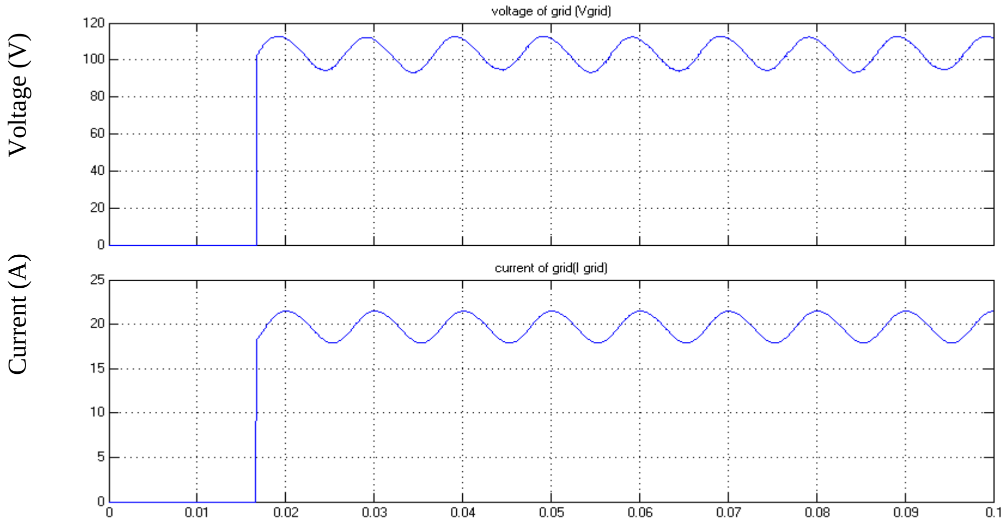
Time in sec

Figure 12.Output voltage of the rectifier; boost chopper and inverter for variations in the output voltage of the generator without PI controller



Time in sec

Figure 13.Output voltage of the rectifier, boost chopper and inverter and output current of the inverter for variations in the output voltage of the generator with PI controller



Time in sec

Figure 14.output voltage and current of the grid

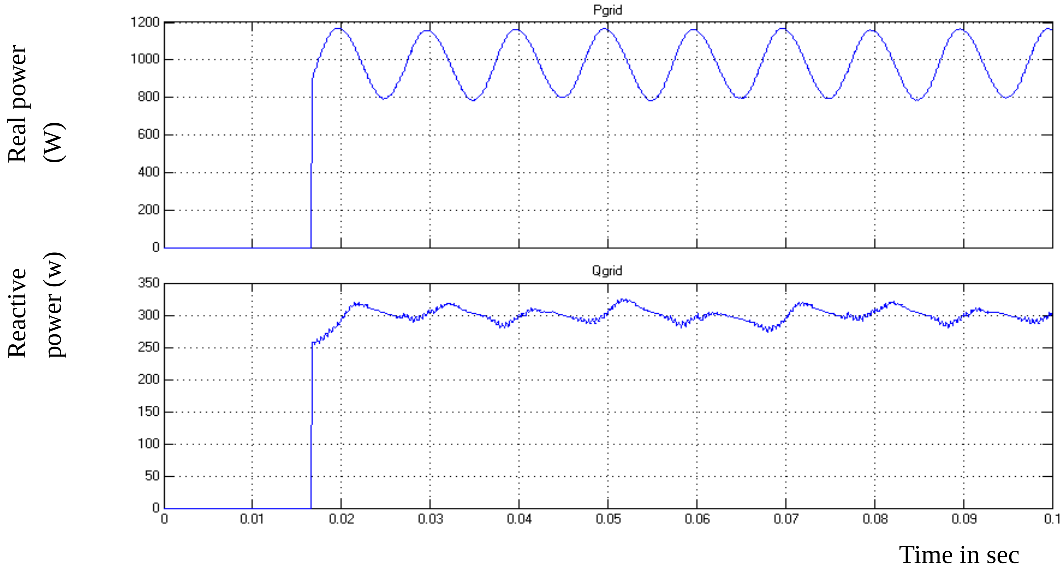


Figure 15. real and reative power of the grid with switched capacitor compensator

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