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PI-CCC Based Switched Reluctance Generator Applications for Wind Power Generation Using MATLAB/SIMULINK

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Abstract – This paper presents a novel nonlinear model of Switched Reluctance Generator (SRG) based on wind Energy Conversion system. Closed loop control with based Proportional Integrator current Chopping Control machine model is used. A Power converter in SRG can be controlled by using PI-CCC proposed model, and can be produced maximum power efficiency and minimize the ripple contents in the output of SRG. A second power converter namely PI based controlled PWM Inverter is used to interface the machine to the Grid. An effective control technique for the inverter, based on the pulse width modulation (PWM) scheme, has been developed to make the line voltage needs less power switching devices and each pair of turbine the generated active power starts increasing smoothly. This proposed control scheme feasibility and validity are simulated on SIMULINK/SIM POWER SYSTEMS only.

Keywords: Switched reluctance generator (SRG), Proportional integrator current chopping control (PI-CCC), Finite element analysis (FEA).

1. Introduction

Currently, due to the large global consumption of power, researches on renewable energy sources, like photovoltaic, wind power, Biomass and others are being conducted. Among all the renewable energy sources wind power presents the higher global growth in the last years.

Wind generators have been widely used both in autonomous systems for power supplying remote loads and in grid-connected applications. At present, many existing wind generators are Induction Generators, Double Fed Induction Generators (DFIG) or Permanent Magnet Synchronous Generators (PMSG). The speed of an Induction Generator is close to a constant value. Thus, the wind energy utilization factor cannot be maintained at the optimal value during wind speed variation. The DFIG can change its operating speed and has better utilization of wind energy. However, the structure of DFIG is complex and a gear box is required which results in reducing system reliability, Extra energy losses and more maintenance works. The variable speed of PMSG can be directly driven without gearbox, but its material cost is high and more efforts are required further to improve its performance, reliability and reduce its cost and size.

The Switched Reluctance Generator (SRG) offers a number of advantages compared to other type of generators, such as simple and robust machine structure, convenience of control, high efficiency in a wide speed range and high power density [1-3]. These features make it very suitable for the application of direct-driven wind turbines.

To analyze the operating performance of SRG, lots of modelling methods were presented. The circuit simulation program "SPICE", has certain limitations [4]. Reference [5] which uses object oriented program technique is very flexible, but it is difficult to actualize, because it needs the complete mathematical model of the system. It introduces some modules and M-file in MATLAB to build the nonlinear mathematical model of the magnetization curves, it is inaccurate, and the simulation speed is slow [6].

A novel method for nonlinear modelling based on circuit simulation is built by self defining M-functions and basic modules SIMULINK/simpowersystems library. The model built in this paper is very flexible and visual and also simulation speed is very fast but, the turn on and turn off angles is fixed [7].

The most efficient turn-off angles are a function of power level and speed that are discussed in FEA[8].A novel Simulation based on Four phase 8/6 PICCC closed loop control SRG model are reduces the torque output ripple and simulation speed high [9-10].

This paper presents a novel modeling of PI-CCC based on SRG with fixed pitch angle wind turbine interconnected with the Grid connected inverter system modelled simulation on SIMULINK/Sim Power Systems (PSB). In this simulation model of the wind turbine, SRG design of each phase model, Controlled PWM Inverter, and loads are simulated only through SIMULINK/Sim power system. The proposed model for producing maximum output power is obtained to control the output power. If there is any variation of wind speeds, the output performance of the SRG with PWM controlled inverter have the capability of

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Generating (or) absorbing reactive power and could be used to control the reactive power.

2. Nonlinear Mathematic Model of SRG.

In SRG, there are three types of inductance models such as linear model, quasi-square model and nonlinear model. In this paper to study the characteristics of SRG accurately, according to the nonlinear inductance model, a nonlinear SRG model is built based on the electromagnetic field finite-element analysis.

The dynamic mathematical model of SRG includes two basic equations, such as electromagnetic Eq. (1) and flux linkage Eq. (2) which are respectively as:

$$\pm V_K = Ri_k + \frac{d\psi_k(\theta, i_k)}{dt} \quad (1)$$

$$\psi_k(\theta, i_k) = L_k(\theta, i_k) \cdot i_k \quad (2)$$

Where Vk is terminal voltage of the winding, R is phase resistance, i_k is phase current, ψ_k is phase flux linkage, L_k is phase inductance, θ is position angle of the rotor. The sign before V_k is determined by the operating mode of the system is excited, the sign is plus, when the system is working as a generator and the sign is minus.

3. Wind Turbine Power Characteristics

The tip speed ratio λ is defined as:

$$\lambda = \frac{\omega R}{v} \quad (3)$$

Where, ω, R and V represent turbine rotational speed, Turbine blade radius and the wind velocity respectively.

In general, the power captured from the wind turbine can be written as:

$$P_m = C_p(\lambda, \beta)\rho \frac{A}{2} v^3 \quad (4)$$

Where *Cp* (λ, b) is the power coefficient, ρ is the air density, *V* is the wind speed, *R* is the blade radius, β is the blade pitch angle and λ is the tip speed ratio. The power curve speeds of a typical wind turbine are shown in "Fig. 1". The value of maximum wind turbine output power per unit can be obtained by putting zero pitch angle and Betz limit, when the velocity of wind turbine is 12 m /s.

From the above figure maximum power can be obtained at 12 m/s only in the generator. It is not suitable for real time application. In this proposed paper, maximum power can be captured in different wind turbine speeds.

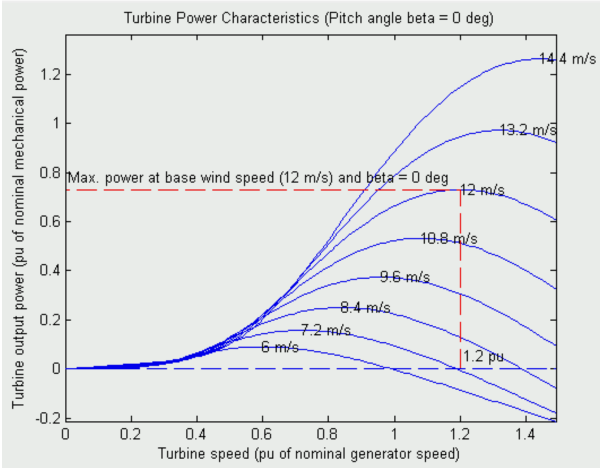

Fig. 1. Turbine Output Characteristics(Zero Pitch angle)

4.1 Nonlinear simulation model Of SRG

In order to simplify the simulation process, in this paper four assumptions are introduced as follows:

* Parameters of each phase in SRG are symmetrical.
* Ignore mutual inductance and leak inductance.
* Ignore hysterics and eddy effect.
* The exciting source is constant.

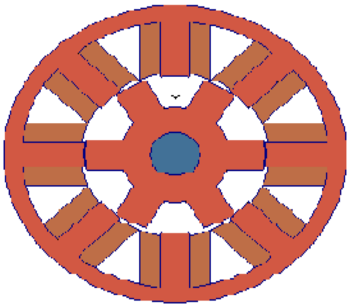

Fig. 2. implified diagram of SRM's structure

4.2 Nonlinear model of inductance

"Fig. 2", shows that order of analyzing the SRG by MAGNET software, the geometrical model of the machine should be plotted at first and appropriate materials are assigned to different regions respectively, "Fig. 3" and "Fig. 4". Show that align and unaligned position of the SRG. A nonlinear SRG model is built and is based on the electromagnetic field's finite-element analysis.

To simulate the dynamic performance accurately, the relational expression of inductance position angular of rotor and phase current must be described exactly.

$$L_K(\theta, i) = L_0(i) + L_1(i) * (\cos(N_r\theta) + \pi) \quad (5)$$

$$L_o(i) = \frac{L_{\max}(i) + L_{\min}(i)}{2} \quad (6)$$

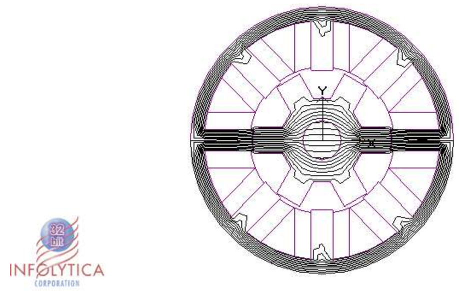

Fig. 3. Distribution of flux lines in the aligned position.

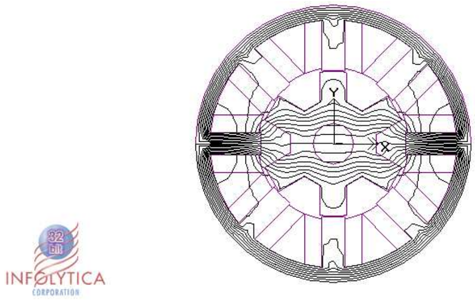

Fig. 4. Distribution of flux lines in the unaligned position.

$$L_1(i) = \frac{L_{max}(i) - L_{min}(i)}{2} \quad (7)$$

Where $L_{max}(i)$ is aligned position of and inductance, $L_{min}(i)$ is the unaligned position of inductance. L_k is phase inductance can be obtained through experiments of electromagnetic field finite-analysis(FEA).$L_{max}(i)$ can be also expressed as a polynomial function with respect to the phase current(i) which can also be obtained by curve fitting "Fig. 5",

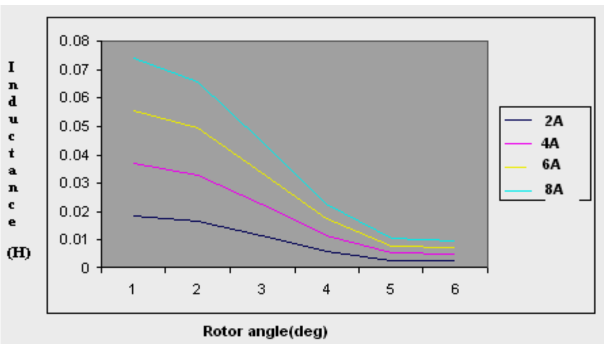

Fig. 5. Relationship between inductance, turn angle of rotor and phase current.

$$L_{max}(i) = 0.136 - 0.0045i + 0.0056i^2 - 0.0022i^3 + 0.00035i^4 \quad (8)$$

The Eq. (8) is obtained from fig no.5.The The Eq. (5) is obtained by subsuiting the value of $L_o(i)$ &$L_1(i)$. The value of θ is fixed in Eq. (5). Inductance is a function of rotor angles for different current ratings in SRG input.

4.3 Model of each phase

The parameters of each phase are symmetrical. The L_k by Eq. (5) and the $L_{max}(i)$ is obtained from Fig. 5 using FEM analysis is applied in motor windings in Fig. 6. This explains the detailed structure of the nonlinear machine modeling.

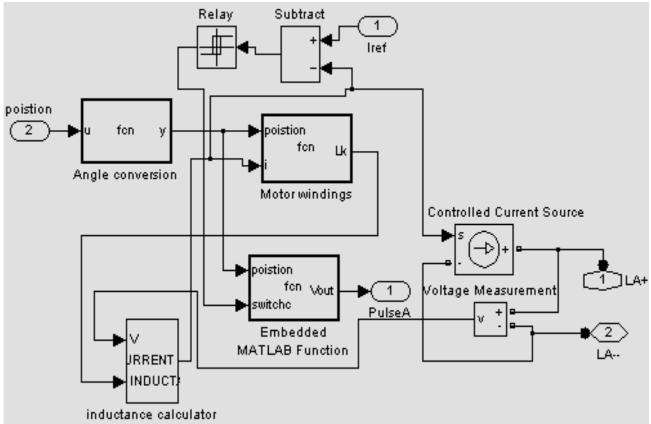

Fig. 6. The simulation model of Phase A

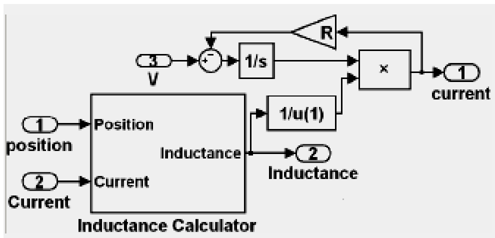

Fig. 7. Inductance Calculator

The detailed view of L_k block is shown in above Figure. The Eqs. (5-8) are applied inEmbedded block using SIMULINK.

4.4 Proposed PI-CCC control method

The control objective of controller is creating high performance control and commanding to maintain the output voltage of the system. Accordingly, there are three typical control strategies such as Angle position Control (APC), Current Chopping Control (CCC) and Pulse Width Modulation (PWM) in SRM.

The performance of the system is very sensitive to the turn-off angle, and so the implement of APC has certain difficulties. In PWM, there are two modes: Two switches chopping (TSC) and Single Switches Chopping (SSC). The SSC mode has higher efficiency and small vibration than TSC mode. The efficiency of system reduces slightly, when high switch frequency increases in loss of converter. In

Current Chopping Control (CCC) phase current is uncontrollable during the region of generating.

In this proposed PI-CCC method has two closed loops: outer voltage control(VC) and inner current closed loop(CC).In the former control method, the V_{OUT} is given as input to the PI Controller in Fig 8. The output current of PI controller is I_{ref}.

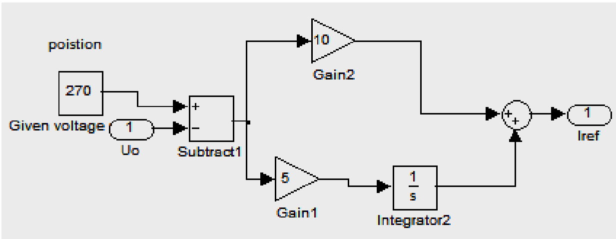

Fig. 8. The Simulation Model of Outer Voltage Controller

Feedback can be taken from motor windings input and combine with I_{ref} and fed into Relay block. The output of the relay block is the input to the motor windings. Current chopping process is taking place using Relay block. Finally it appears as a pulse to switch.

Table 1. Provides the parameters used in the voltage and power controller.

Quantity	Value	Units
K_P(Power)	0.033	°/W(electrical)
K_i(Power)	1.899	°/Jelectrical)
Θ_{cond}	178	°(electrical)
K_1	7.41e-7	°sW(electrical)
K_2	5.55e-4	°s(electrical)
K_3	4.44e-3	°/W(electrical)
K_4	31.33	°(electrical)
K_P(Voltage)	140.65	W/V
Ki(Voltage)	1620.80	W/Vs
C	1600e-6	Farad

The optimum turn-off angles can be represented as

$$\theta_{off} = k_1 \omega p + k_2 \omega + k_3 p + k_4 \quad (9)$$

Where, ω is rotor speed is the output power and $k_1, k_2, k_3 k_4$ are crve fit parameters. For our simulation work the curve fit parameters are based on a least squares fit to the collection of optimal turn off angles overall operation points above base speed. The curve fit parameters are based on the optimized data for four operating points representing all combinations of low speed, high speed, low power and high power in ref [14]. The turn on and turn off angles are the two parameters through which we can control the electric power generation.

$$\theta_{ON} = \theta_{OFF} - \theta_{COND} \quad (10)$$

$$V_O = fcn(\theta_{on}, \theta_{off}) \quad (11)$$

In this proposed method, the value of θ_{OFF} inn variable one,but in previous literature, θ_{OFF} value is fixed one.From Eq. (10) θ_{cond} is fixed value.The value of V_o is easily found.

The closed loop power control can then provide the turn-on angle.Since the turn-off angle is optimum for a given speed and power,the turn-off angle is being an outputby the power controller which is maintained while enforcing optimal efficency.

4.5 Exciting circuit and loads

"Fig. 9", shows the PSB model of exciting source and loads. Two capacitances (C1, C2) are connected in parallel and an inductance is connected in series with the output ports of the power inverter. They compose a filter in system's output. DC is direct current exciting source which supplies the original exciting current to the windings. The Diode module over DC is used to prevent the current of SRG from returning to DC.

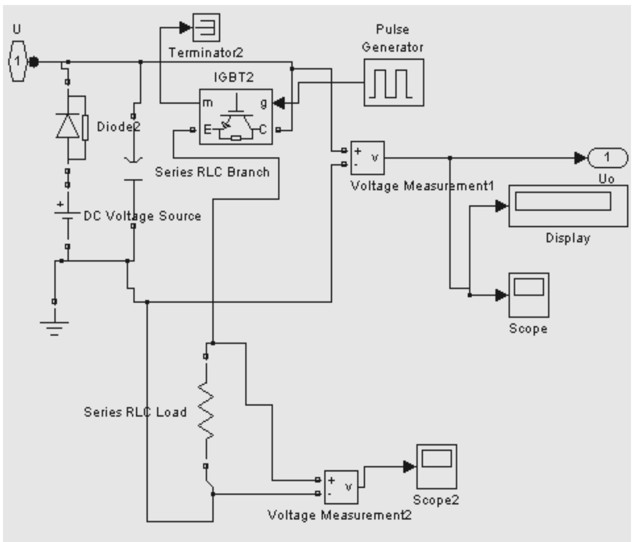

Fig. 9. PSB simulation model of exciting source and loads

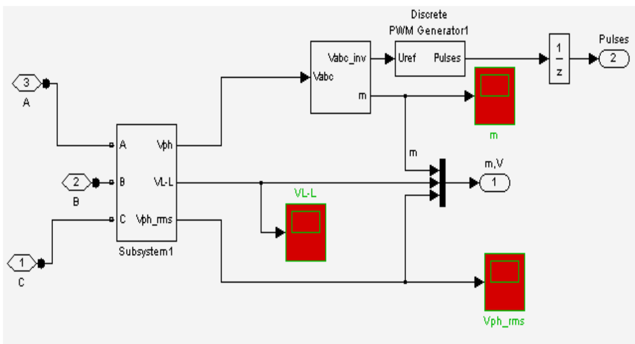

Fig.10. Simulation model of Control Circuit

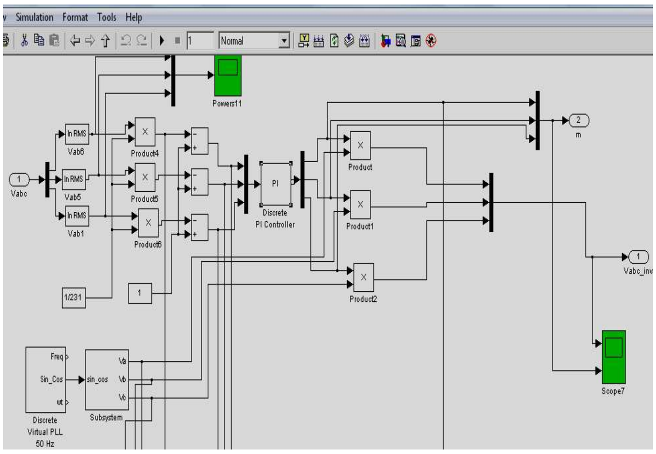

Fig.10. Simulation of PI-PWM Controller

4.6 DC to DC (CCM Mode)

The simulation process of CCM converter is relatively simple.The simulation process of DCM converters is not so quite as direct as that of CCM converters.In DCM,the inductor currrent must be extinguished before the start of the subsequent switching period.Consequently,to simulate the effect of the Diode in the circuit ,any computed negative values of current must be replaced by zero in off time intervel.

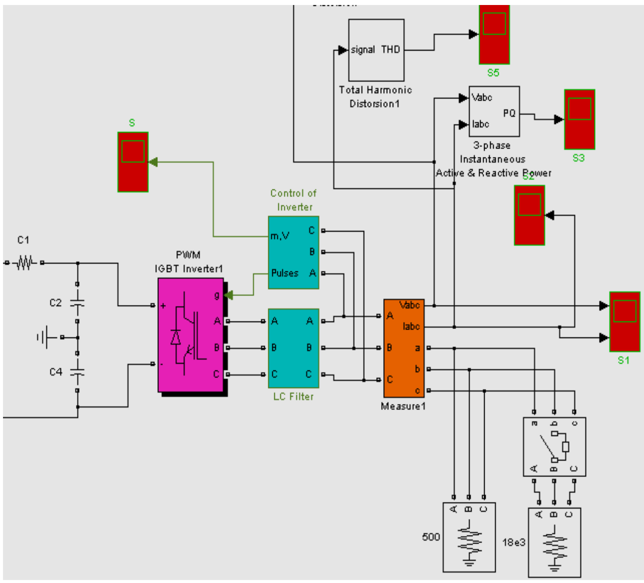

Fig. 11. Simulation model of Controllable Inverter with Load.

4.7 DC to AC with filters

An Inverter is used to generate AC Voltage from a DC source. If AC load is purely resistive, the actual wave form produced at the secondary will not be critical A capacitor is sometimes added across the secondary winding to attempt a smooth voltage and to render more sinusoidal shape. In this case it is more complicated but essential PWM Inverter is employed to provide voltag5e regulation, sinusoidal shape and output voltage control and this is shown in 'Figs. 10-12'.

The wind turbine model and the SRG model is built from the SIMULINK library. The SRG used in this model is configured as a four phase 8/4 machine in 12V DC supply and diode are used to excite the SRG. A 1000 Ohms resistor is connected to the bus as a fixed load in "Fig.13".The 12V Renewable Energy Application, 12V Battery and load resistors are connected in parallel to the Inverter.

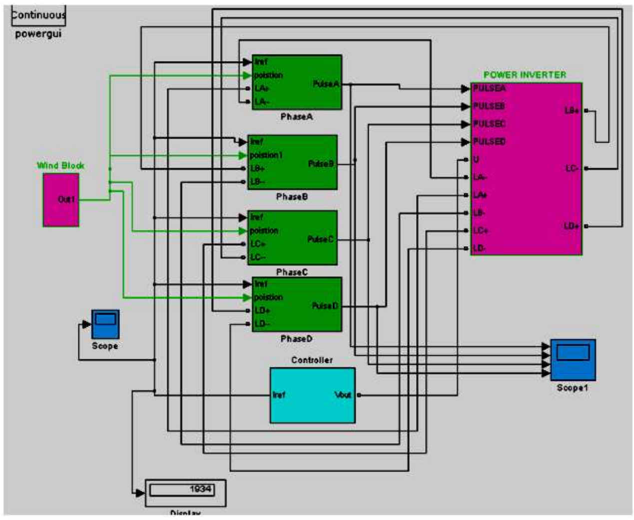

Fig. 12. Complete Simulation Model of SRG with Wind Turbine

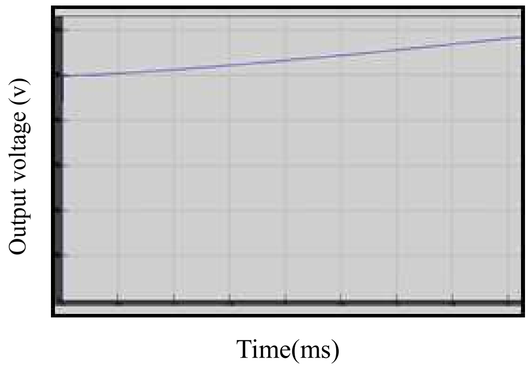

Fig.13.D.C link output voltage of SRG with no load

5. Nonlinear Simulation Results

"Figs. 14, 15", shows the output voltage response of SRG with no load and fluctuation of the voltage. The voltage will stabilize at 302 V after 0.05 second. The ripples of the voltage are very small. The output voltage can be stabilized at 304V after a short regulating period.

The current in stator phase is controlled by four independent hysteresis controllers. The hysteretic control results, however, in variable frequency operation of semiconductor switches. Generally, a constant frequency is preferred in power electronic circuits for easier elimination of electromagnetic interference. It is preferred and better for utilization of magnetic components.

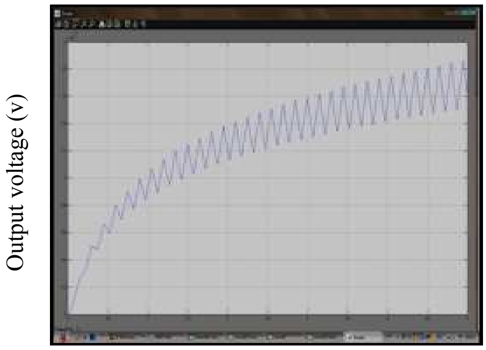

Fig.14. Fluctuation of the output voltage

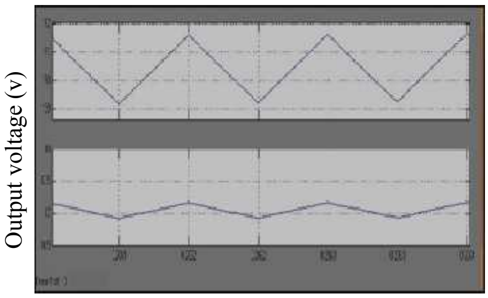

Fig. 15. D.C to D.C without Ripple Voltage

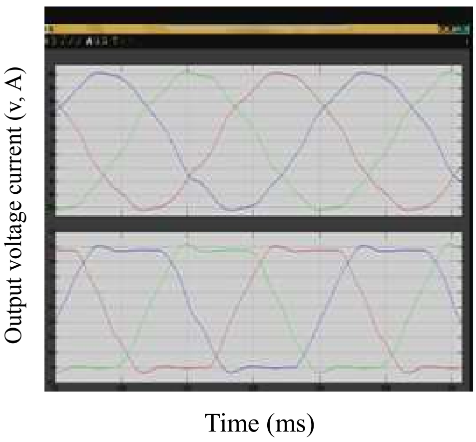

Fig. 16. Three Phase Controlled AC output Voltage and Current

The SRG operation depends much on the combination of turn on and turns off angles, because these parameters have stored influence on the current waveform**.** In practices many larger capacitances are used significantly to reduce the ripple. Simulation results of the proposed system indicate that the WG output power increased from 10% to 40%, when compared to the case where the WG is directly connected to a rectifier bank.

If any ripple in the output of SRG, it can be eliminated by buck converter. The output of the buck converter may be pure DC voltage. Fig.16. shows the simulation result of DC link voltage that remains a constant value. Thus, it proves the effectiveness of the established regulators. Fig.17 shows the variation and a closer observation of three phase current and voltage of GRID. The frequency imposed by the grid is 50 Hz. It's obvious that unity power factor is achieved approximately. This DC voltage as input to a controlled PWM Inverter, the output could be obtained from inverter is pure three phase sinusoidal voltage.

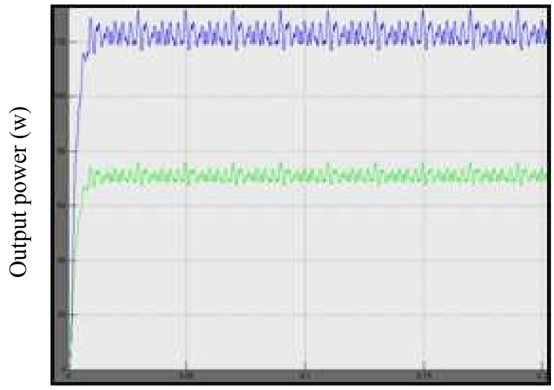

Fig. 17. Active and reactive power

Controllable PWM Inverter have the capability of generating or absorbing reactive power and could be used to control the reactive power of the voltage at the load. The simulation results demonstrate that the power control shows very good dynamic and steady state performance and works very well in this Fig. 18, 19.

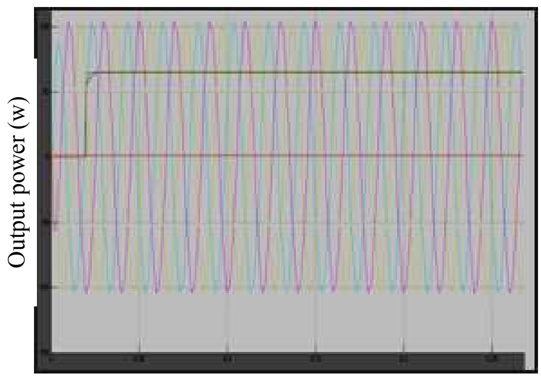

Fig. 18. Three phase voltage and reactive power

Though wind speed is different at m/sec, the Resistive load changes and again the voltage remains constant. The overall system and control is simulated with the SRG model based on MATLAB/SIMULINK. The results of these tests show that the new control simulink model provides an efficient SRG controller that is easy to implement wind energy conversion system. The proposed method results in a better exploitation of the available wind energy, especially in the low wind speed range, the power production of the battery converter configuration is relatively low. In addition, using PI-CCC method, the Controlled PWM Inverter is controlled to maintain the DC-bus voltage and regulate the grid-side power factor. Thus, the WECS with the SRG can maintain the frequency and amplitude of the output voltage with unity power factor. Finally, simulation results show clearly that the proposed PI-CCC controllers are quite efficient for the WECS and demonstrated the effectiveness and applicability of the proposed system. According to the above simulation results, it is obvious that SRG with Wind Turbine system has better dynamic and static performances with PI-CCC.

6. Conclusion

This paper proposes a PI-CCC based Switched Reluctance Generator based wind turbine system for maximizing the output power. A model of SRG has built using MATLAB/SIMULINK Software. The Generator performance, including output power, without torque ripple are simulated in terms of turn on and turn off angles for different wind speeds while the DC bus voltage is maintained of a constant value. The current in the SRG phase are limited to a maximum admissible value. The proposed model by this paper can be used to analyze the variations of different load status

7. Appendix

Values of parameters used in modeling and simulation.

N_r=6, L_{min}=0.01H, $V_{exciting}$=250v, R_L=1000Ω, $\theta_{original}$=10°, K_p=10, K_i=5.β=0.

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