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Design and Simulation of Dual Inverter Based Energy Storage Systems for Wind Energy Systems Using MATLAB/SIMULINK

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ABSTRACT:
This paper proposes the design and simulation of dual inverter based Energy Storage Systems(ESS) for wind energy systems. A dual inverter consists of MAIN inverter which is connected to grid side and an auxiliary inverter for which an energy storage system is interfaced. Typical grid connected wind energy systems includes wind turbine, PMSG, DC-DC converters, three phase dual inverter ,energy storage system and related power electronic devices. The detailed model of design and simulation of dual inverter based Wind energy system starts with wind turbine coupled PMSG which is connected to three phase diode rectifier and Boost converter which in-turn connected to a dual inverter which is used to deliver the wind energy to grid and also to store the energy in energy storage systems during surplus periods. Also Short term power fluctuations are mitigated and harmonics are reduced. Maximum Power point Tracking (MPPT) method, Energy storage system interfacing is also studied. The overall system model is designed and simulated by using MATLAB/SIMULINK.
KEYWORDS: *Dual inverter, Energy storage system, MPPT, PMSG, Wind turbine, MATLAB/SIMULINK*

I Introduction

Due to the cost increase, limited reserves, and adverse environmental impact of fossil fuels renewable energy sources have been attracting great attention. Among them, wind energy is one of the fastest growing renewable energy sources. Wind energy has gained an increasing worldwide interest due to the continuous increase in fuel cost and the need to have a clean source of energy. Wind is naturally occurring and abundant resource and is one of the cleanest ways to produce electricity.

The main objective of the wind energy systems is to extract the maximum power available in the wind stream. The change in the wind speed poses a great threat to grid stability so; wind energy must be supplemented with other energy storage systems to ensure grid stability. Energy storage systems(ESS) typically considered for wind applications include: Pumped hydro, flywheels, batteries, supercapacitors, compressed air, superconducting magnetic energy storage systems and hydrogen. Their characteristics (e.g., energy capacity, power capacity, cycles, response time, efficiency and cost) are used to select the suitable system for an application. Large batteries, flywheels, supercapacitors and SMES are chosen as promising storage options due to the ability to directly specify a system with the necessary power and energy capacity [1]. Among them which have a relatively high energy storage density simultaneously with a high power density is used for energy storage system [2].

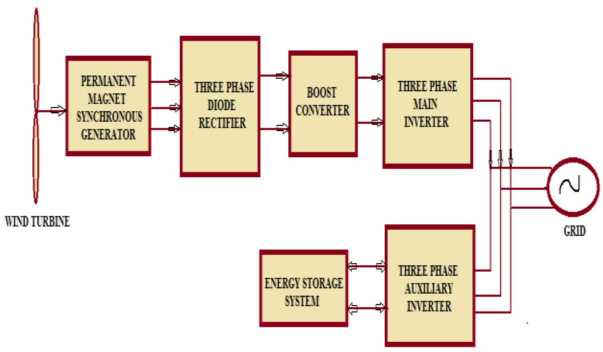

Figure 1: Block diagram of dual inverter based energy storage system for wind energy systems

In this paper, auxiliary inverter acts as active filter and it operates at highswitching frequency. It will reduce the harmonics produced by main inverter as it operates at low frequency. As wind speed is intermittent in nature due to this power fluctuations will occur.

Power fluctuations are periodic dips or spikes in the electrical current. Block diagram as shown in figure1 consists of wind turbine coupled PMSG which is connected to dual inverter through a diode rectifier and an intermediate boost converter which is used to extract maximum power from wind turbine. Power electronic interface devices are used for charging/discharging of energy storage system. The associated theoretical and analytical formalism is used to validate the solution. The simulation results are presented.

II Dual Inverter Based Energy Storage System For Wind Energy Systems

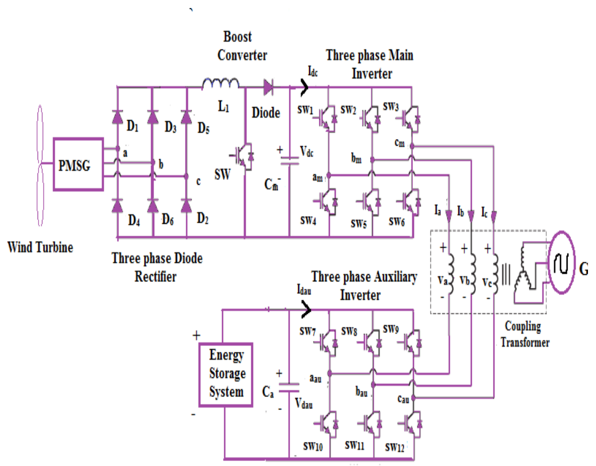

Figure 2: Schematic diagram of energy storage system for wind generation power system

Figure 2 shows the schematic diagram of wind energy generating systems interfacedwith energy storage systems. The system consists of wind turbine coupled PMSG, a DC/AC converter, DC/DC unidirectional boost converter, AC/DC converter. The PMSG output is connected to main inverter through a diode rectifier and boost converter. The energy storage system is interfaced with auxiliary inverter.

The wind turbine is regulated by DC/DC boost converter to a fixed dc output and is used to provide the power required by the grid. The energy storage system may be a battery bank, fuel cell, supercapacitor bank which is connected to auxiliary inverter. When the wind speed is high the excess energy can be saved in energy storage system which is used to charge the energy storage system.

A) *Modelling of wind turbine:*

A wind turbine is a device that converts kinetic energy from the wind into electrical power. The kinetic energy obtained by the blades from the wind is transformed to mechanical torque on the rotor shaft of the wind turbine[3]. The power obtained from the wind can be calculated asshown

$$P_w = \frac{1}{2}\rho_{air}\, A_r\, V_w^{\ 3} C_p(\lambda, \beta) \qquad \textbf{(1)}$$

Where,$_{air}$is the air density,

$V_w$is the wind speed experienced by the rotor

A_r is the swept rotor area

$C_p(\lambda,\beta)$is the power coefficient

The power coefficient depends upon tip-speed ratioλ and pitch angle of blades β.

$$\lambda = \frac{R\omega}{v} \qquad \textbf{(2)}$$

The torque on the rotor shaft, can be calculated from the power with the help of the rotational speed

$$T_A = \frac{P_w}{\omega} \qquad \textbf{(3)}$$

$$T_A = \frac{P_w}{\omega} = \frac{1}{2}\rho_{air} A_r \frac{V_w^{\ 3}}{\omega} C_p$$

$$T_A = \frac{1}{2}\rho_{air}\pi R^3 V_w^{\ 2} \frac{C_p}{\lambda} \qquad \textbf{(4)}$$

The wind turbine torque coefficient can be expressed as

$$C_T = C_p/\lambda \qquad \textbf{(5)}$$

$$T_A = \frac{1}{2}\rho_{air}\pi R^3 V_w^{\ 2} C_T \qquad \textbf{(6)}$$

B) *Dynamic model of PMSG:*

Figure 3 shows a general dq-axis model of a synchronous generator. To model the rotor circuit, the field current in the rotor winding is represented by a constant current source $I_f$in the d-axis circuit.in the PMSG, the permanent magnet that replaces the field winding can be modelled by an equivalent current I_f with a fixed magnitude.

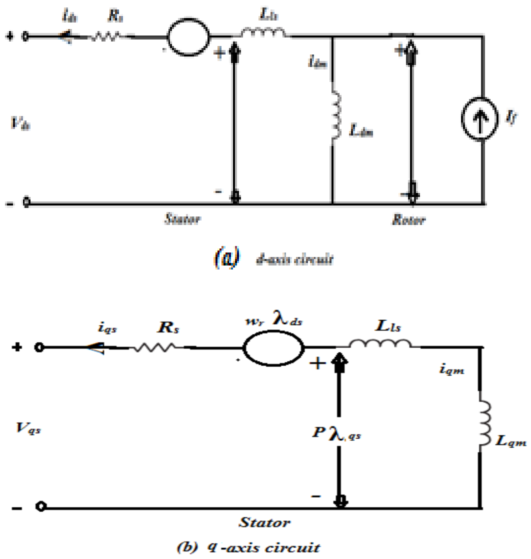

Figure 3: dq-axis model for PMSG

To simplify the PMSG, the following mathematical manipulations can be performed. The voltage equations for the synchronous generator are given by

$$V_{ds} = -R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds} \qquad (7)$$

$$V_{qs} = -R_s i_{qs} - \omega_r \lambda_{ds} + p\lambda_{qs} \qquad (8)$$

Where λ_{ds} and $\lambda_{qs}$are the d-axis and q-axis stator flux linkages.

$$\lambda_{ds} = -L_d i_{ds} + \lambda_r \qquad (9)$$

$$\lambda_{qs} = -L_q i_{qs} \qquad (10)$$

Where λ_r,is the rotor flux, and L_d and L_q are the stator dq-axis self-inductances, defined by

$$\lambda_r = L_{dm}\ I_f \qquad (11)$$

$$L_d = L_{ls} + L_{dm} \qquad (12)$$

$$L_q = L_{ls} + L_{qm} \qquad (13)$$

Substituting and corresponding $d\lambda_r/dt$ =0 for constant $\lambda_r$inthe PMSG, we have

$$V_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \qquad (14)$$

$$V_{qs} = -R_s i_{qs} - \omega_r i_{ds} + \omega\lambda_r - L_q\ p i_{qs} \qquad (15)$$

The electromagnetic torque produced by the Synchronous generator canbecalculated by

$$T_e = \frac{3p}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}) \qquad (16)$$

Substituting into 4, we have

$$T_e = \frac{3p}{2}[\lambda_r i_{qs} - (L_d - L_q) i_{ds} i_{qs} \qquad (17)$$

The rotor speed ω_r is governed by motion equation

$$\omega_r = \frac{P}{JS}(T_e - T_m) \qquad (18)$$

To derive the SG model for dynamic simulation of synchronous generators, eqation is rearranged as,

$$i_{ds} = \frac{1}{s}(-v_{ds} - R_s i_{ds} + \omega_r L_q i_{qs}) / L_d (19)$$

$$i_{qs} = \frac{1}{s}(-v_{qs} - R_s i_{qs} + \omega_r L_d i_{ds}) / L_q (20)$$

Based on the above three equations the block diagram for computer simulation of the SG is derived the input variables of the SG model are the dq-axis stator voltages V_{ds} and $v_{qs,}$ the rotor flux linkage λ_r and the mechanical torque T_m, whereas the output variables are the dq-axis stator currents i_{ds} and i_{qs}, the rotor mechanical speed $\omega_{m,}$ and the electromagnetic torque T_e.

C) Three phase diode rectifier:

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC). This process is known as rectification. The diode rectifier converts variable generator voltage to a DC voltage[4]. Because of the alternating nature of the input AC sine wave, the process rectification alone produces a DC current that, though unidirectional, consists of pulse of current.

D) Boost Converter:

The DC/DC boost converter is one of the converter often used in synchronous generator (SG) based wind energy conversion systems. The DC-DC converters can be used as switching mode regulators to convert an unregulated dc voltage to a regulated dc output voltage [6].

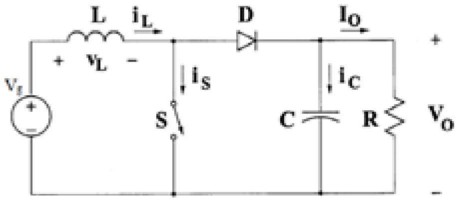

Figure 4: Boost Converter

When the switch SW is closed i.e., ON state, the boost inductor current increases and energy is stored in inductor and the diode D_1 is turned off. When the switch SW is open OFF state the stored energy in inductor is released through the diode to the load. When the switch SW is ON, the total sum of the inductor voltage and the input voltage appears across the load voltage when the switch SW is OFF, the inductor is charged from the input voltage V. When the switch is closed, on state the inductor charged from the input voltage sourceV_{in} and the capacitor discharges

Design values:

The duty cycle, $d= T_{on}/T$ (20)

Where $T=1/f$ (21)

Inductor,$L =d(1-d)^2R/2f$ (22)

Capacitor,$C=d/2Rf$ (23)

E) *Modelling of three phase dual inverter:*

The proposed three phase dual inverter consists of main inverter, and an auxiliary inverter. Inverter is a two-level voltage source converter. The converter is composed of six switches Sw_1 to Sw_6, with an anti-parallel free-wheeling diodeforeach switch. When the converter transforms a fixed DC voltage to a three-phase AC voltage with variable magnitude and frequency for an AC load it is often called Main inverter.

When the converter transforms an AC grid voltage with fixed magnitude and frequency to an adjustable DC voltage for a DC load, it is normally known as an active rectifier or PWM rectifier. Whether it serves as an inverter or a rectifier, the power flow in the converter circuit is bidirectional [4].

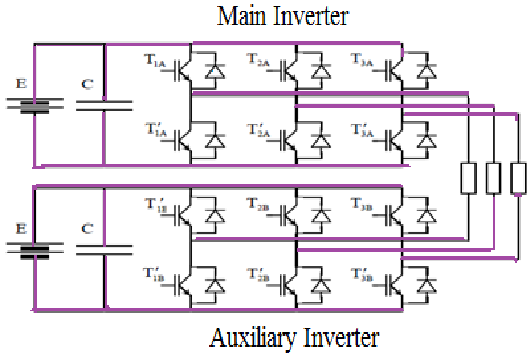

Figure 5: Three phase dual inverter

The proposed system consists of DUAL inverter as shown in Figure in which the main inverter operates in six-step mode, which moves slowly from one vector to the next. The main converter is often connected to an electric grid, and delivers the power generated from the generator to the grid. Square wave outputs are obtained from main inverter which gets smoothened by auxiliary inverter and it operates at low-frequency operation. Auxiliary inverter acts as an active filter, and it is operated at high switching frequency and it uses Space vector modulation (SVM). Space vector modulation (SVM) is one of the real-time modulation technique and is used for digital control of voltage source inverters. The active and zero switching states can be represented by active and zero space vectors. The six active vectors V_1 to V_6 from a regular hexagon with six equal vectors. The zero vector V_0 lies at the centre of the hexagon.

Assuming the operation of the inverter is three-phased balanced,

$$V_a(t) + V_b(t) + V_c(t) = 0 \quad (24)$$

V_a, V_b, $V_c$are the instantaneous load phase voltages. It is possible to transform the three-phase variables to two phase variables through the abc/αβ transformation

The active switching states of load phase voltages are

$$V_a(t)=\frac{2}{3}V_{dc},\ V_b(t)=\frac{2}{3}V_{dc}\ V_c(t)= \frac{2}{3}V_{dc} \quad (25)$$

The dual inverter topology injects the wind energy to the load, and energy storage system and reduces power fluctuations in the grid side and makes energy balance.

Dual inverter based energy storage systems need to reduce powerfluctuations, provide energy balanceand reduce the cost, power losses and complexity. If energy storage system is connected with dc-dc converter then the complexity, cost will increase. To solve these problems, the synchronous reference frame proportional – integral (PI) controller is used three phase inverters to obtain a zero steady-state error.

F) Energy Storage System:

Power fluctuations are Due to the change in thewind speed. Therefore the energy storage system capacity is also a function of wind speed. The wind is modelled as the sum of series of harmonics and dc quantity.

The power captured from the wind is

$$v_w(t) = V_{w0} + \sum \Delta V_{wi} \sin(\omega_i t) \qquad (26)$$

$$v_w(t) = V_{w0}(1+0.2\sin(2\pi/T*t)) \qquad (27)$$

$$p(t) = 0.5\rho A C_p v_w(t)^3 \qquad (28)$$

Where$v_w$is the instantaneous wind speed , V_{w0} is the mean wind speed., ΔV_{wi} is the harmonic amplitude, $\omega_i$is the angular frequency, ρ is the density of air, A is the swept area of wind turbine blades and C_p is the coefficient of power conversion. The power fluctuations caused by wind speed have to be compensated by the energy storage system.

In the proposed system battery is used as an energy storage system. When the wind speed is maximum the required energy is supplied to the grid and the excess of energy is stored in the battery and when the wind speed is low, the energy from the battery is provided to the grid.

Figure 5 shows the battery which is modelled as a nonlinear voltage source whose output voltage depends not only on the current but also on the battery state of charge (SOC), which is a nonlinear function of the current and time represents a basic model of battery.

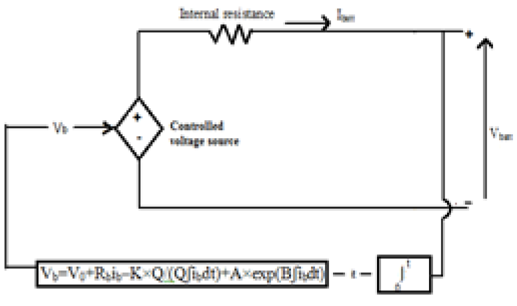

Figure6: Internal circuit of battery model

Two parameters to represent state of a battery i.e. terminal voltage and state of charge can be written

$$V_b = V_0 + R_b i_b - K \times Q/(Q \int i_b dt) + A \times \exp(B \int i_b dt) \qquad (29)$$

$$SOC = 100(1 + \int i_b dt/Q) \qquad (30)$$

III MATLAB SIMULINK CIRCUITS

Simulink Model of dual inverterbased Energy Storage Systems

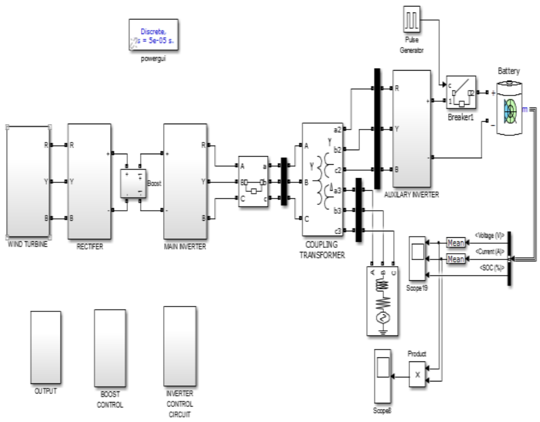

Figure 7: Simulation model of dual inverter based energy storage system

The complete system is modelled on MATLAB^{TM} R2013a and SIMULINK^{TM}. The simulation figure shows the Simulink model of dual inverter based energy storage system which consists of wind turbine, Diode rectifier, boost converter, three phase main and auxiliary inverter and battery. Wind turbine is delivering power of 100KW to grid. The output power of grid is 60KW and energy storage system used here is a battery.

Battery is charged when the wind speed is maximum and it discharges when the wind speed is low. Battery is interfaced with the auxiliary inverter of dual inverter topology.

Wind turbine Simulink model

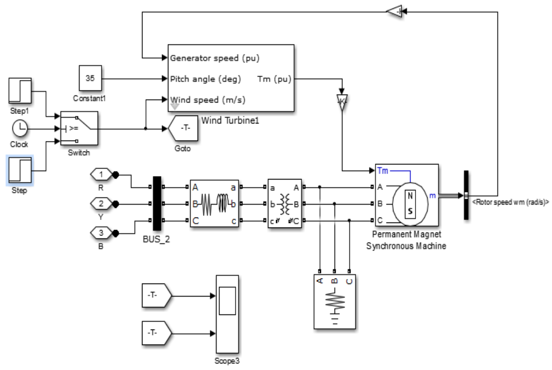

Figure 8: Simulink model of wind turbine coupled PMSG

For the wind turbine coupled PMSG modelling 100KW input is given and different wind speeds are given.

Simulink Model of Three Phase Inverter:

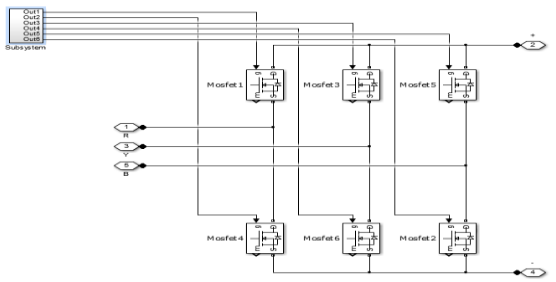

Figure9: Simulationmodel of three phase voltage source inverter

Simulink model of internal circuit of Inverter

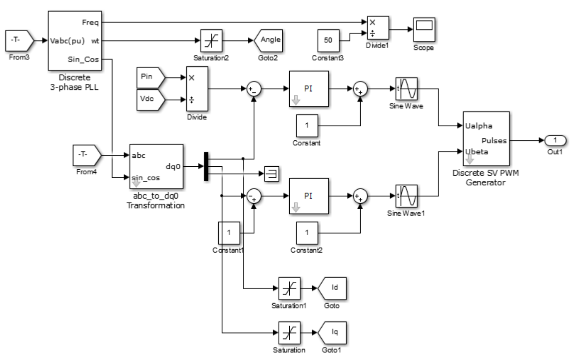

Figure 10: Simulink model of internal circuit of control scheme of inverter

Figure 10 shows the control scheme of inverter. Inverter employs inner current controller and output power controller. The voltage and current injected into the grid are converted into synchronous reference frame. The direct component of the inverter current controls the active current and the quadrature component of the inverter current controls reactive current. The reference active and reactive current components are compared with actual and the error is given to PI controller to produce voltage references.

SIMULINK model of gate signal generator

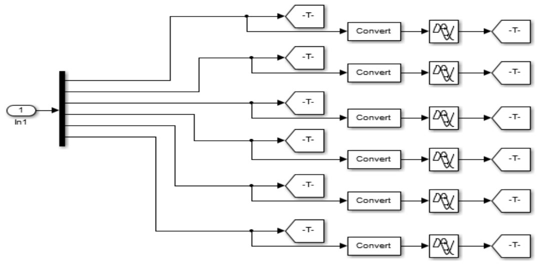

Figure 11: Simulink model of Generating SVPWM signals to gate terminal of inverter.

SIMULINK model of Battery:

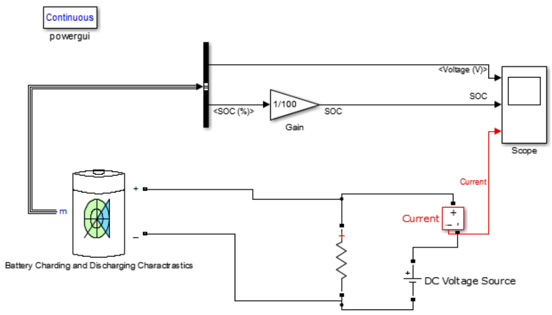

Figure 12: Simulation model of Battery.

IV MATLAB SIMULINK WAVEFORMS:

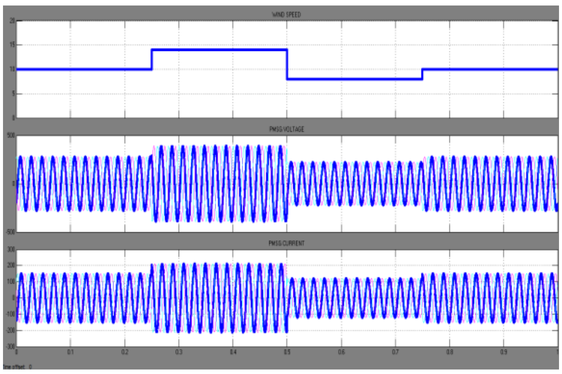

Figure 13: Waveforms for different wind speeds, PMSG output voltage, and current.

With the wind turbine simulation model the wind speeds are set to different values like 10m/s, 14m/s,8m/s and the pitch angle control as 25deg.the input of PMSG is 100KW,the output voltage is 397V and the current is 198A.

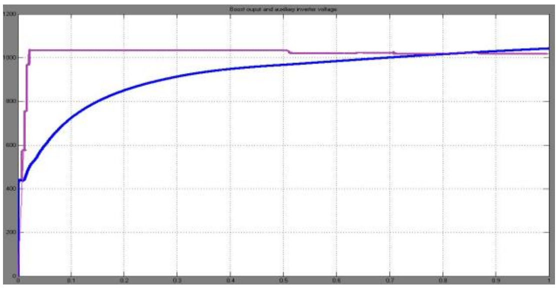

Figure14: Boost converter output voltage and Battery voltage waveforms

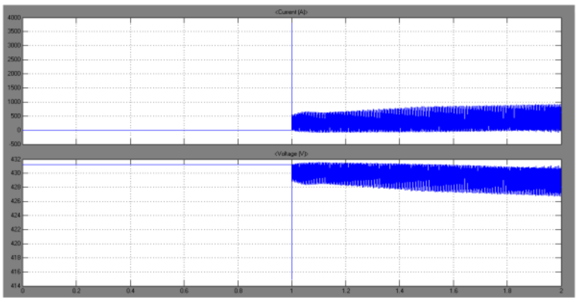

Figure15: Output Voltage and Current of battery

The above Figure.15 shows the output current and voltage waveform of battery. The battery nominal voltage is 430V DC, the capacity of battery is 1000Ah, DOD is 60%. At starting 0 to 1 seconds wind turbine gives the required power to the load, the battery is in open circuit condition so the battery current is zero, voltage is around 430V. After 1 sec WT and Battery is connected, so the battery current starts increasing while battery voltage starts decreasing.

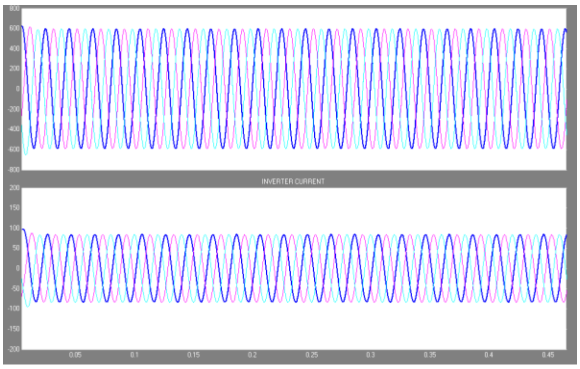

Figure 16: Main inverter output voltage waveform.

Figure 16 shows the waveform of main inverter voltage. Until battery chargeis not given to the grid there are some disturbances in voltage after the battery charge given the voltageisconstant. The output voltage is 415V and current is 100A.

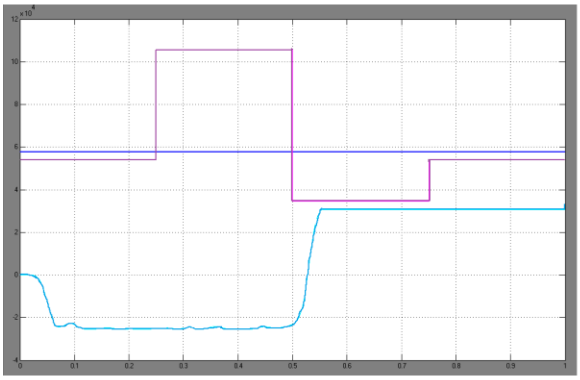

Figure 17: Output power of PMSG,Grid and Battery

Figurec17 shows the input power ranging from 30 to 100KW, and the grid output power is constant at 54KW and battery charging and discharging process is also shown. For the first half time of the simulation battery will charge if the energy is excess and it discharges when the energy is in demand.Thesimulated performance analysis of voltage and current characteristics of battery are determined in Figure. the battery is charged at the rate of 50%. When the phase angle of battery reduces a part of wind power is used for charging. When there is reduction in wind power the stored energy from battery is charged to the load which is controlled by MPPT.

Conclusion and Future Scope

In this paper, energy storage systems are interfaced with auxiliary inverter and power fluctuations are mitigated and also energy balance is done. By using ESS power losses, cost, complexity is reduced. The results shown are charging and discharging of battery for different wind speeds. The concept is extended for the better energy storage system like supercapacitor bank, modelling of multilevel inverters with different control strategies to reduce the fluctuations, harmonics significantly.

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