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Grid Connected Wind Power System with Battery Storage for Power Smoothing

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Abstract—**This paper aimed to evaluate the use of wind turbine storage systems to provide electricity in the distribution grid through a three-level inverter. The proposed system is composed by two wind turbine generators with MPPT (optimal torque control) control, two battery storage systems connected to each capacitor of the DC link and a three level diode clamped inverter connected to the grid by three phase transformer. The system operator controls the power production of the two wind turbine generators by sending out reference power signals to each input side regulation unit, the input side regulation units regulate the voltage of each capacitor of the DC link, regulate the voltage and the state of charge of each battery storage system.**

***Keywords*—Wind turbine generator, Permanent magnet synchronous generator (PMSG), Battery storage, three level diode clamped inverter, Space vector modulation.**

I. INTRODUCTION

The use of the wind energy conversion systems has been considerably expanded over the last few decades, in the present work, wind turbines with variable speed are adopted, due to their advantages cited in [1]. Among problem related to variable-speed wind systems is presence of gearbox connecting wind turbine to generator [1], permanent magnet synchronous generators (PMSG) turns out to be increasingly attractive, due to reason cited in [1], [2]. Energy storage systems (ESSs) have some important applications in operations like grid stabilization, load shifting, grid operational support, smooth power injection to the grid. Several power smoothing methods have been introduced in literature [3]; Battery energy storage system (BESS) is selected as an energy storage medium and incorporated into wind farms for dispatching the wind power, and maintain power and energy balance as well as to improve power quality. Multilevel inverters appear to be a very good solution for renewable energy applications, various types of topologies are presented in the literature [4]. The diode clamped inverter topology appears to be more attractive for the reason cited in [5]. Different methods of modulation techniques exist to control the inverter they are developed in [4]. In this paper as shown in Figure 1, two variable speed wind turbine battery storage system connected to the grid with three level diode clamped inverter topology is presented, each turbine is connected to each capacitor of the DC link of the inverter via an AC / DC converter and for each of this capacitor of the DC link a battery bank is also connected, the inverter is controlled by a simplified space vector modulation and its output is connected to the network via a transformer. The proposed structure (connection of battery bank to each capacitor of DC link of the inverter) gives benefit of direct connection to the grid, reduced parts count, improved reliability and high power capacity and balancing voltages across each capacitor without using complex algorithm.

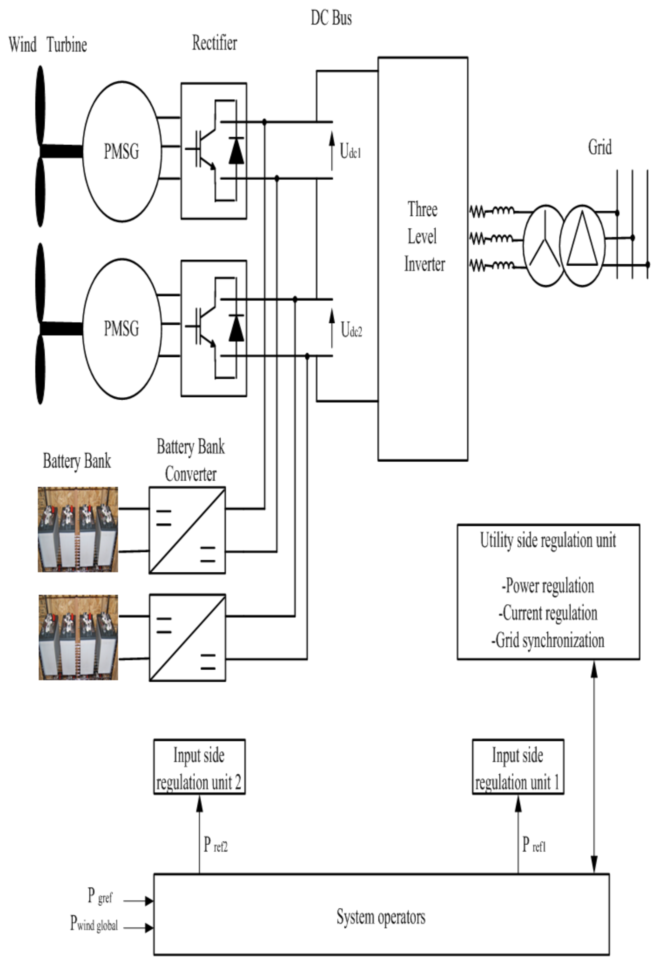

Fig. 1 Global wind turbine connection system

II. MODELLING OF WIND ENERGY CONVERSION SYSTEM

660kW PMSGs are used; the mathematical model and control strategies are widely developed in the literature, the model of PMSG-based wind turbines, including the electrical and mechanical part, control of power converters and grid side control are detailed in [6], while the model of the battery bank is explained in [7].

A. Multilevel inverter model

The general structure of the multilevel inverter is to synthesize a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. The diode clamped inverters, particularly the three-level structure, have a wide popularity in motor drive applications besides other multilevel inverter topologies. However, it would be a limitation of complexity and number of clamping diodes for the DC-MLIs, when the level exceeds three. An *m*-level diode clamped inverter typically consists of *m* -1 capacitors on the DC bus and produces *m* levels of the phase voltage. A three phase three-level diode clamped inverter circuit diagram is shown in Figure. 2. Each of the three phases of the inverter shares a common DC bus, which has been subdivided by two capacitors into three levels. The voltage across each capacitor is $\frac{E}{2}$, and the voltage stress across each switching device is limited to $\frac{E}{2}$ through the clamping diodes [4].

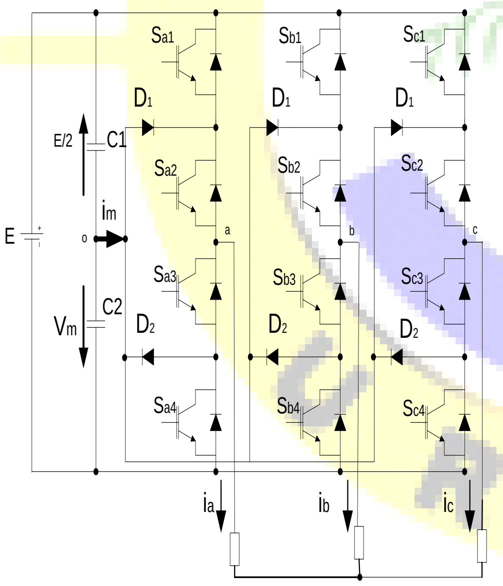

Fig. 2 Circuit diagram of three level diode clamped inverter

Table 1 lists the output voltage levels possible for one phase of the inverter with source neutral as a reference. State condition '1' means the switch is ON and '0' means the switch is OFF. Each phase has two complementary switch pairs such that turning on one of the switches of the pair require that the other complementary switch be turned off. The complementary switch pairs for phase leg a are (S_{a1}, S_{a3}) and (S_{a2}, S_{a4}).

TABLE I.
Diode clamped inverter voltage levels and switching states

Switching symbol	Switch state				Voltage
	S_{a1}	S_{a2}	S_{a3}	S_{a4}	V_a
+	1	1	0	0	$\frac{E}{2}$
0	0	1	1	0	0
-	0	0	1	1	$-\frac{E}{2}$

Using the complementary control between upper switches and lower ones, so to have:

$$\begin{cases} S_{k1} = 1 - S_{k3} \\ S_{k2} = 1 - S_{k4} \end{cases} \quad (1)$$

Where *k*= (1,2,…3) is the leg number. Assuming ideal power switches, connection functions are defined as follows:

$$\begin{cases} G_{k1}^{a} = S_{k1}.S_{k2} \\ G_{k2}^{a} = S_{k3}.S_{k4} \end{cases} \quad (2)$$

Voltage of leg *k* (*k*=1,2,3) of three-level inverter relative to middle point O is given by the following equation:

$$\{V_{kO} = (G_{k1}^{a} - G_{k2}^{a})\,\frac{E}{2} \quad (3)$$

Output voltage of the inverter is given by:

$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}\begin{pmatrix} V_{10} \\ V_{20} \\ V_{30} \end{pmatrix} \quad (4)$$

III. CONTROL OF WIND ENERGY CONVERSION SYSTEM

A. Control of battery bank storage

The schematic of the battery converter control is shown in Figure 3. The power output of the two wind turbines is controlled by supervision system controls by sending reference power for each of the two control unit on the input side such as:

$$P_{refi} = \frac{P_{windi}}{P_{windglobal}}\,P_{gref} \quad (5)$$

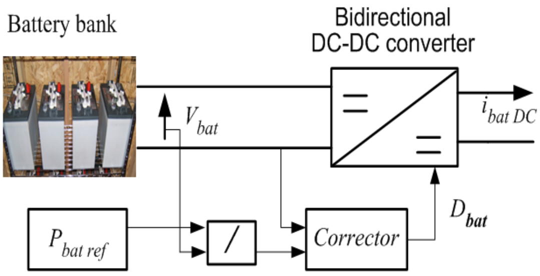

Fig. 3 Battery bank storage control

The battery power reference is produced by the supervisory system. The corrector adjusts the current i_{bat} in the aim to track the reference $i_{bat\ ref}$, with an objective of charging or discharging the battery depending to the need. Figure 4 shows flow chart of operation of storage battery system.

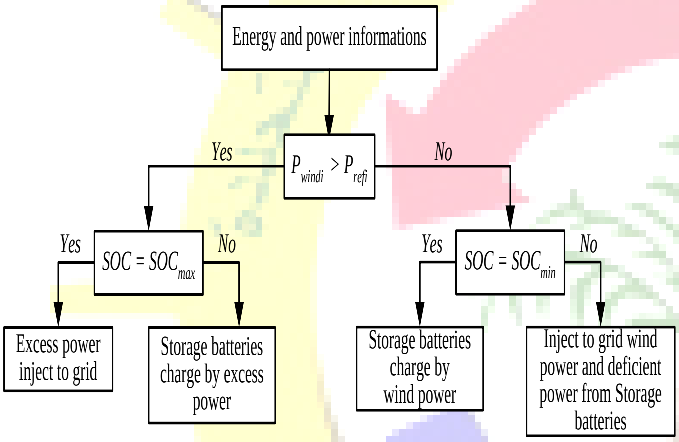

Fig. 4 Operation of storage battery

B. *Control of inverter*

One of the most known control approach for multilevel inverters is known as SVPWM, which directly applying the control of the variable provided by the control system and identifies each commutation vector as a point in the complex area of (α, β). Three-level NPC inverter has 27 switching states like shown in Figure 5. Each phase arm of inverter consists of four switching element and has three different switching states that are +, 0, - representing positive, zero and negative switching sequences.

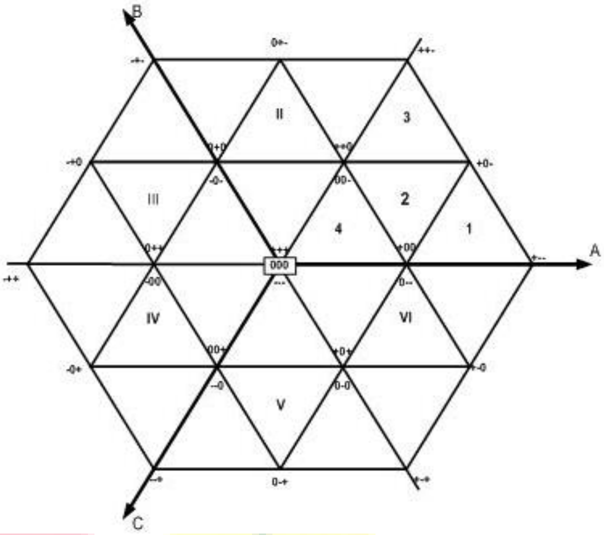

Fig. 5 Three-level space vector diagram

In this part, a simplified technique is used where the hexagon of Figure 5 is subdivided into six smaller two-level hexagons as it can be seen in Figure 6.

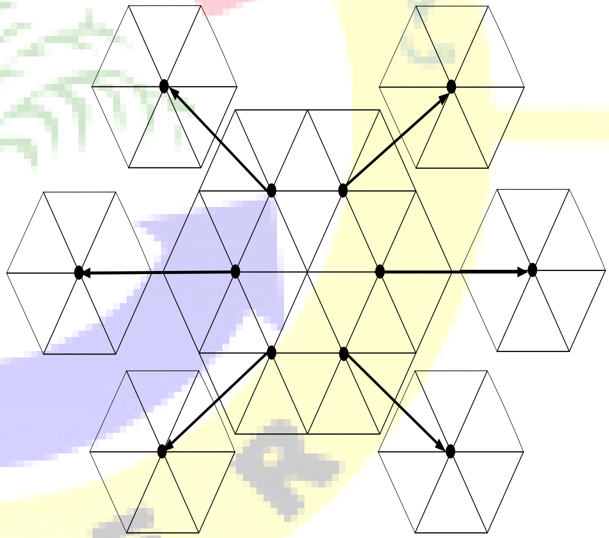

Fig. 6 Simplification three-level space vector diagram

The idea is to find in which two-level hexagon is located the reference vector to apply the SVPWM for two-level inverter. By knowing the position of reference voltage, we can determine in which two-level hexagon the tip of the reference voltage vector lies. Every hexagon is recognized by the angle θ such as:

$$\begin{cases} 1\ if\ \frac{11\pi}{6} \leq \theta < \frac{\pi}{6} \\ 2\ if\ \frac{\pi}{6} \leq \theta < \frac{\pi}{2} \\ 3\ if\ \frac{\pi}{2} \leq \theta < \frac{5\pi}{6} \\ 4\ if\ \frac{5\pi}{6} \leq \theta < \frac{7\pi}{6} \\ 5\ if\ \frac{7\pi}{6} \leq \theta < \frac{3\pi}{2} \\ 6\ if\ \frac{3\pi}{2} \leq \theta < \frac{11\pi}{6} \end{cases} \quad (6)$$

After having selected a hexagon, the new reference vector $V^{*'}_s$ is calculated as follows:

TABLE 2
Correction of reference voltage vector

Hexagon	$V_\alpha^{*'}$	$V_\beta^{*'}$
1	$V_\alpha^* - 1/2$	V_β^*
2	$V_\alpha^* - 1/4$	$V_\beta^* - \sqrt{3}/4$
3	$V_\alpha^* - 1/4$	$V_\beta^* - \sqrt{3}/4$
4	$V_\alpha^* - 1/2$	$V_\beta^{*'}$
5	$V_\alpha^* - 1/4$	$V_\beta^* + \sqrt{3}/4$
6	$V_\alpha^* - 1/4$	$V_\beta^* + \sqrt{3}/4$

C. *Control of the grid side*

Our system must (PMSG / battery bank) inject sinusoidal currents (amplitude and frequency) same to those of network with the aim to generate the PMSG/battery bank active power to grid. Active and reactive powers are given using components of grid voltage current (V_{gd}, i_{gd}, V_{gq} and i_{gq}) by [8]:

$$\begin{cases} P_g = V_{gd} i_{gd} + V_{gq} i_{gq} \\ Q_g = V_{gd} i_{gq} - V_{gq} i_{gd} \end{cases} \quad (7)$$

By controlling $i_{gd,} i_{gq}$, references for active and reactive power can be obtained:

$$\begin{cases} i_{gd\ ref} = \frac{P_{gref}.V_{gd} - Q_{gref}.V_{gq}}{V_{dg}{}^2 + V_{qg}{}^2} \\ i_{gq\ ref} = \frac{P_{gref}.V_{gq} + Q_{gref}.V_{gd}}{V_{gd}{}^2 + V_{gq}{}^2} \end{cases} \quad (8)$$

Figure 7 shows us diagram of grid side control.

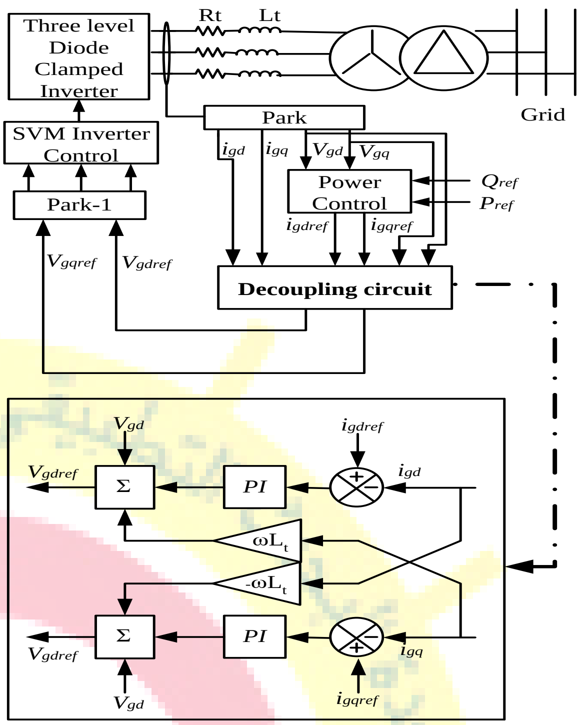

Fig.7 Diagram of the grid side control

IV. Simulation Results of Global Wind Turbine System

In this section, global wind turbine system is simulated using MATLAB- SIMULINK, variable wind profile is taken for each turbine as shown in Figure 8.

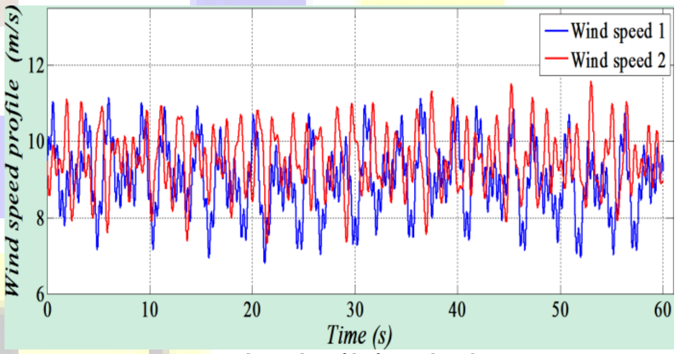

Fig.8 Wind speed profile for each turbines

Figure 9 shows the mechanical power for each turbine and a global power produced by the group of wind turbine, it can be noted that they depend on the variation of the wind speed.

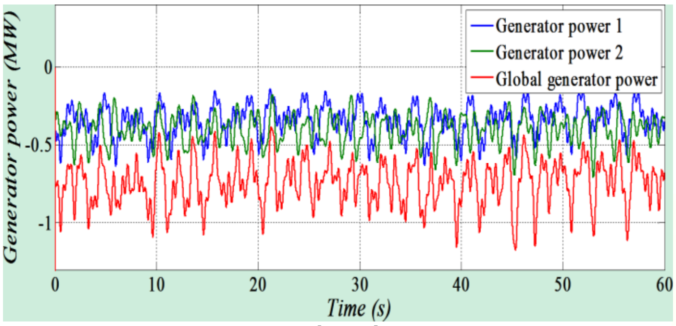

Fig.9 Mechanical power

The strategy adopted allows controlling the level of storage of each storage unit the wind productions are different and compensate the fluctuations of the wind power as illustrated in Figures 10-13. Positive power of battery banks means that power produced by wind generators is more than power demanded by consumers than the surplus is used to charge batteries, negative power of battery banks means that power produced by wind generators is less than power demanded by consumers; battery banks are used to inject the power deficit to grid.

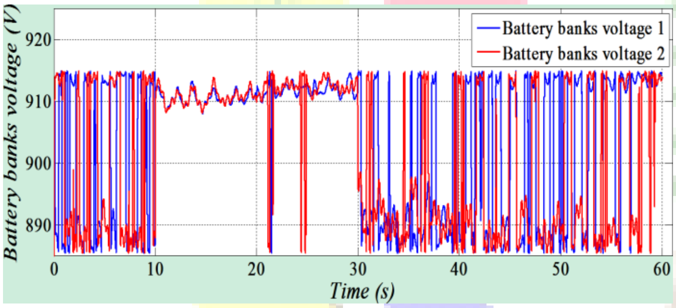

Fig.10 Battery banks voltage

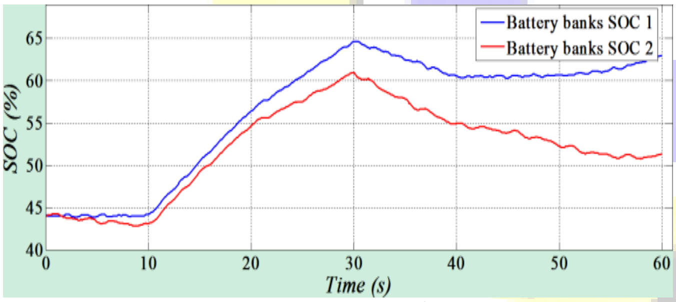

Fig.11 Battery banks state of charge

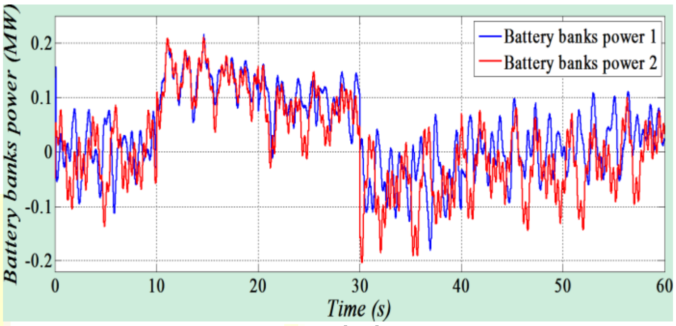

Fig.12 Battery banks power

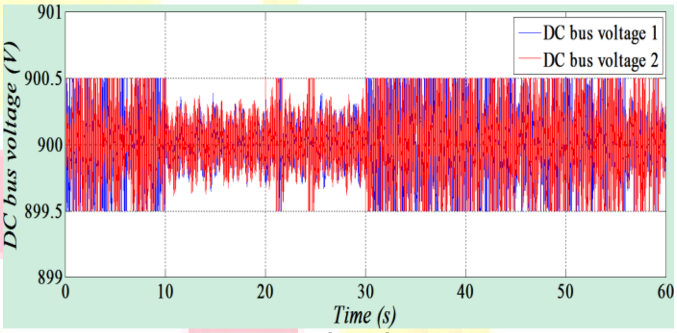

Fig.13 DC bus voltages

The injected currents are sinusoidal with a constant frequency (50 Hz) and have a good quality Figure 14.

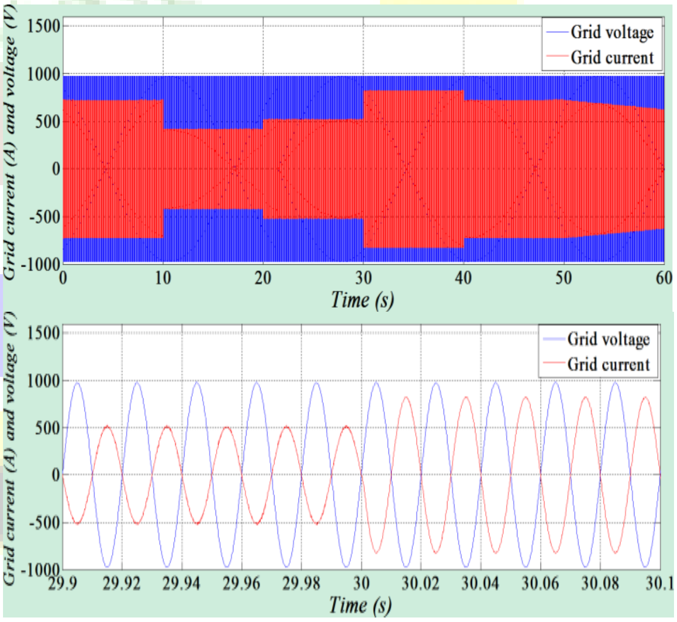

Fig.14 Grid current and voltage and their zoom

Reactive power is kept at zero (unity power factor) after charging the capacitor Also, the results show that the connection of multiple wind turbines using a single multilevel inverter can inject more power to grid as shown in Figures 15.

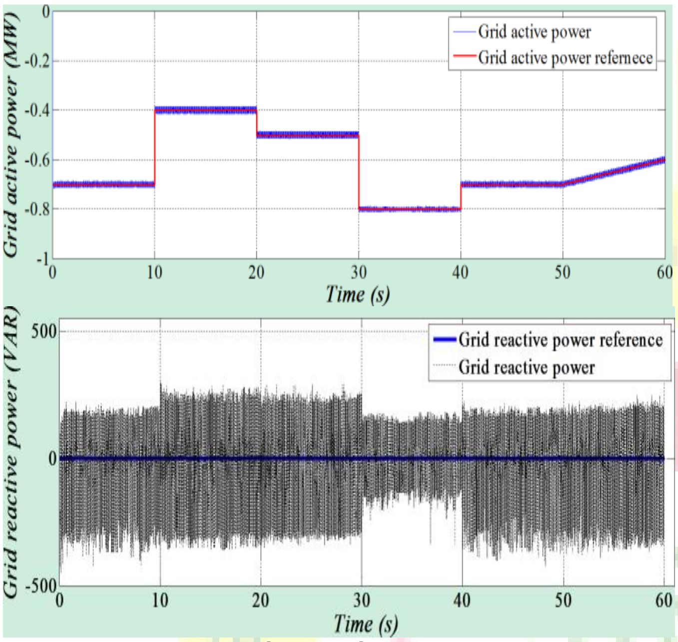

Fig.15 Grid active and reactive power

V. Conclusions

This paper presents the study and the control of variable speed wind system with battery storage connected to grid, a wind energy conversion system based on PMSG was proposed. In order to maximize the extracted power from the wind, MPPT control with speed controller is applied, it is a simple and good control method with satisfactory dynamic performance. The PMSG was controlled by vector control; it gave good dynamic performances according to the wind speed variation. The use of a three level diode clamped inverter, with his simplified space vector modulation as a grid interface, gives good results in term of power quality, also, in this work, the aim was, to inject fixed power to the grid with a variable wind speed, Furthermore, the applied control strategies can benefit a high efficiency, especially by using the PMSG. The validity of the studied system has been verified by simulation results using Matlab Simulink.

Appendix

System parameter values:

Turbine: Turbine radius R = 23.5m, Turbine inertia = 222963 kg.m^2, Air density ρ = 1.225kg/m^3, Number of blades = 3. **Grid**: V= 690 V, f = 50Hz. **PMSG :** Rated power P = 660kW, Stator resistance R = 0.01Ω, d, q axis stator inductances L_{ds}= L_{qs} = 0.001H, Magnetic flux Ψ_f= 2.57 Wb, Pair number of poles P= 64. **DC bus:** Udc_1 = Udc_2= 900 V

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