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Grid Power Leveling using Ultra Capacitor, Battery and an Optimal Control Strategy for Reactive Power in DFIG based WECS

Diptoshi Roy, Chandasree Das

Abstract—To harness the wind power efficiently the most reliable system in the Wind Energy Conversion system (WECS) is grid connected doubly fed induction generator (DFIG). Inconstancy in the output power and consequently voltage of the system is the result of random wind speed and turmoil of blade rotational speed. Battery energy storage system (BESS) is one, which helps to reduce the power fluctuations on the grid caused due to the varying and unpredictable nature of wind. This paper presents a comparative study between BESS and ultra- capacitor and the combination of both in a DFIG based WECS to reduce the power fluctuation on the grid. The performance analysis of the following cases (a) battery alone in dc-link (b) ultra- capacitor in dc-link (c) battery and ultra-capacitor in dc-link , have shown that the response with ultra-capacitor is best among all these cases. The analysis is done for all three modes of speed i.e. sub synchronous, synchronous and super synchronous and in all three modes, the power fed to the grid is kept constant. As the doubly fed induction generators used in grid interfaced wind energy systems are being called upon increasingly to address voltage regulation and provide adequate reactive power support; a reactive power control strategy is also studied and is included in this paper with grid and rotor side converters for voltage regulation and reactive power support respectively. The validity of this new approach has been tested in 16 bus IEEE power distribution system. The results obtained shows considerable reduction in losses by reactive power compensation. The modeling of battery, ultra-capacitor including model of rotor side converter for reactive power analysis are simulated in MATLAB-SIMULINK which helps to predict the behavior of the system in various aspects. An effort is made in this paper to study few issues like energy storage by ultra-capacitors, long term storage, reactive power control and a case study using 16-bus distribution system for grid connected DFIG based WECS.

Keywords: DFIG, Ultra capacitor, grid power leveling, 16 bus distribution system..

I. INTRODUCTION

The two major challenges that the planet (Earth) is facing are the change in climatic condition and decline in the fossil fuel reserves. Wind power energy adds diversity to the national energy portfolio and it also reduces reliance on imported fossil fuels, positively impacting electricity cost stability, reducing variation in price spikes, challenges in supply disruption, and improving the national energy self-sufficiency. In DFIG the stator is directly connected to the grid and the rotor is also connected to the grid through voltage source PWM converters.

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The energy flow through the rotor converters is bidirectional, in sub-synchronous wind speed energy flows to the rotor and in super-synchronous wind speed energy flows from rotor to the grid. Energy always flows from stator terminals to the grid. Because of the shared energy transport the rating of the rotor converters is smaller and it depends on the speed range of the WECS and is mostly one third of the synchronous speed The converter enables control of the generator speed, power and power factor, thus providing a wider speed range and improving the energy yield and ability to feed reactive power to support the grid. The Doubly fed (DF) concept therefore represents an economical way of achieving semi-variable speed operation and satisfying basic grid code requirements [1],[2]. As the speed of wind is unpredictable, the rotor speed will vary which leads to the variation in frequency of voltage. This form of electricity cannot be directly connected to a grid, and hence some measures must be employed so that its frequency becomes constant. To achieve this condition power converters are used, which uncouples the wind turbine from the transmission system [3],[4]. Incorporating a battery or any other energy storage device in the dc link enables temporary storage of energy and, therefore, the ability to provide constant output active power, which is both deterministic and resistant to wind speed fluctuations to ensure "power-leveling" at the grid side [5],[6]. As BESS are ideal for small size applications and becomes too expensive for multi MW load leveling applications ,ultra-capacitor is utilized in place of BESS. Currently many operators prefer unity power factor operation since it is the active power that is rewarded [7]. The control of DFIG based WECS is already been illustrated in literature considering unity power factor operation [6] and the same control strategy is considered in this paper for the comparative study of the ultra-capacitor and BESS. The schematic diagram of DFIG based WECS with BESS is shown in figure 1. With increasing levels of wind power penetration into the grid, ancillary services of DFIG such as voltage control and network reactive power support are becoming more important issues in present scenario. Hence in this paper the reactive power control of DFIG is considered where the RSC is used to provide reactive power support to the network and GSC is used as the default voltage controller. To provide a practical view point, this approach is studied by implementing 16 bus IEEE power distribution system.

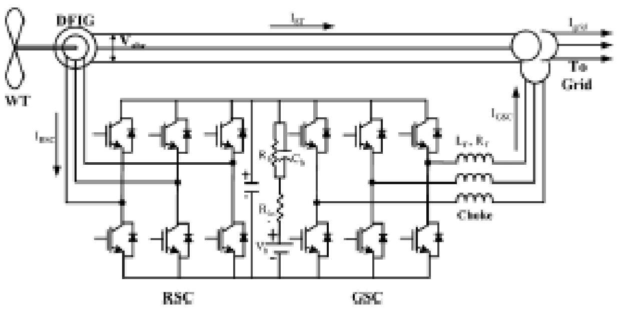

Fig. 1: DFIG based WECS with BESS in the Dc-Link [6]

II. SYSTEM ARCHITECTURE AND DETAILS

A. Wind Turbine

Windmills convert the kinetic energy of the wind into mechanical energy. The total power of the wind stream is equal to the time rate of kinetic energy. The output power (P) varies as cube of the wind velocity (V), which is given by

$$P = 0.5*Cp\ (\lambda, \beta)\ \rho A V^3 \text{ Watts.} \quad (1)$$

where Cp (λ, β) is the power coefficient and is defined as the fraction of the free flow wind power that can be extracted by a rotor, ρ is air density and A is intercept area. Windmill produces maximum power at high wind velocity but wind velocities below 5m/s and above 25m/s are not suitable for wind turbine. Wind power is proportional to the intercept area (A), thus windmill with a large sweep area has high power. Normally, area is circular (considering diameter "D") thus

$$A = 0.25\pi D^2 \quad (2)$$

$$\text{Thus, } P = 0.125\ Cp\ (\lambda, \beta)\ \rho D^2 V^3 \quad (3)$$

Maximum theoretical power coefficient is given by 0.593.

B. Battery

Thevenin battery model is used in this work, which consists of an ideal no-load battery voltage (E_0), internal resistance (R), capacitance (C_0) and overvoltage resistance (R_0). C_0 represents the capacitance of the parallel plates and R_0 represents the non-linear resistance contributed by the contact resistance of plate to electrolyte.

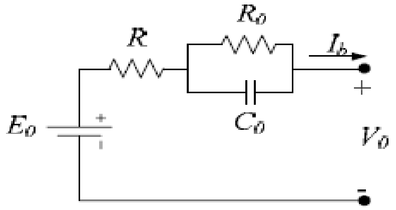

Fig. 2: Thevenin Battery Model

The main drawback of the Thevenin battery model is that all the elements are assumed to be constant, but in fact all the values are functions of battery conditions.

C. Design and Power Smoothening using Ultra Capacitor

As a battery is incorporated in the dc link to ensure power-leveling at the grid side, suitable rating of the BESS has to be designed for satisfactory operation. The battery will store the excess power produced and hence the extra power, which is more than the average power of a particular place, will determine the rating of the BESS [6] but batteries cannot be discharged all the way down to zero during each charge cycle. For example, a lead acid battery is used for 80% of its charge, leaving 20% left in the battery i.e. the depth of discharge (DOD) of lead acid battery is 80%.Also according to the Peukart effect some battery chemistries give much fewer amp hours if it is discharged fast. This is a prominent effect in chemical batteries. BESS are ideal for small size applications and becomes too expensive for multi MW load leveling applications. So ultra-capacitors can be used in place of battery. The principle of operation of ultra-capacitor is same as the battery, as it is an energy storage device and helps to maintain constant output power on the grid side but with a high capacity. Apart from having high capacity ultra-capacitor also helps to smooth the wind variation and obtain constant output power within short time. Ultra-Capacitor is preferred over battery because the capacity and discharge current of ultra-capacitor is very much higher than that of traditional battery. Further in ultra-capacitors huge amounts of current can be produced and it has high efficiency with very short charging and discharging time. Apart from these it has low internal resistances, even if they are coupled together. The voltage is proportional to the current state of charge which allows the control system to estimate the actual level of stored energy in ultra-capacitor. It resist very high number of cycles without deterioration of its properties.

III. PRINCIPLE OF OPERATION

The principle of operation of this topology for grid power leveling is that, by incorporating an ultra-capacitor in the dc link, the power fed to the grid is kept constant. The average power for a given place (where the wind turbine is installed) is calculated from the available wind speeds and this calculated average power is fed to the grid to reduce the power fluctuations on the grid. At the higher wind speeds (and the machine operating at super-synchronous speed), power output of the WECS is higher as compared to the average power and therefore, the extra power generated is stored in the ultra-capacitor. In contrast, at the lower wind speeds (and the machine operating at sub synchronous speed) the power is drawn from the ultra-capacitor to maintain a constant average power fed to the grid. Thus it is ensured that the power fed to the grid is always "leveled" resulting in an efficient and reliable source of electrical power to the grid. To design the rating of ultra-capacitor, the average power is calculated from the power generated at a place Bapatla (Andhra Pradesh) situated in India on a day 11 November 2009 [8], and it is found to be nearly 750 kW for that day. Fig 3 shows the DFIG based WECS with ultra capacitor in the dc-link as a storage system.

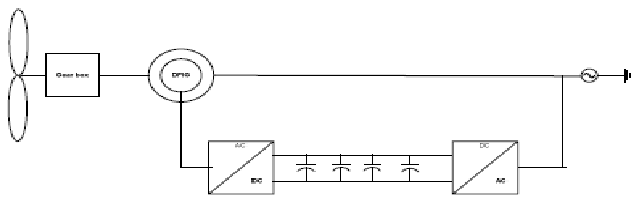

Fig. 3: DFIG based WECS with Ultra Capacitor in Dc-Link

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IV. SYSTEM CONTROL SCHEME

The control system of GSC and RSC has both active and reactive power loops.. The active power loop of the system helps to maintain constant power on the grid side. With the help of this strategy extreme power from the wind can be extricated and unity power factor operation of the stator in the RSC side can be maintained. The strategy for active power loop is taken from the literature at unity power factor [6] but the reactive power control strategy considering non-unity power factor is done as a part of this work.

V. RESULTS AND DISCUSSION

MATLAB/SIMULINK is used to analyze the grid power, rotor speed and stored power for the DFIG based WECS for three different wind speeds (super synchronous, synchronous, sub synchronous) considering ultra-capacitor in place of battery and the results are discussed below.

A. Sub-Synchronous Speed

Figure 4 shows the performance of DFIG based WECS with ultra-capacitor in the dc link at sub-synchronous speed. From figure 4(a) we can see that the grid power is maintained constant at 0.75MW.The rotor speed is taken as 0.9 p.u. for sub synchronous speed as can be seen from Fig 4(b). At sub synchronous speed, the ultra capacitor discharges power to maintain grid power leveling and so the power is obtained at negative value as shown in Fig 4(c). Fig 4(d) shows the dc-link voltage.

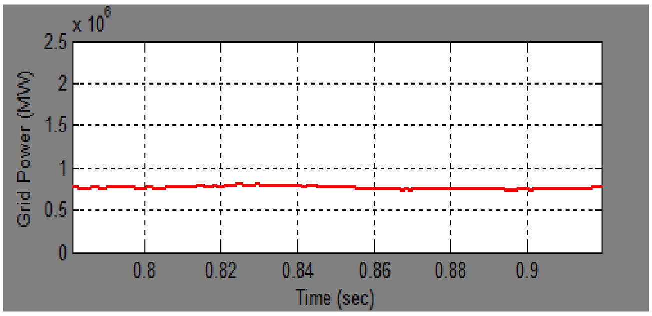

Fig. 4(a) Grid Power at Sub Synchronous Speed

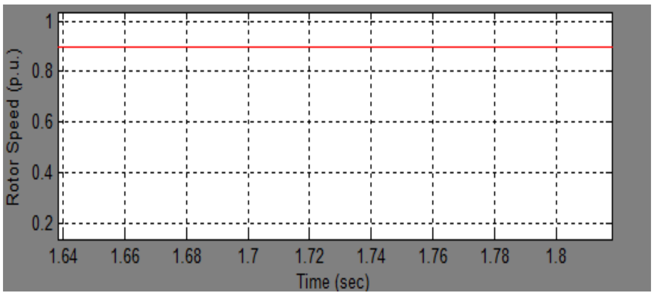

Fig. 4(b) Rotor Speed at Sub Synchronous Speed

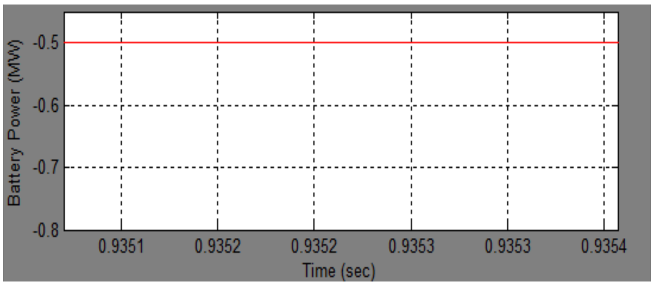

Fig. 4(c) Power at Sub Synchronous Speed

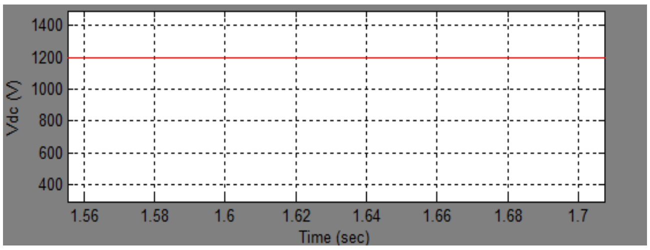

Fig. 4(d) Dc-Link Voltage at Sub Synchronous Speed

B. Super-Synchronous Speed

Figure 5 shows the performance of DFIG based WECS with ultra-capacitor in the dc link at super-synchronous speed. From the figure 5(a) we can see that the grid power is maintained constant at 0.75MW.The rotor speed is taken as 1.2 p.u. for super synchronous speed as shown in Fig 5(b). At super synchronous speed, power is stored in the ultra capacitor as the generated power is more than the average power and so the power is obtained at positive value as shown in Fig 5(c). Fig 5(d) shows the dc-link voltage.

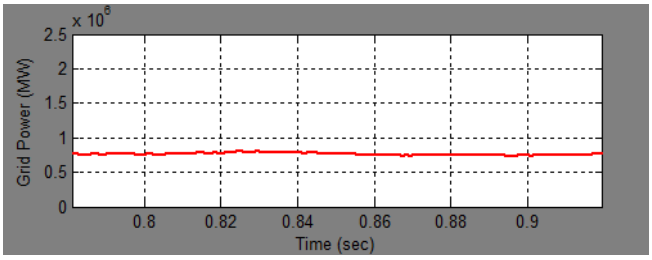

Fig. 5(a) Grid Power at Super Synchronous Speed

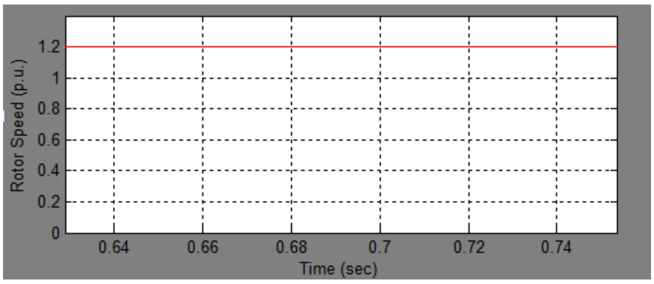

Fig. 5(b) Rotor Speed at Super Synchronous Speed

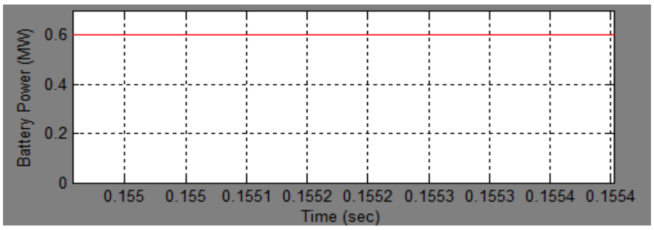

Fig. 5(c) Power at Super Synchronous Speed

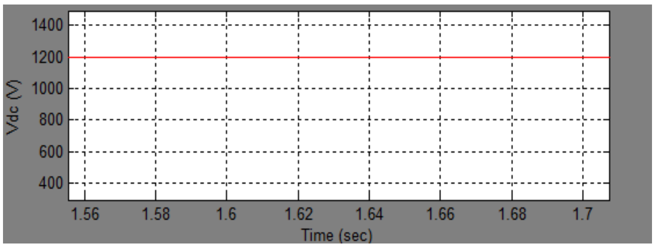

Fig. 5(d) Dc- Link Voltage at Super Synchronous Speed

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C. Synchronous Speed

Figure 6 shows the performance of DFIG based WECS with ultra-capacitor in the dc link at synchronous speed. From the figure 6(a) it is seen that the grid power is maintained constant at 0.75MW.The rotor speed is taken as 1 p.u. for synchronous speed and same can be seen from Fig 6(b). At synchronous speed, the power is slightly greater than zero as can be seen from the Fig 6(c). At synchronous speed neither charging nor discharging takes place. The dc-link voltage is shown in Fig 6(d).

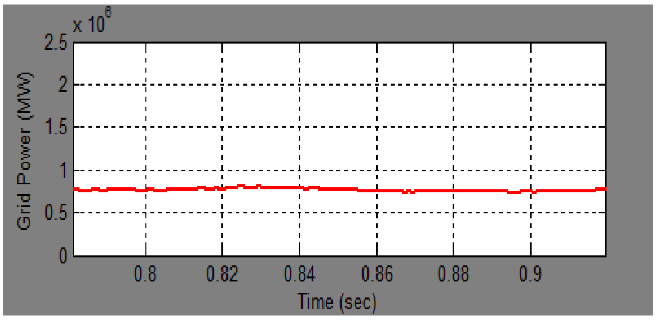

Fig. 6(a) Grid Power at Synchronous Speed

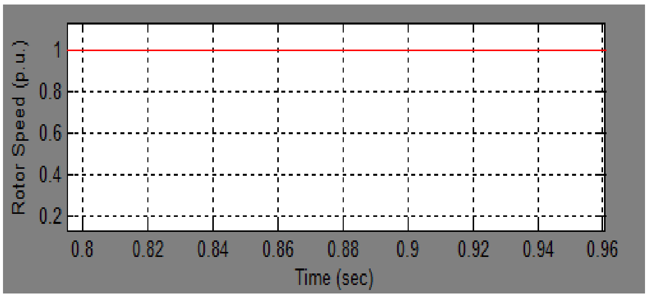

Fig. 6(b) Rotor Speed at Synchronous Speed

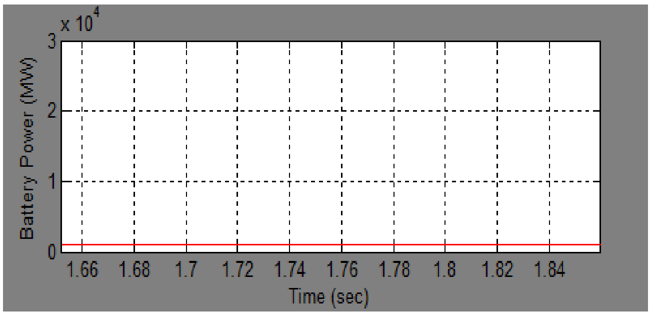

Fig. 6(c) Power at Synchronous Speed

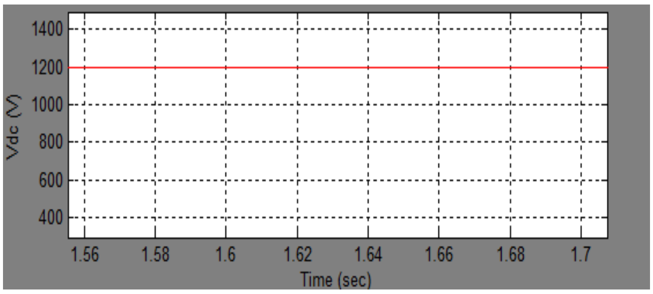

Fig. 6(d) Dc Link Voltage at Synchronous Speed

Load-leveling is an important issue because fluctuations in grid power may lead to several problems which includes damage of power electronic devices. In all the three wind speeds the grid power i.e the real power is maintained constant at 750KW with the help of control strategy. The dc-link voltage (V_{dc}) is also maintained constant as shown in Fig 4(d), 5(d), 6(d), failure of which will lead to damage of power electronic switches that are used in RSC and GSC.

D. Comparison between Ultra Capacitor and Battery

The figure 7 (a), (b) and (c) show the comparison of responses of ultra-capacitor, battery and battery and ultra-capacitor used together in the system in terms of dc link voltage. When ultra-capacitor is used in the system the stability in dc link voltage is reached between 0.4 sec to 0.6 sec as can be seen from the figure 7 (a).When battery is used the stability is achieved after 1sec as shown in figure 7 (b). With a large amount of wind power increasing every year, long-term storage is definitely becoming important. Using batteries and Ultra capacitor in the same system the amount of storage can be increased. It is a long-term storage system, also when both are used together in the system the stability in dc link voltage is reached before 0.5 as can be seen in the figure 7(c).

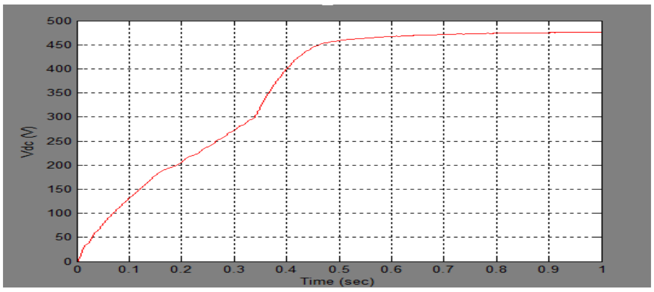

Fig. 7(a) VDC of Ultra Capacitor

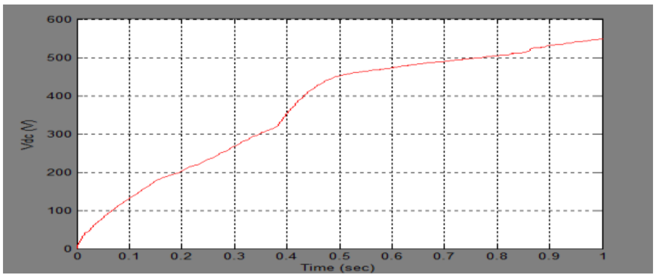

Fig. 7(b) VDC of Battery

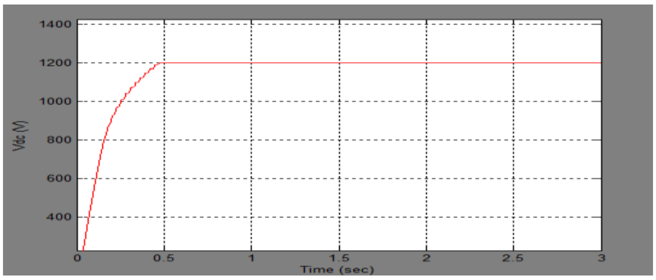

Fig. 7(c) VDC of Ultra Capacitor and Battery Together

VI. MODIFICATION IN TERMS OF REACTIVE POWER

Due to the development of wind power generation technology, variable-speed constant-frequency (VSCF) wind turbine generator system (WTGS) such as doubly fed induction generator (DFIG) has gradually become the mainstream model type in newly set-up wind farms.

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Such type of WTGS can achieve active and reactive power decoupling control, absorb or output reactive power according to the requirement of system operation plan and control strategy, so that they can be applied in the voltage control of wind farms. Currently many operators prefer unity power factor operation (UPF), but with increasing levels of wind power penetration into the grid, ancillary services of DFIG such as voltage control and network reactive power support are becoming more important. A coordinated control of DFIG and fixed speed induction generator based wind farms is already illustrated in literature [9], where the RSC is used to provide reactive power support to the network, but GSC contribution is not taken to account. If both the GSC and RSC are used, care must be taken to ensure that the operation is coordinated to avoid the risk of circulating reactive power currents between the DFIG and GSC. Therefore, it is proposed that either to designate the GSC, or the RSC as the default voltage controller while the other one only commutes reactive power during transients [7]. Another coordination method presented in [7] uses both GSC and RSC for voltage regulation and sharing reactive power between them. This approach has a disadvantage that producing or absorbing reactive power by DFIG stator (RSC control) causes more losses and decreases the system efficiency. Hence in this paper the reactive power control of DFIG is considered where the RSC is used to provide reactive power support to the network and GSC is used as the default voltage controller. Figure 8 (a) shows the reactive power flow at unity power factor which is zero [6]. The reactive power is incorporated into the system by introducing inductive loads in the grid side and further compensated by connecting capacitors bank. The capacitance which is connected to the grid at time equal to 0.5 sec with the help of circuit breaker compensates the reactive power. The controller controls the reactive power consumed by inductive load at 0.2 p.u. The PI controller compares the reactive power with the reference signal (0.2 p.u.) and maintains it at this value till 0.5 sec at which the circuit breaker operates isolating the inductive load from the grid and so the reactive power drops to zero as shown in figure 8 (b).

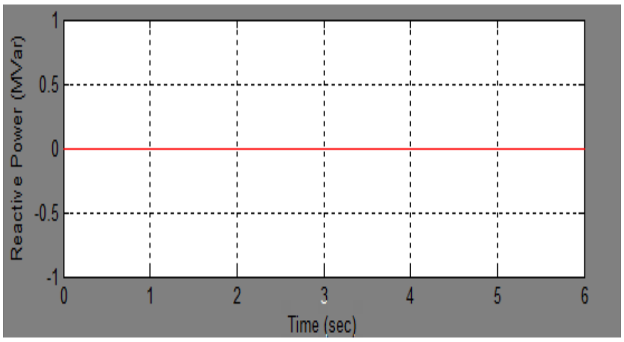

Fig. 8(a) Reactive Power with UPF as in [6]

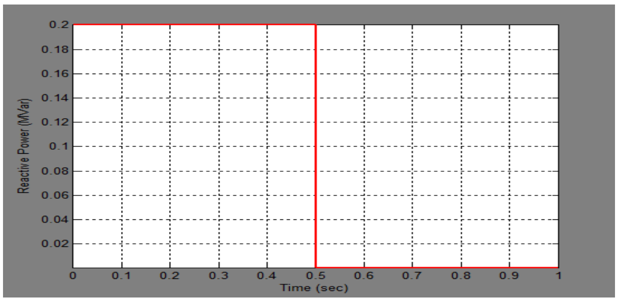

Fig. 8(b) Reactive Power Control with Capacitor

VII. CASE STUDY WITH 16 BUS IMPLEMENTATION

The validity of this new approach has been tested in 16 bus IEEE power distribution system. The results obtained shows considerable reduction in losses by reactive power compensation. The 16 bus distribution system is connected to two generators and one DFIG based wind turbine system and in the overall system the reactive power compensation is provided by the capacitors. The results obtained prove that due to the compensation provided the reactive power flow through the system is reduced to a great extent and thereby improving systems stability and reliability. By providing capacitive compensation at bus no 5 and 11 reactive power requirement comes down to -1 x 10^{-6} VAR and 8.9 x10^{-4} VAR for bus 5 and 11 respectively which was 0.026 VAR and 0.0275 VAR respectively. Fig 9 shows Reactive Power flow at buses 5 and 14 respectively with capacitive support.

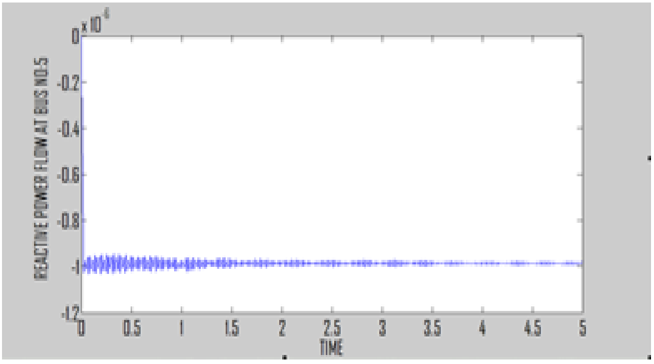

Fig. 9(a) Reactive Power Flow at Bus 5

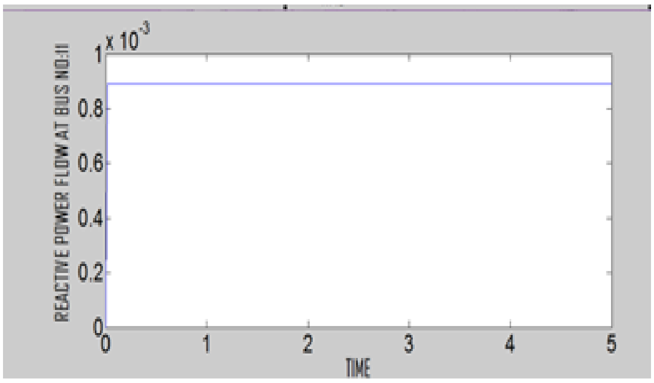

Fig. 9(b) Reactive Power Flow at Bus 14

VIII. CONCLUSION

A configuration of a DFIG based WECS with Ultra capacitor in the dc link has been proposed and demonstrated for different speeds (Sub-synchronous, Synchronous, Super-synchronous).The proposed strategy is compared with battery in the dc link and it has been found that the stability response of ultra capacitor is better than that of battery.As the penetration of wind power is increasing in electricity system,the ancillary service of DFIG i.e. reactive power control is also implemented in the proposed system.To analyse a practical implementation, this approach is studied in 16 bus IEEE power distribution system.

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