

Power Smoothing of DFIG based WECS using Lithium-Ion Capacitor

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ABSTRACT: Wind energy is a fluctuating and unpredictable energy source. The output power produced by wind turbine generators is varied due to the variations of wind velocity. This fluctuating nature of power causes voltage and frequency deviations from nominal values which may lead to activation of relay, that may result in disconnection of wind turbines from grid. In this paper, Lithium-Ion capacitor is used as short term energy storage device in doubly fed Induction generator based wind energy conversion system to mitigate high frequency power fluctuations. Simulation studies are carried out in MATLAB on a wind farm equipped with 9 DFIG based wind turbines to verify the effectiveness of proposed scheme.

KEYWORDS: Doubly fed Induction generator (DFIG), Energy storage, Lithium-Ion capacitor, Wind Energy Conversion System (WECS).

I. INTRODUCTION

Despite advantages of wind energy, there are many technical challenges to integrate large amount of wind energy. The wind speed variations are the causes of many technical issues that have to be addressed in order to make utilization of this energy source as economically reliable. During integration of wind energy, power fluctuations can cause frequency and voltage deviations and which results in difficulties in power system operation planning, optimal scheduling, and unit commitment. Voltage and frequency deviations can also be significant in cases when wind turbines are connected to a weak grid or in the distributed power generation system when wind power supplies local loads at the distribution level. Due to these problems associated with grid integration of wind energy conversion system, utility companies are developing technical requirements which have to be met in order to wind power plants into the grid. The major technical requirements are defined by the standard IEEE1547-2004, FERC Order No. 661A and regional and reliability organizations (RRO) that describe requirements that has to be satisfied by any grid connected power sources.

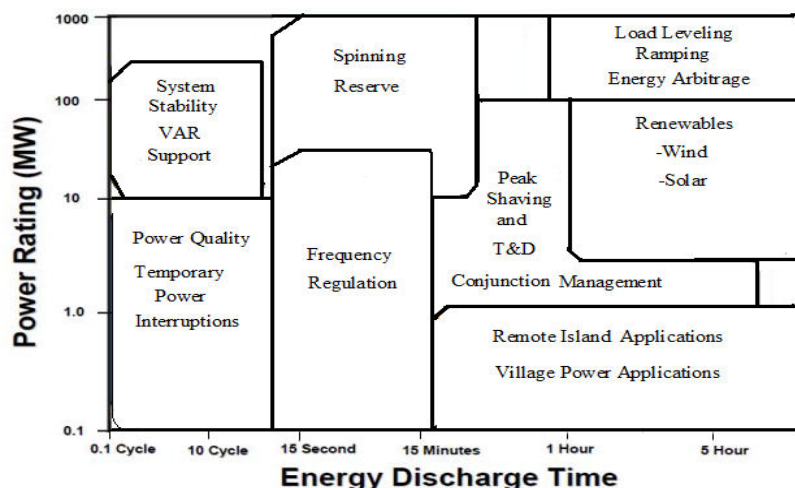


Fig.1 Energy storage applications in power systems [10]

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Frequency and voltage deviations can cause relay to trip which may have severe impact on power system stability and may lead to power outages. In [1], the authors described the impact of power variations caused by WPPs in power system consisting of numerous thermal power plants. They also analyzed the filtering capabilities of governor control and automatic generator control systems to filter power fluctuations. The spectrum of output power from wind turbine can be divided in three regions. The slow power variations can be mitigated by automatic generator control (AGC) and fast power variations can be compensated by governor control system, while filtering of medium frequency power fluctuations in range of 0.01Hz-0.1Hz remains poor, which restricts the maximum wind power penetration without causing significant frequency deviations. In large synchronous generators, the governor systems are responsible for frequency control of a power system. The large power variations cause increased wear on governor systems of generators in conventional power plants in power systems with large wind power penetration [2]. In [2], the authors proposed a detailed model of small power system consisting of thermal power plant and wind farms and explained that maximum allowed frequency deviation of 1% from the nominal value limits the peak power fluctuation from WPPs to 5% of total rated power of thermal power plants. In [3], the authors described that energy storage can increase power system reliability during low wind speed conditions.

In [4], the projected method combines blade pitch control and primary speed control of the generator to reduce power fluctuations that result in frequency deviations. The method proposed in [5] is based on prediction of wind speed to optimize output power set point that would result in reduced frequency deviations. Various methods are proposed to address the issues of variable power output of wind turbines on electrical power systems. These methods can generally be divided into two categories: methods that do not require energy storage [6]–[9], and methods which use additional energy storage systems [12]–[21].

II. ENERGY STORAGE FOR WIND APPLICATIONS

Energy storage is necessary for a WPP to make possible to meet imposed limits from power system operation and dispatching control, such as power ramp rate limiting or power shifting when a wind turbine has to provide power even if there is not sufficient wind. Fig. 1 illustrates energy storage applications based on energy and power density in power systems [10]. Reference [11] gives an outline of various energy storage systems and their applications in renewable energy resources. Advantages of using energy storage in a real WPP are explained in [12] and [13]. In [12], the author explains the increase of power system reliability and system efficiency by using energy storage. The energy storage in [13], is used to store energy during the maximum power production. It can be later used, when power production is low due to reduced wind speed. As a result, the wind power plant with storage increases the power system availability. In [14], the authors analyze the control method of energy storage that optimizes usage of the storage capacity under constraints such as limits on charge and discharge rates and upper and lower limits on state of charge. Another configuration based on STATCOM and battery bank connected at the terminals of a wind turbine is explained in [15]. In [16], the authors proposed the energy storage based on a zinc-bromine flow battery for wind energy conversion system. The Control system is based on artificial neural network (ANN) manages energy storage which increases predictability of the power production by the wind turbine. The application of SMES for increased stability of a wind turbine connected to the grid is proposed in [17]. In spite of its high efficiency and high power density of SMES systems, the cost of such systems still limits the practical applicability.

In [18], the authors analyzed the operation of a power system with large scale wind energy integration and large compressed air energy storage (CAES). All these methods, deal with very low frequency power variations called long term power variations which require large energy density storage systems. On the other hand, the methods which deal with higher frequencies, called short term power variations that typically needs larger power density as large amounts of power has to be stored or released in short time intervals.

Electrolytic double layer ultra capacitor (EDLC) is used as energy storage for wind power applications have been proposed by several researchers [19]–[21]. In [19], a variable speed doubly fed induction generator (DFIG) is equipped with ultra capacitor energy storage system (UCESS) connected to the DC link of the rotor side back to back power conversion circuit is proposed. The ultra capacitor module along with buck/boost DC/DC converter is connected to the DC link. The Ultra capacitor energy storage management system is based on fuzzy rule-based controller which uses prediction algorithm and state of charge of the ultra capacitor module to calculate the reference for the output power that

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will be supplied to the grid. In [18], another method of ultra capacitor storage integration into energy conversion system of Wind power plants is proposed. In this, the ultra capacitor module is connected through a DC/DC converter and a current source inverter (CSI) to the AC terminals of an induction generator based wind turbines. The reference for the current controller of the CSI is calculated using low pass filter (LPF). The reactive power at the AC terminals of the wind turbine is also controlled using an energy storage associated with power conversion circuit. Similar configuration is explained in [21], with voltage source inverter instead of CSI. Although these methods effectively reduce power fluctuations, the main disadvantage of these methods is the need of two additional conversion stages—DC/DC in addition to DC/AC converter. The power losses on these converter stages considerably reduce efficiency. In addition, control system is more complex and thus reduced reliability.

In this paper, a novel method for output power smoothing by using ultra capacitor in the DC link of a DFIG-based WECS is proposed. The ultra capacitor module is connected directly to the DC link and therefore not requiring additional DC/DC converter. The Li-ion capacitors are used due to their higher energy density and power density as compared with the EDLC. Lithium-ion capacitors are considered as a solution for short term power fluctuation. The proposed method has been evaluated by excessive simulations using MATLAB/SIMULINK environment.

III. LITHIUM-ION CAPACITORS

Li-ion capacitors are ultra capacitor that store energy in form of potential energy of electrostatic field, in the same way as ordinary capacitors. The difference is that ultra capacitors have much larger capacitance, as its name suggests. The attractive characteristic of ultra capacitors is that no chemical reactions are involved in energy storage/release process and therefore the life cycle has increased as compared to batteries. Li-ion capacitors structure have illustrated in Fig. 2.

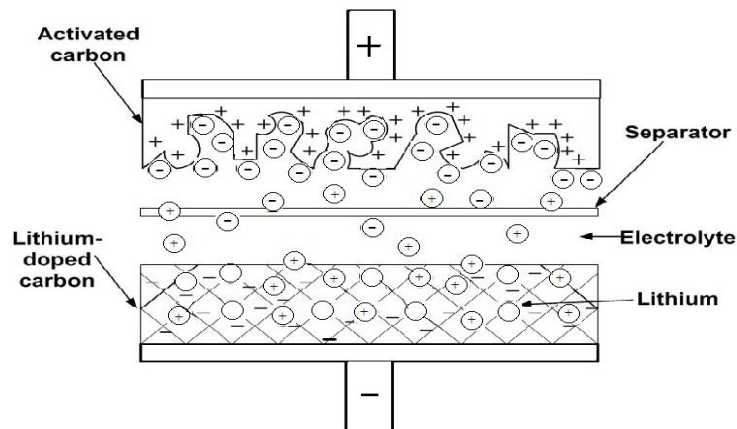


Fig.2 Structure of a lithium-ion capacitor

Positive electrode is a metal plate coated with activated carbon and this is similar to an electrode of an EDLC. Negative electrode is a metal plate coated with lithium-doped carbon and it is very similar to the negative electrode of a lithium-ion battery. An additional similarity is the electrolyte used is lithium salt organic solution.

During charging process, negative ions from electrolyte travels toward the positive electrode that has large surface area due to activated carbon. At the same time, positive ions are being intercalated into carbon-coated negative electrode. The process is inverted during discharging. Voltage has to be low, in order to avoid chemical reactions between electrolyte and carbon. However, main advantage of lithium ion ultra capacitors over EDLC is that voltage between electrodes can be increased nearly twice, due to lithium doping of the negative electrode. Energy stored in a capacitor is proportional to capacitance and the square of voltage across its terminals. As a result, lithium ion ultra capacitors have close to four time larger energy density compared to EDLC, while keeping equally large power density.

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IV. EQUIVALENT CIRCUIT MODEL OF LITHIUM-ION CAPACITOR

A mathematical model of an ultra capacitor is a set of differential equations that gives a relation between voltage, current, and temperature throughout charging and discharging processes. There are several approaches for modeling the ultra capacitors. Models based on equivalent circuits consist of serial and parallel combinations of resistors and capacitors which forms a circuit, which has similar voltage and current characteristics as the ultra capacitor [22]–[25]. Normally, series of tests required to be performed, during which the ultra capacitor was charged or discharged and voltage and current profiles were recorded [23]–[25]. In order to study electrical performance of a lithium-ion ultra capacitor cell, extensive laboratory tests were performed. The charging and discharging tests were repeated for various charging and discharging current profiles as described in [25]. The equivalent circuit is shown in fig 3.

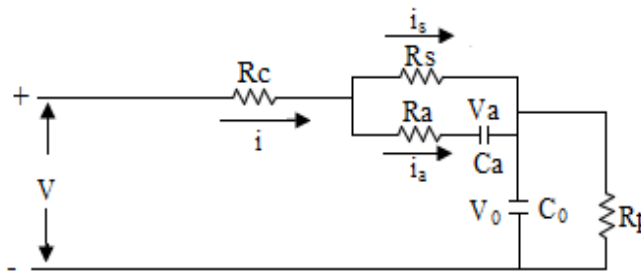


Fig.3 Equivalent circuit model of a lithium-ion capacitor

For the modeling purpose, this nonlinear voltage–capacitance dependence is approximated by the fourth order polynomial (1). The additional details about testing procedure and parameter calculation are given in [25].

$$C_o = a * V_{oc}^4 + b * V_{oc}^3 + c * V_{oc}^2 + d * V_{oc} + e \quad (1)$$

Where $a = -703.394$, $b = 9359.727$, $c = -45\ 480.904$, $d = 96\ 048.084$, and $e = -73\ 516.729$.

Self-discharging process is modeled by adding parallel resistor Rp. However, according to the manufacturer’s data, estimated discharging time from 3 to 2.2 V is 20 years. Also, laboratory measurements showed no change in the open circuit voltage (Voc) of an ultra capacitor cell for a period of 1 month. Therefore, it is valid to neglect this resistance in further calculation. From the equivalent circuit shown in Fig. 3, and by neglecting Rp, it follows:

$$i - i_s + i_a = 0 \quad (2)$$

$$v - R_c \cdot i + R_s \cdot i_s + v_{C_0} = 0 \quad (3)$$

$$R_s \cdot i_s - R_a \cdot i_a - v_{C_a} = 0 \quad (4)$$

$$i = C_0 \frac{dv_{C_0}}{dt} \quad (5)$$

$$i_a = C_a \frac{dv_{C_a}}{dt} \quad (6)$$

$$v = \left[1 \quad \frac{R_s}{R_s + R_a} \right] \begin{bmatrix} v_{C_0} \\ v_{C_a} \end{bmatrix} + \left[R_c + \frac{R_a \cdot R_s}{R_a + R_s} \right] [i] \quad (7)$$

In order to model series connection of the ultra capacitors the output voltage, (7) has to be multiplied by the number of capacitors in the series. Parallel connection is modelled by dividing input current by number of parallel branches. For practical application of the ultra capacitor-based energy storage, multiple series strings of ultra capacitors should be

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connected in parallel, thus forming the energy storage module. A model of the capacitor is built and added to the Simulink model of a grid connected DFIG-based WECS.

V. LI-ION CAPACITORS IN THE DC LINK OF DFIG BASED CONVERSION SYSTEM

Conventional wind turbines based on power conversion system have electrolytic capacitor in DC link. This capacitor simply filters the voltage ripple of the DC link voltage and cannot store significant amount of energy, relative to the energy produced by the wind turbines. To reduce the cost of power electronic components and to store significant amount of energy, instead of connecting the storage such as Ultra capacitors via DC/DC converter, the short-term energy storage is placed on the DC bus. The block diagram of DFIG based wind energy conversion system is shown in fig 4.

Wind is highly unpredictable in nature, so variable speed DFIG based WECS has many advantages compared to the squirrel cage induction generators and permanent magnet synchronous generators, such as reduced converter rating, cost and losses. Therefore it results in enhanced efficiency, easy implementation of power factor correction, variable speed operation and four quadrants active and reactive power control capabilities.

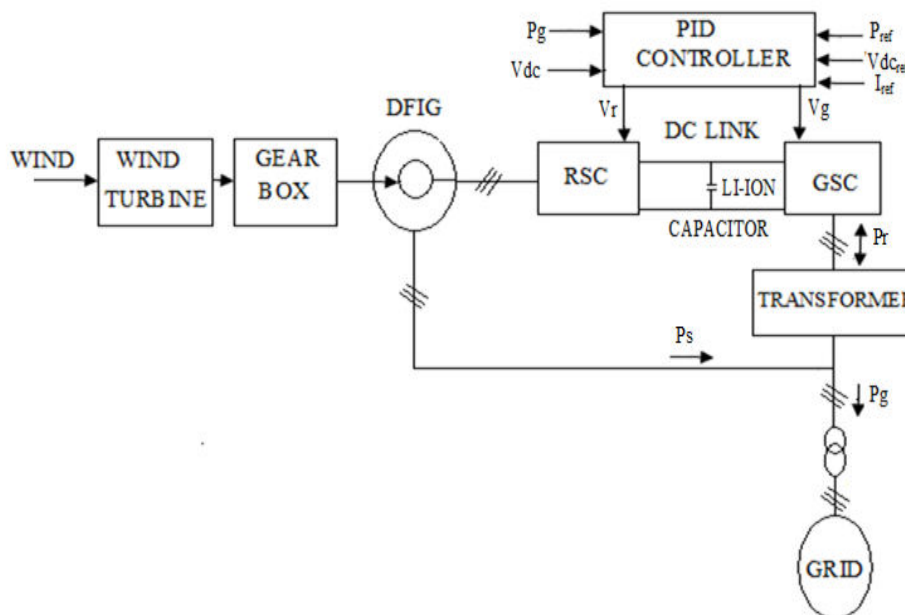


Fig.4 Energy storage on the DC link of a DFIG-based wind turbine.

The wind turbine absorbs kinetic energy from the wind and converts it into mechanical energy. The output power (P) produced from wind power systems varies as cube of the wind velocity and it is given by

$$P = 0.5 * C_p \rho A V^3 \tag{7}$$

where C_p is the power coefficient, ρ is air density, A is intercept area and V is wind velocity. The power coefficient is defined as the ratio of maximum power extracted from wind to actual power available in the wind. The maximum theoretical power coefficient is 0.593 and this is called as Betz limit.

The mechanical energy is fed as an input to DFIG through gear box. In this, the stator is directly connected to the grid and the rotor connected to grid via back to back converter. The back to back converter is used to convert slip frequency into line frequency. The rotor side converter is used to control the torque production of DFIG through direct control of rotor currents. The grid side converter controls the power factor and maintains the dc link voltage as constant.

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The DFIG will operate in two modes: sub synchronous mode and super synchronous mode. At sub synchronous speed, only stator supplies power to grid. During super synchronous speed, both stator and rotor supplies power to grid. The stator power (P_s) and rotor power (P_r) depends on the following equations.

$$P_s = \frac{P_m}{1 - s} \tag{8}$$

$$P_r = -\frac{sP_m}{1 - s} \tag{9}$$

Where P_m is mechanical power and s is slip. Slip will be negative during super synchronous speed and positive during sub synchronous speed. In this PID controller is used due to its fast response, low overshoot, no offset and reduced oscillations. The lithium-ion capacitor is used to store the energy and reduce the power fluctuations. In addition the capacitor provide backup power for actuators in wind turbine pitch system, so blade pitch can be adjusted even if main supply fails.

VI. SIMULATION RESULTS

The case study illustrated the 9 MW wind farms consists of six 1.5MW wind turbines connected to a transmission system exports the power to the grid. The performance of DFIG with lithium-ion capacitor is analyzed and the simulated results are

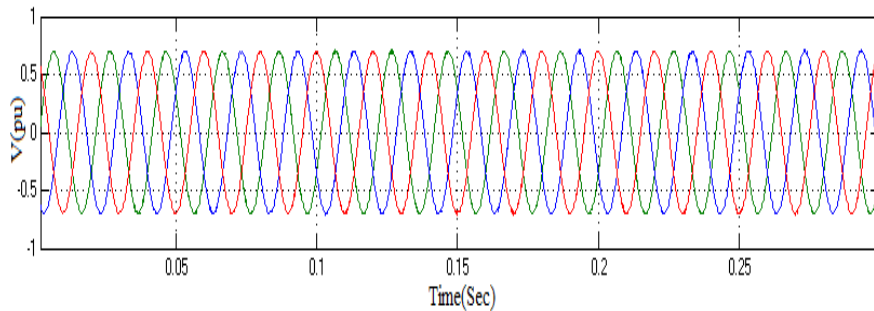


Fig.5 Generated Voltage

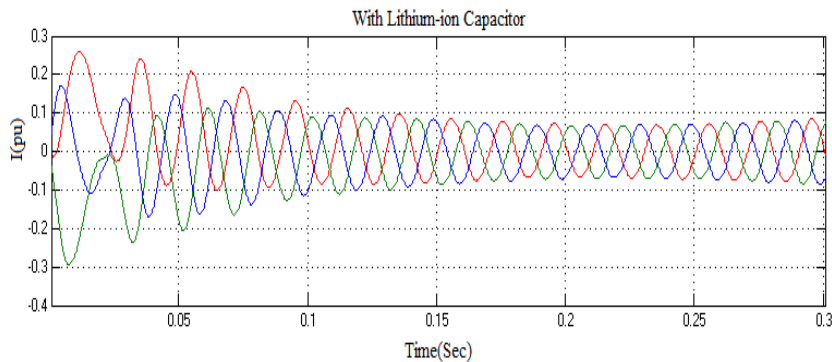


Fig.5 Current Waveform

Fig 5 shows the generated voltage of wind turbines and the output power developed from DFIG wind turbines is shown in fig 7.

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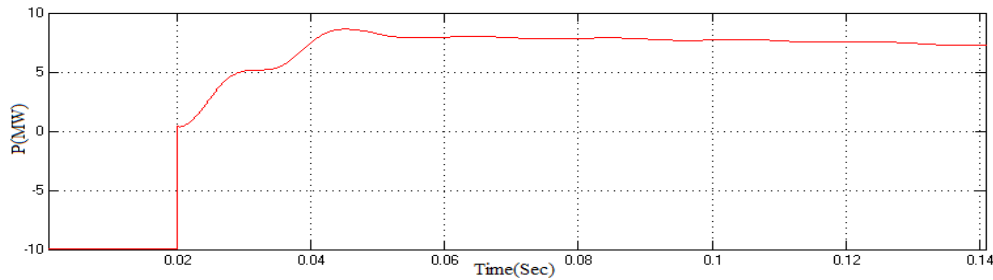


Fig.7 Real power

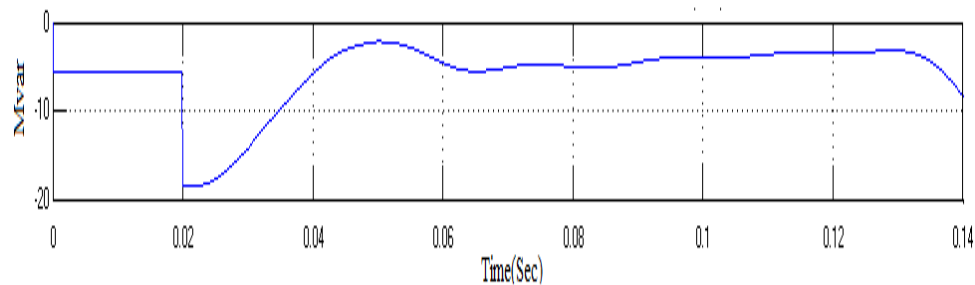


Fig.8 Reactive power

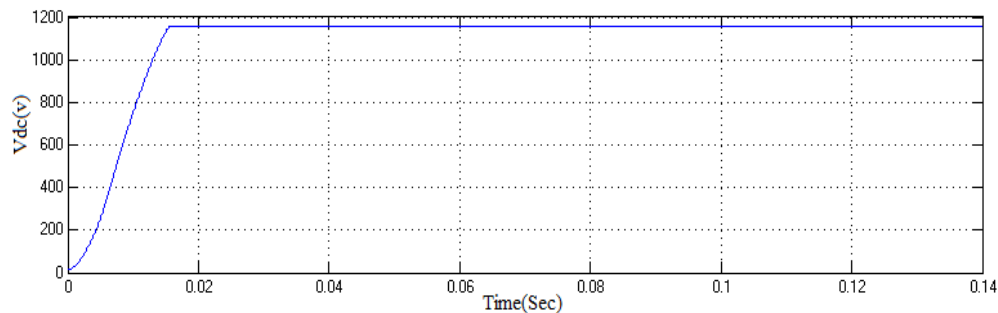


Fig.9 DC link voltage

Fig.9 shows the dc link voltage and it is maintained as constant to improve the power factor.

VII. CONCLUSION

In this paper, a new power conversion topology of a wind turbine incorporated with an energy storage element to reduce wind energy variations is presented. The energy storage device is Lithium-ion capacitor with higher energy and power density compared with existing ELDC technology. The capacitors are directly connected to the DC bus to avoid the extra power conversion stage. Detailed modeling of the wind energy conversion system with the energy storage has been performed. The analysis shows that the proposed system can be very effective to smooth the output power of wind turbines.

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