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Hybrid Protection to Enhance the LVRT Capability of a Wind Turbine Based DFIG

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Abstract: The problems posed by electric energy generation from fossil sources are, high costs due to large demand and limited resources, pollution and large volume of CO_2 production. These problems can be overcome by alternative sources that are renewable energy sources which are cheap, easily available, pollution free and sustainable. The most widely used variable speed machine for wind turbine is the doubly fed induction generator (DFIG). As the wind power penetration continues to increase, wind turbines are required to provide Low Voltage Ride-Through (LVRT) capability. In order to enhance the low voltage ride through (LVRT) capability of a wind turbine driven doubly fed induction generator (DFIG), a combined protection and control strategy including the Active Crowbar (AC) and Battery Energy Storage System (BESS) is proposed in this paper, hence we call it as Hybrid protection. Normally, when the grid fault occurs, the crowbar is triggered if the overvoltage in DC bus or the over-current in rotor winding exceeds the corresponding threshold value. Simulation results are shows the improved performance of the DFIG.

Keywords: Doubly Fed Induction Generator (DFIG), Low Voltage Ride through (LVRT), Active Crowbar (AC) & Battery Energy Storage

1. Introduction

TWENTY first century is becoming green and clean electric power industry as world's energy sources in crisis and environment pollution increasingly; renewable energy has become a new development trend in future. Utilization of renewable energy coming up from view points of environmental conservation and depletion of fossil fuel. Renewable energies such as solar, wind, hydro power and others are a promising alternative to fossil fuels. Renewable energy is relatively cheap, widely available, and the supply is unlimited. Costs have come down considerably and are now close to competitive with fossil fuels. Some of renewable, notably wind, are intermittent and thus a poor match for electricity systems. But still we are going for wind energy for electricity generation because it is abundantly available in nature for free of cost.

Advancements in power electronics, made easy to control active and reactive powers independently with small capacity converters, the double fed induction generator (DFIG) has been widely used in wind power generation [1]-[2]. To connect the wind turbine DFIG with the grid need to control the low voltage ride through (LVRT) problem.

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In order to protect the rotor side converter, should switch the protective device (i.e Crowbar) to short-circuit the rotor of the doubly-fed generator [3-5], in order to protect the DC side capacitors and to enable the DC-side voltage stability generally use unloading unit to consume the excess energy of the DC side [6], [7] presented a storage battery, but only analysis smooth out the output powers or maintain a desirable power output as the wind speed varies.

This paper presents a combination of crowbar and BESS protection and control strategy to improve the transient performance of the DFIG. A wind farm including six DFIG with capacity of 1.5MW wind turbines is simulated to verify the effectiveness of this method. Each DFIG is equipped with an active crowbar and a battery energy storage device. A control scheme which is auto-switching the crowbar according to the size of rotor current is adopted for the crowbar protection to decrease the adverse effects on the system which is caused by the crowbar premature or too late removal. A combined control scheme is used for the battery energy storage devices to attenuate the transient DC voltage ripple in the DC bus when voltage sags in power failure situations. The combined protection and control strategy are tested on a simulation model. Results show that the hybrid protection and control strategy can well protected the rotor side converter and the dc side capacitor during the power system on fault condition.

2. Power flow of Doubly fed Induction Generator (DFIG)

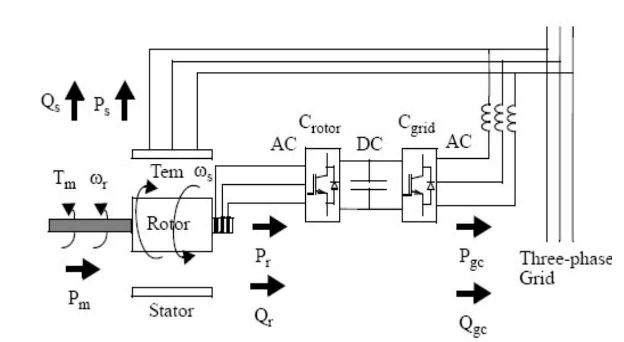

Fig.1 Power flow diagram of DFIG

Figure 1 shows the power flow diagram of DFIG. In this slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor- or stator-side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor- side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, rotor-side converter operates as an inverter and stator side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine.

Generally the absolute value of slip is much lower than 1 and, consequently, P_r is only a fraction of Ps. Since Tm is positive for power generation and since Ws is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super synchronous speed operation, Pr is transmitted to DC bus capacitor and tends to raise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter P_{gc} is equal to Pr and the speed of the wind turbine is determined by the power P_r absorbed or generated by C_{rotor}. The phase-sequence of the AC voltage generated by C_{rotor} is positive for sub-synchronous speed and negative for super synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. C_{rotor} and C_{grid} have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

3. Modelling of Protective Devices

3.1. Modelling of Active Crowbar

The block diagram of DFIG with both the crowbar protection and battery energy storage system (BESS) is shown in figure 2. The crowbar is connected to the rotor circuit to protect the rotor side converter. BESS is connected in between the back to back converters and across the DC link capacitor. Its function is to maintain the DC link voltage at constant value.

The crowbar may comprise of a set of thyristors that will short-circuit the rotor windings when triggered and thereby limit the rotor voltage and provide an additional path for the rotor current. Different values of the crowbar resistors result in a different behaviour. The active crowbar is composed of three-phase Diode Bridge in series with a bypass resistor and an IGBT power switch. A switching function is defined for the power switch, which takes the values, 1 when the switch is closed and 0 for its open state. The operation of the crowbar protection can be expressed as:

Activated, s =1
Inactivated, s = 0

The dynamic behaviour of such system during grid faults is very sensitive to the value of the bypass resistor, the resistor should be properly selected to limit the over current, and also to avoid large voltage ripple in DC bus.

3.2. Modelling of Battery Energy Storage System

The battery stores energy in the electrochemical form, and is the most widely used device for energy storage in a variety of applications. The characteristics of the rechargeable battery are given by:

$$V_b = V_o - R_b i_b - k\frac{Q}{(Q-\int i_b dt)} + Ae^{(-B\int i_b dt)} \quad \ldots\ldots(1)$$

$$SOC = 100\left(1-\frac{\int i_b dt}{Q}\right) \quad \ldots\ldots\ldots(2)$$

Where R_b is the internal resistance of the battery, Vo is the open circuit potential (V), K is the polarization voltage (V), Q is the battery capacity(Ah), A is the exponential voltage (V), and B is the exponential capacity (Ah). The battery is in discharging state if it is positive, while in charging state if it is negative. The State-

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Of-Charge for a fully charged battery is 100% and for an empty battery is 0%.

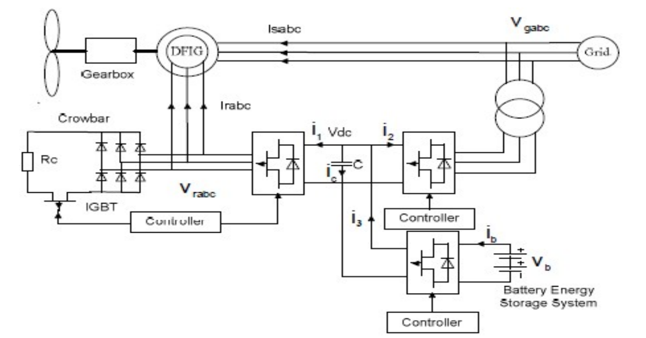

Fig.2 DFIG with hybrid Protection

4. Control Strategy of the protective Devices

4.1 Crowbar Control Strategy

Normally, when the grid fault occurs, the crowbar is triggered if the overvoltage in DC bus or the over-current in rotor winding exceeds the corresponding threshold value. In the mean time, the rotor-side converter will be disconnected from rotor winding by cutting off the pulses of the power switches in the rotor-side converter. The crowbar will be activated during the whole fault inter valueless the grid fault is cleared. During this interval, the controllability of the DFIG is lost, even worse, as a result, the DFIG will behave as a squirrel cage induction generator with a variable rotor resistance and absorb large amount of reactive power from the grid which will lead to the system voltage dips further. In order to improve this main drawback of the crowbar protection, a kind of control strategy is adopted to minimize the operation time of the crowbar for a particular voltage dip. With the proposed control strategy, the crowbar is activated and the rotor-side converter is disabled once the rotor current exceeds the predefined threshold value i.e. 1.5.The crowbar will be cut off and the rotor-side converter is restarted if the rotor current decreases to be less than a safety value. This control strategy is demonstrated with the figure 3.

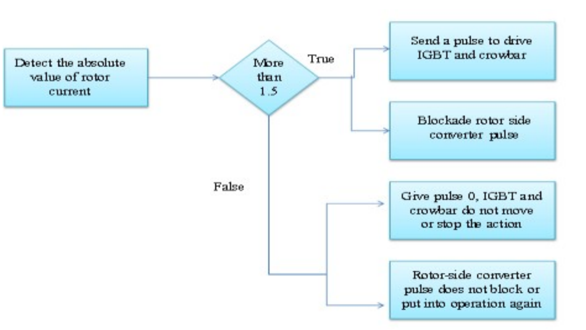

Fig. 3 Control strategy of Crowbar

4.2 BESS Control Strategy

The objective of battery-side converter is to maintain the DC bus voltage stable. Assume that the power losses in the three converters and the harmonics due to the switching actions are ignored, the following relationship can be obtained

$$\frac{V_{ds}(s)}{i_b(s)} = \frac{V_b}{CV_{ds}(s)} \quad \dots\dots\dots(3)$$

Equation (3) indicates that the transfer function from DC voltage and battery current is a linear first- order system. Therefore, a cascade control strategy is applied for the control of battery-side converter. The outer regulation loop consisting of a DC voltage controller is used to maintain the DC voltage stable under fault condition. The output of the DC voltage controller is considered as the reference current i_b ref for the inner current controller. The inner current regulator is to force the battery current to follow the reference produced by the outer voltage control loop. The schematic diagram of battery-side converter control is shown in Figure 4.

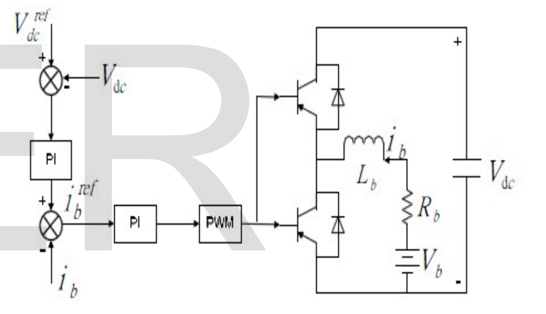

Fig. 4 Control diagram of the BEES bidirectional converter

As shown in the figure 4, V_{dc} reference is taken as 1200 V which is compared with the value of V_{dc}. The error signal is sent to the PI controller. The PI controller is used to reduce the rate of change of error. This is called as outer loop of the BESS which is used to maintain a constant voltage across the dc link capacitor. The difference value sent through the PI controller which is converted into current which is i_b reference. This ib reference value is compared with the i_b value taken from the battery. The battery is connected with an inductor and a resistor in order to limit the high currents which flow through the battery in fault conditions. The two converters G1 and G2 are connected to the battery for charging and discharging purposes.

5. SIMULATION RESULTS

This combined protection and control strategy to improve the transient performance of the DFIG. A wind farm including six 1.5MW wind turbines is simulated to verify the effectiveness of this method the simulation model was show in figure 5.

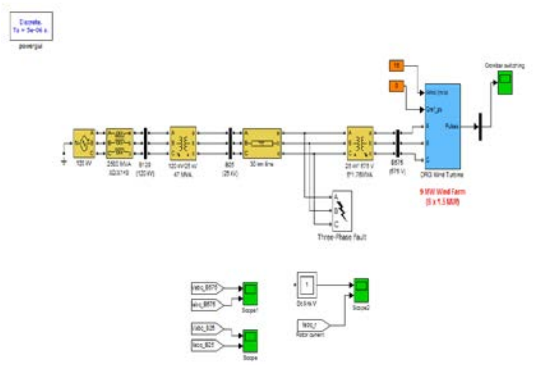

Fig. 5 Simulation block of a wind turbine DFIG connected to power network

For wind speeds lower than 10 m/s the rotor is running at sub synchronous speed. At high wind speed it is running at hyper synchronous speed. The turbine mechanical power as function of turbine speed is displayed for wind speeds ranging from 5 m/s to 16.2 m/s.

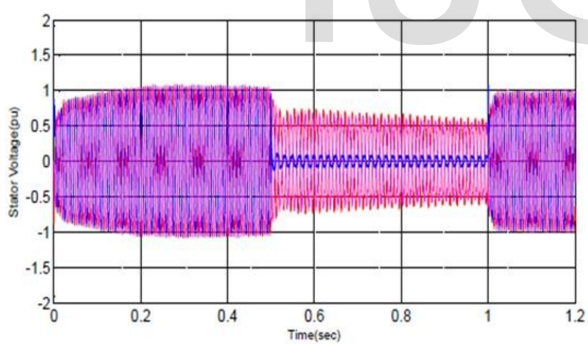

Fig.6 Stator voltages without protection under 2LG fault

The stator (p.u) voltages without protection under the 2LG fault condition are shown in the figure 6. The fault condition is considered to occur at 0.5 seconds to 1 second, where the stator voltages are decreased from the previous constant voltage under normal condition

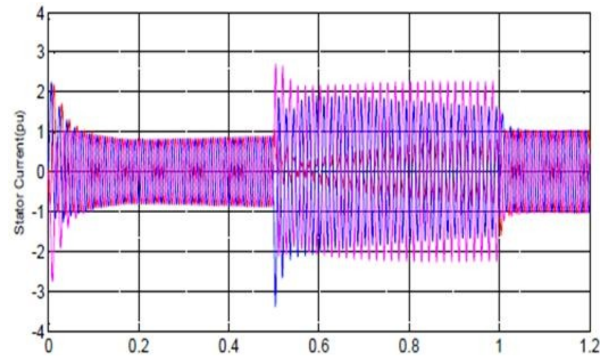

Fig.7 Stator currents without protection under 2LG fault

The stator currents without protection under the fault condition can be observed in the figure 7. It can be observed that under the fault condition the stator currents are increased than the previous value. These increases in currents are corresponding to the decreased stator voltages

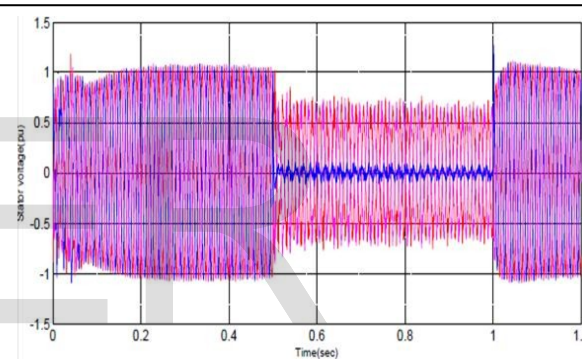

Fig.8 Stator voltages with crowbar and BESS 2LG fault

The stator voltages under the fault condition with the crowbar and BESS protection are shown in the figure 8.It can be observed that the magnitudes of the stator voltages are increased than the previous value of without protection and with only crowbar protection.

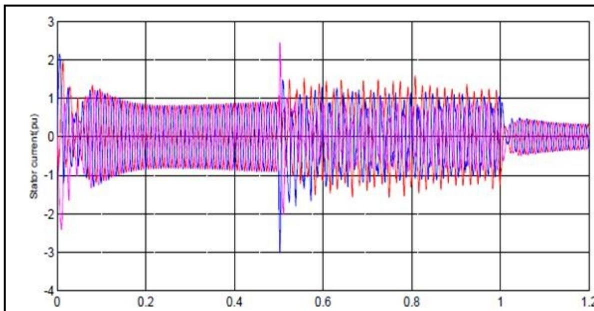

Fig.9 Stator currents with crowbar and BESS

The stator currents under the fault condition with the crowbar and BESS protection are shown in the figure

9. The magnitudes of the stator currents are decreased than the previous values without the protection and only with crowbar protection.

When compared to other graphs of individual protections of BESS and Crowbar protection there is a lot of improvement in the output of dc link capacitor voltage which is to be maintained as constant shown in figure 10.

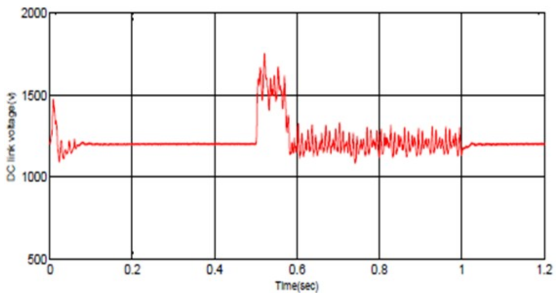

Fig.10 Dc link capacitor voltage with Crowbar and BESS (under 2LG fault condition)

From the figure 11,when compared to other graphs of individual crowbar and BESS protection in which the currents are slightly higher than the value of reference value that is 1.5pu. Thus we can say there is a great improvement in result because of the hybrid protection.

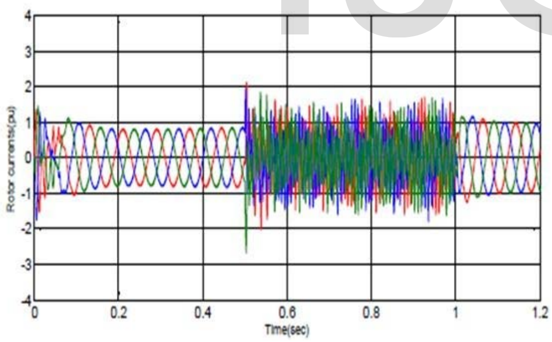

Fig.11 Rotor current with Crowbar and BESS (under 2LG fault condition)

Under fault condition that is from 0.5s to 1s the voltage across the capacitor rises to a peak value of 2200V, but we have used the crowbar protection only which tries to bring the voltage less than 2200 V show in figure 12. But by using hybrid protection we can maintain a constant voltage across the dc link capacitor of 1200 V which is the reference value.

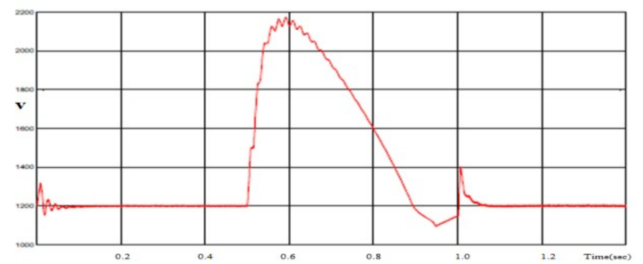

Fig.12 Capacitor dc link voltage with crowbar protection only (under 3LG fault condition)

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provided, the higher currents of the rotor are reduced to 2pu. By using the hybrid protection that is both crowbar and BESS we can reduce rotor current value to 1.5pu in figure 13.

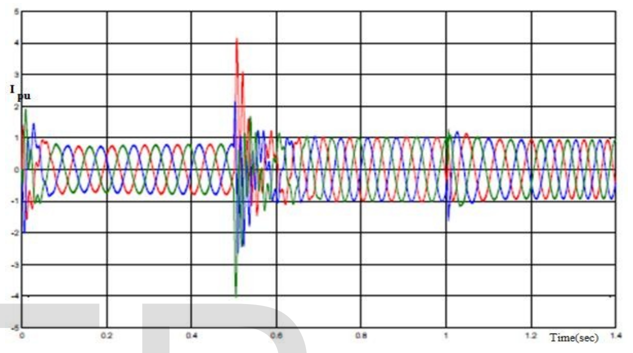

Fig.13 Rotor current with crowbar protection only (under 3LG fault condition)

The figure 14 represents the dc link capacitor voltage with crowbar protection only under 3LG fault condition. Under fault condition that is from 0.5s to1s the voltage across the capacitor rises to a peak value of 2200V, but we have used the crowbar protection only which tries to bring the voltage less than 2200V. But by using hybrid protection we can maintain a constant voltage across the dc link capacitor of 1200V which is the reference value.

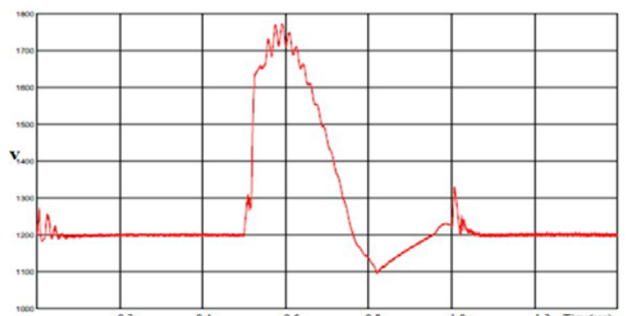

Fig.14 Dc link capacitor voltage with Crowbar and BESS (under 3LG fault condition

The figure 16 shows the crowbars ac voltages during its activation and deactivation time. Under the fault condition from 0.5s to 1s the crowbar is activated and its ac and dc voltages are as shown in the graph. Under normal condition that is before 0.5s and after 1s the crowbar is deactivated and its ac and dc voltages are as shown in the graph.

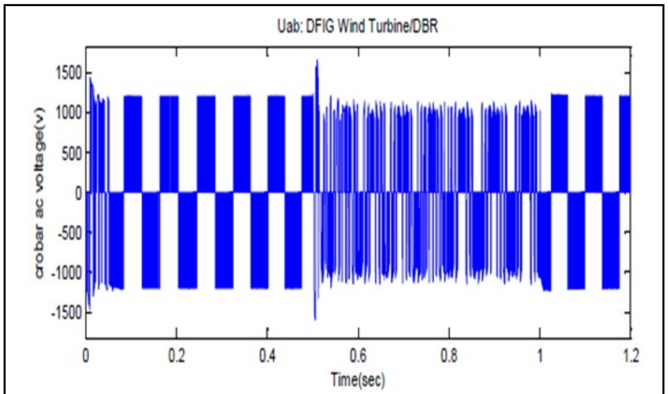

Fig.16 Crowbar ac voltages

The figure 17 represents the crowbars dc voltage during its activation and deactivation periods. During the fault condition from 0.5sec to 1 sec crowbar is activated and its corresponding voltages are shown in the graph.

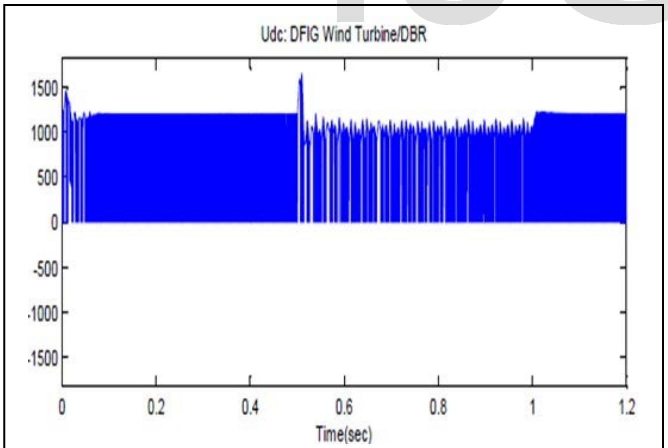

Fig.17 Crowbar dc voltage

The figure 18 represents the crowbar gate pulses during its activation and deactivation time. From the figure we can see the gate pulses which are activated from 0.5s to 1s which is the fault time (we have created fault in the grid at 0.5s to 1s) and under normal condition that is without any fault or after the clearance of the fault the crowbar is deactivated because of no gate pulses after or before the fault time.

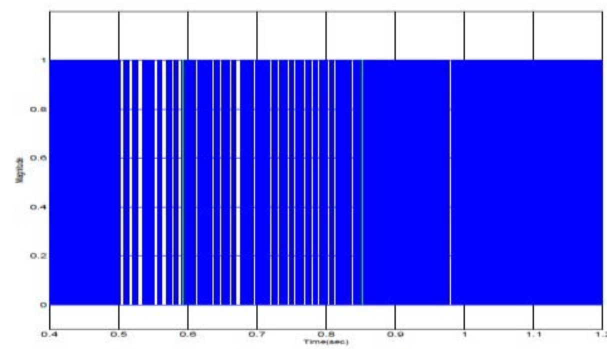

Fig.18 Crowbar gate pulses

The figure 19 represents the BES's state of charge (SOC). BESS's rate of change of power is shown in the graph (fig 6.13a). As shown in the graph from a time of 0.5sec to 1sec (that is during the fault condition in the grid) rate of change of power gradually decreases, which was initially high.

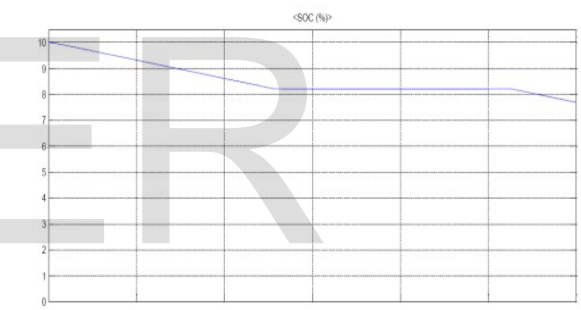

Fig.19 State of charge in BESS

The figure 20 represents the BESS combined gate pulses during its boost and buck operation. During the buck operation of BESS, the capacitor gets charged and the BESS is discharged. During the boost operation of BESS, the BESS is charged because of the presence of excess voltage across the dc link capacitor voltage. Because of these operations a constant voltage is maintained across the dc link capacitor.

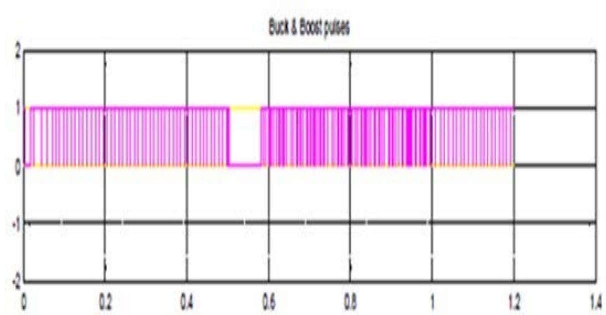

Fig.19 State of charge in BESS

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6. CONCLUSION

A combined protection and control strategy including Active Crowbar and Battery Energy Storage System has been presented to enhance the LVRT capability of a wind turbine driven DFIG. The mentioned control strategy of the Active Crowbar is not same as the conventional one, which can auto- switching the crowbar according to the size of rotor current. This paper also presented a battery energy storage system connected to the DC bus which is controlled to attenuate the DC voltage ripple via absorbing the redundant power stored in the DC link capacitor during the power system on fault condition, which can protect the DC side capacitor, thus improved the LVRT capability. The combined protection and control strategy are tested on a simulation model of a 1.5MW DFIG wind turbine system developed in MATLAB/Simulink R2012a (7.14.0.739). Simulation results show that the combined protection and control strategy can well protected the rotor side converter and the DC side capacitor during the power system on fault condition, thereby better improved the LVRT capability.

Integration of BESS with FACTS has been shown to further improve the transient stability of the whole system. The heat energy which is dissipating from the active crowbar can be utilized without wasting by using some energy storage systems. we can use advanced energy storage systems such as EDLC (Electric Double Layer Capacitor) in place of BESS. The double-layer capacitor (DLC) for power applications is a new device. Recently, the double-layer capacitor which has drawn attention as a new energy storage element has a lot of advantage such as no maintenance, long lifetime and quick charge/discharge characteristics with large current.

REFERENCES

[1] S. Towito, M. Berman, G. Yehuda, and R. Rabinovici,"Distribution Generation Case Study: Electric Wind Farm with Doubly Fed Induction Generators," IEEE 24thConvention of Electrical and Electronics Engineers in Israel, pp. 393 – 397, Nov.2006.

[2] R. Datta and V. T. Ranganathan, "Variable- speed wind power generation using doubly fed wound rotor induction – a comparison with alternative schemes,' IEEE Trans. Energy Conversion, vol. 17, no. 3, pp. 414-421, Sept. 2002.

[3] X. Dawei, R. Li, P. J. Tavner, and S. Yang, "Control of a doubly fed induction generator in a wind turbine during grid fault ride-through," IEEE Transactions on Energy Conversion, vol. 21, pp. 652-662, 2006.

[4] W. Gao, G. Wang, and J. Ning, "Development of low voltage ride-through control strategy for wind power generation using real time digital simulator," in 2009 IEEE/PES Power Systems Conference and Exposition, PSCE 2009, Seattle, WA,2009.

[5] X. G. Zhang and D. G. Xu, "Research on control of DFIG with active crowbar under symmetry voltage fault condition," Dianji yu Kongzhi Xuebao/Electric Machines and Control, vol. 13, pp.99-103,2009.

[6] E. Koutroulis, D. Kolokotsa, and G. Stravrakakis, "Optimal design and economic evaluation of a battery energy storage system for the maximization of the energy generated by wind farms in isolated electric grids," Wind Engineering, vol. 33, pp. 55-81, 2009.

[7] J. Zhenhua and Y. Xunwei, "Modeling and Control of an Integrated Wind Power Generation and Energy Storage System," in IEEE Power Energy Society General Meeting, 2009.