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Ahmed M. Haidar
University of Wollongong, ahaidar67@hotmail.com

Mehrdad Tarafdar Hagh
University of Wollongong, mehrdadh@uow.edu.au

Kashem M. Muttaqi
University of Wollongong, kashem@uow.edu.au

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Abstract

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Keywords

voltage, ride, super, capacitor, dc, link, improving, doubly, low, fed, induction, generator, wind, turbine

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Improving Low Voltage Ride-Through using Super Capacitor at the DC Link of Doubly-fed Induction Generator based Wind Turbine

Ahmed M. A. Haidar
School of Electrical, Computer and Telecommunications Engineering
University of Wollongong
NSW, Australia
ahaidar@uow.edu.au

Mehrdad T. Hagh
School of Electrical, Computer and Telecommunications Engineering
University of Wollongong
NSW, Australia
mehrdadh@uow.edu.au

Kashem M. Muttaqi
School of Electrical, Computer and Telecommunications Engineering
University of Wollongong
NSW, Australia
kashem@uow.edu.au

Abstract*—This paper presents a simple methodology to improve the low voltage ride-through (LVRT) capability of Doubly Fed Induction Generator (DFIG) based wind turbines in order to ride through higher voltage sags and durations. The proposed method is based on selection of an appropriate value for DC side super capacitor (SC) in such a way that it could help wind turbine for LVRT without any need to crowbar protection. The operation of SC based wind turbine in normal and fault conditions is simulated using MATLAB/SIMULINK. The simulation results show that the proposed method can be used effectively for LVRT improvement and it is not necessary to use crowbar in fault conditions.

***Index Terms*--- DC link; Super capacitor; Low voltage ride through; Fault ride through; Doubly-fed induction generator, Wind turbine**

I. INTRODUCTION

The development of renewable energy integration and the installation of high capacity wind turbine generators in power grid have become a new trend in recent years due to their attempt to reduce greenhouse gas emissions. Fixed speed wind turbines were mostly used in wind industry. However those turbines have a negative impact on power system dynamics. Recently, variable speed wind turbines became more popular choice providing very efficient utilisation of wind energy with maximum power extraction, low mechanical stress and low power fluctuation. One of the most effective schemes to utilize wind energy is a DFIG operating on variable speed and constant frequency principles. Application of DFIG has increased significantly in wind electricity generation mainly because of its following advantages:

1- The power rating of power electronic converters is about 30% of wind turbine power rating
2- It is possible to regulate the speed of DFIG in a wide range around synchronous speed.
3- DFIG can operate in both sub-synchronous and super-synchronies speeds.
4- Whereas the stator of DFIG connects directly to the grid, it is possible to control the magnetising of generator from rotor side.
5- DFIG could support the voltage at point of utility connection by reactive power exchange.

Fig. 1 shows a DFIG based wind turbine that is connected to the utility at Point of Common Coupling (PCC). The rotor side converter (RSC) and grid side converter (GSC) are connected back to back through a DC link capacitor.

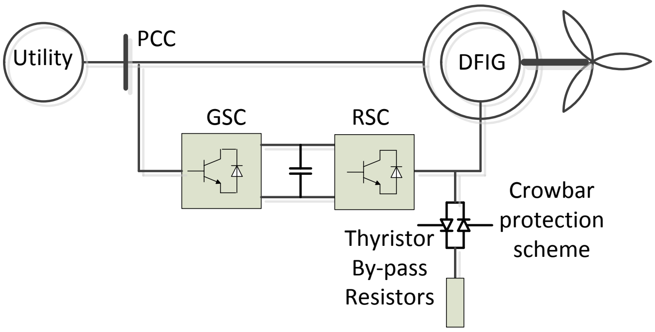

Fig. 1. DFIG with Crowbar protection

Despite of attractive operation of DFIG in wind electricity generation in normal condition, its performance during fault condition is a challenging issue. During fault, the rotor current will be very high. This huge current may damage the rotor windings as well as the rotor side converter. On the other hand, the recent grid codes require that wind turbines should not be disconnected from the utility for a pre-specified voltage sag value and duration during fault condition in power system. Low Voltage Ride-Through (LVRT) or Fault Ride through (FRT) capability is a term used to describe the extent and duration to which the voltage can fall before the wind turbine is disconnected from the grid [1]. Different countries have different LVRT requirements based on many factors such as renewable energy penetration level, government policy, security and power quality requirements and local experience of utility's operators [2].

The most common method for FRT improvement of DFIG is using AC crowbar which connects in parallel with rotor circuit [3–5]. The existing AC crowbar protection scheme for a DFIG is used to prevent the damages on the converters caused by voltage dips. The crowbar protection limits the rotor current by providing a bypass for the current through a set of resistors (see Fig. 1) without physically disconnecting the RSC from the rotor windings. The drawbacks when using this technique are:

1- Considerable power will be dissipated in the crowbar resistors during high voltage sags.
2- The performance of crowbar depends on optimum selection of its resistor values which is not an easy task.
3- The control signals of RSC should be disconnected because the power flow cannot be controlled. This means that, it will not be possible to control the DFIG during fault and the machine will operate as a conventional squirrel cage induction generator (SCIG).
4- Operation of machine as a SCIG during fault condition results in high reactive power demand from utility. It is because, the magnetization of machine should be provided from utility. Reactive power absorbing leads to further voltage dip on machine’s terminal.

Different solutions are suggested to overcome the disadvantages of AC crowbar. Paper [6] has proposed application of DC chopper for FRT improvement of DFIG. In this method, a resistor connects in parallel with the DC link by operation of a power electronic switch during fault to dissipate the extra charge of DC capacitor. In [7] application of a series dynamic breaking resistor (SDBR) in rotor circuit is proposed.

The energy storage system connected to the DC link as seen in Fig. 2 was proposed in [8–10] as an alternative protection technique to provide an extra spinning reserve facility, which then can be used as a sink when DFIG operates in super synchronous mode, or source of active power when DFIG operates in sub synchronous mode. The wind system with energy storage protection can be recovered after fault condition faster than the system with a crowbar protection. Additionally, the energy storage enables tight regulation of the DC voltage and the machine control is less affected during system disturbances [9]. However, adding an extra energy storage system connected to the DC link would be highly capital intensive as it will need additional construction, power lines, control circuits and coordinated operation with the control system of wind turbine.

Different researchers have reported solutions oriented to enhance fault ride-through capabilities of wind energy generation through using super capacitor energy storage in DC link. In [11] the integration of a short-term energy storage device in a DFIG design was considered in order to smooth the fast wind-induced power variations thereby enhancing its low-voltage ride through (LVRT) capability. A decoupled P–Q control strategy of a super capacitor energy storage system was proposed in [12], this energy storage interfaced through a STATCOM, for low voltage ride through as well as damping enhancement of the DFIG system. Two-layer constant power control scheme has been proposed by [13]. In this scheme, each DFIG wind turbine in the wind farm is equipped with a super capacitor energy storage system. However, the above studies only focused on control and adding extra energy storage systems connected to the DC link of DFIG.

This paper focuses on the effect of DC link SC value on LVRT of DFIG based wind turbine and investigates the possibility of using DC super capacitor instead of crowbar protection energy storage system. The following sections of the summarized paper are organized as follows: Section II explains the analytical analysis of energy storages system for LVRT improvement. The simulation results and discussions are presented in Section III. The conclusion is given in Sections IV.

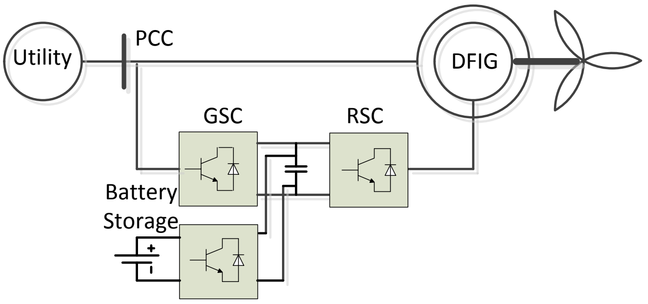

Fig. 2. DFIG with energy storage protection

II. DFIG MODELLING AND CONTROL

A fifth-order state space model and second order drive train model are used in the DFIG modelling. The detailed DFIG modelling and control are well documented [14–17] and hence not presented here. As this paper is focusing on the effect of DC link SC value, this section will first highlight on GSC control. The main function of the GSC is to maintain the DC link voltage at a constant level, and also at super synchronous speeds the wind turbine needs to deliver real and reactive power. If the DC voltage is greater than its reference value, this indicates that more power must be flown from the DC link to power grid via GSC converter. The PWM of GSC is current regulated, with direct and quadrature axis current components. The direct axis current is used to regulate the DC-link voltage, while the quadrature axis current for reactive power regulation. The supply-side converter is connected to power grid through line inductance L and resistance R. With such scheme, an independent control of the DC link voltage and reactive power can be achieved. The dynamic model, described in [16] is used in this work. The voltages in *d-q* space rotating at ω can be written as,

$$V_d = Ri_d + L\frac{di_d}{dt} - \omega Li_q + V_{d1} \qquad (1)$$

$$V_q = Ri_q + L\frac{di_q}{dt} - \omega Li_d + V_{q1} \qquad (2)$$

where, V_d and V_q are 2-axis stator supply voltages; V_{d1} and V_{q1} are 2-axis stator converter terminal voltages.

The GSC reference values V_d^R and V_q^R can be defined by,

$$V_d^R = -V_d^{er} + \omega L i_q + V_d \tag{3}$$

$$V_q^R = -V_q^{er} - \omega L i_d \tag{4}$$

where V_{d1}^{er} and V_{q1}^{er} are the error quantities from the GSC controllers and are found as,

$$V_{d1}^{er} = R i_d + L \frac{di_d}{dt} \tag{5}$$

$$V_{q1}^{er} = R i_q + L \frac{di_q}{dt} \tag{6}$$

The active and reactive powers from the GSC to the power grid are obtained in terms of d-q voltages and currents as follows,

$$P_{GSC} = \frac{3}{2}\left(V_d i_d + V_q i_q\right) \tag{7}$$

$$Q_{GSC} = \frac{3}{2}\left(V_q i_d - V_d i_q\right) \tag{8}$$

where, “3/2” is the scaling factor results from converting 3 phase quantities to a 2 axis space [15–17].

III. METHODOLOGY FOR LVRT IMPROVEMENT

Grid codes currently demand for LVRT capability up to 15% retaining voltage and allow also the reactive support to the network even during the fault conditions. A solution proposed by manufacturers for the LVRT capability of DFIG is the use of crowbar to protect the converter. However, the approach for LVRT as proposed in this paper is based on selection of an appropriate design of DC side capacitor. Therefore, the main goal of this approach lies in the DC side capacitor value. It is well known that the voltage across the energy storage system of the DC link voltage would vary approximately within (+/– 10%) [8], depending on the amount of energy stored. There is a relationship between the power smoothing and the rating of energy storage in wind turbine systems. With a large size of energy storage, a significant improvement in a DFIG can be achieved in terms of output power smoothing and DC link voltage stability. However the larger energy storage is not always a practical solution and would be highly expensive. Equations (9) and (10) are the modification of those given in [8] and can be used to determine an appropriate value for DC side super capacitor.

$$\Delta E = (P_{PCC} - P_{MP})\Delta t \tag{9}$$

$$\Delta E = \frac{1}{2} C\left(V_{\max}^2 - V_{\min}^2\right) \tag{10}$$

where, ΔE is the stored energy change in capacitor; P_{PCC} is the delivered active power to PCC; P_{MP} is the active output power of machine; V_{max} and V_{min} are maximum and minimum DC link voltages respectively; C is DC link capacitor; Δt is the time domain for energy change. Considering the direct change of active power in the utility at point of common coupling, the optimum super capacitor value for the DC link energy storage can be derived as,

$$C_{SC} = \frac{2\left(P_{PCC} - P_{MP}\right)\Delta t}{(V_{\max}^2 - V_{\min}^2)} \tag{11}$$

The optimum value calculated using Eq (11) will also help in smoothing the stochastic wind variations which means that, in one hand, the DC link SC can operate as an additional energy storage for charging when the wind power exceeds the desired level; on the other hand, it can operate as a source when the wind power is less than the desired level thereby helping DFIG ride through the low voltages during system disturbances.

IV. SIMULATION RESULTS AND DISCUSSIONS

The wind farm considered in this study is shown in Fig. 3. DFIG units are connected to grid through a 12 MVA distribution transformer which is used to step up the output voltage (575 V) of the DFIG wind farm to 11 kV. This transformer is connected through a distribution system supplying a 6 MW load. A 20 MVA transformer is used then to step up voltage from 11 kV to 120 kV for exporting the power to the grid through a 120 kV transmission line.

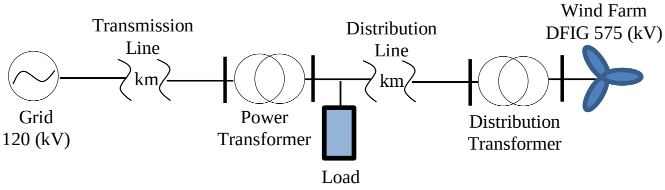

Fig. 3. Single line diagram of simulated power system

MATLAB SimPower was used to simulate the proposed strategy. A synchronously rotating *d-q* reference frame with the direct *d*-axis oriented along the stator flux position is used to control the DFIG model. Initially, the system was evaluated with crowbar protection before integrating DC super capacitor. Then, the operation of the system was tested with DC super capacitor for LVRT capability as well as power smoothing. The following subsections demonstrate the simulation results for each case.

A. AC Crowbar protection

Figs. 4 and 5 show the active and reactive power of the DFIG wind farm at steady state condition. Note that in this scenario, 6 aggregated units of 1.5MW were considered. To analyze the wind energy system response when AC crowbar is used, a three phase short circuit was applied at “0.08 s” close to the wind farm busbar. This fault was cleared at “0.13 s”. The simulation time was chosen small to observe clearly the fast response of AC crowbar protection. The behavior of the system during fault condition is shown in Figs. 6 and 7. It is seen from Fig. 6 (a, b) that the voltage dropped to 15% (i.e. 0.15 p.u.) of the nominal value at the DFIG terminal and to 0.85 p.u. at the power grid. DFIG consumed a high amount of reactive power (Fig. 6 “c”) just after the fault because of the high DC-link voltage, thus decreasing the voltage in the network. Fig. 7 (a) depicts the DC voltage when the system in the steady state condition. It is clearly seen from Fig. 7 (b) that a large rotor current injected to the capacitor during fault condition. Therefore, a large voltage ripple in the DC link was generated. However, when crowbar was used (Fig. 7 “c”), the DC link voltage decreased during the fault condition.

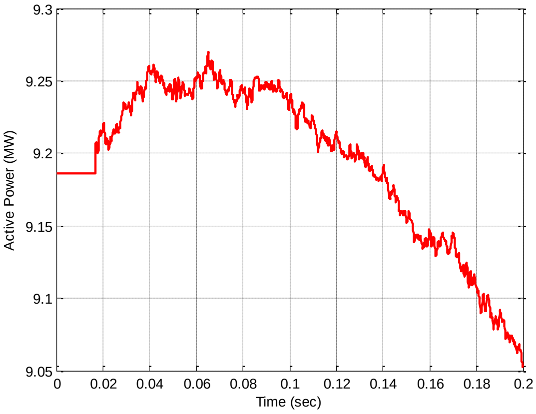

Fig. 4. DFIG active power at steady state condition

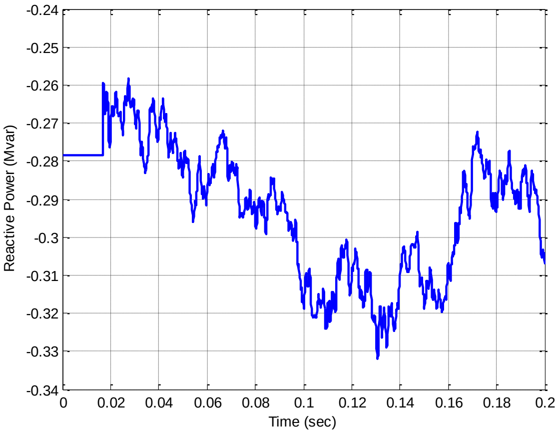

Fig. 5. DFIG reactive power at steady state condition

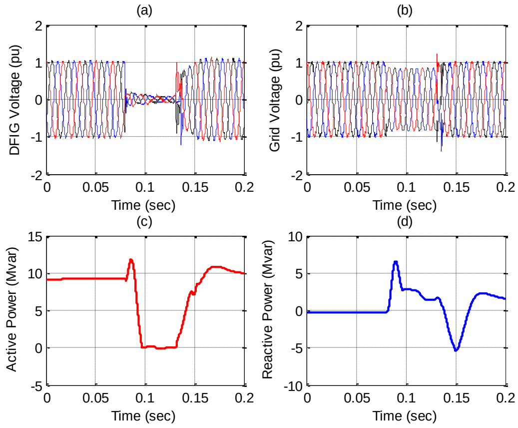

Fig. 6. DFIG grid voltage and active and reactive power during fault conditions

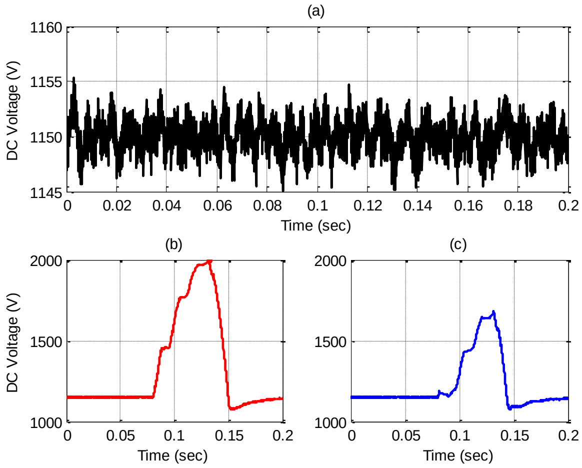

Fig. 7. DC link at steady state voltage with and without crowbar

B. LVRT capability

In the proposed methodology, the DFIG does not have any crowbar protection. In this case, a 10 mF capacitor with a 1200 DC link voltage was selected as energy storage and the wind speed is maintained constant at 12 m/s (Fig. 8 “g”). Note that the DFIG wind farm in this scenario is assumed to feed about 20% of its generation into the power grid.

A voltage sag was applied on 120 kV line at t=1 second (s) and cleared after 0.8 s but the system recovered (back to its initial condition) at 2.6 s. It is seen from Fig. 8 that during the voltage sag (Fig. 8 “e”), the supplied active power (Fig. 8 “a”) to the grid is highly fluctuated (+/– 2 MW), the supplied reactive power (Fig. 8 “b”) to the machine fluctuates approximately (+/– 0.5 Mvar), while the DC link voltage ((Fig. 8 “c”) fluctuation is (+/– 100 V). It was presented in [18] that DFIG with crowbar protection could ride through the voltage sags of 0.2 pu for a very short period of time (i.e. for a few milliseconds). The developed energy storage system with a super-capacitor as presented in this paper can stay connected to the grid for voltage sag of 0.1 pu for duration of 0.8 s as shown in (Fig. 8 “e”). However for a time greater than 0.8 s, the wind turbine has to be disconnected from the grid as the super capacitor of energy storage is 10 mF. For voltage sag of 0.6 pu the wind turbine is able to stay connected to the grid for 4.5 s. However for time greater than 4.5 s, the wind turbine has to be disconnected from the grid.

The LVRT capability was also investigated for the same voltage sag (i.e. for 0.1 p.u.) and wind speed but with different energy storage values as demonstrated in Table 1. The results of this table prove that by selecting higher values for DC link SC, the LVRT can be achieved for longer fault duration.

TABLE I
LVRT CAPABILITY FOR DIFFERENT VALUES OF DFIG’S DC LINK CAPACITOR

Energy storage super-capacitor	Period of wind turbine
5	0.7
10	0.8
15	1
20	1.2
25	1.4
30	1.5
35	2

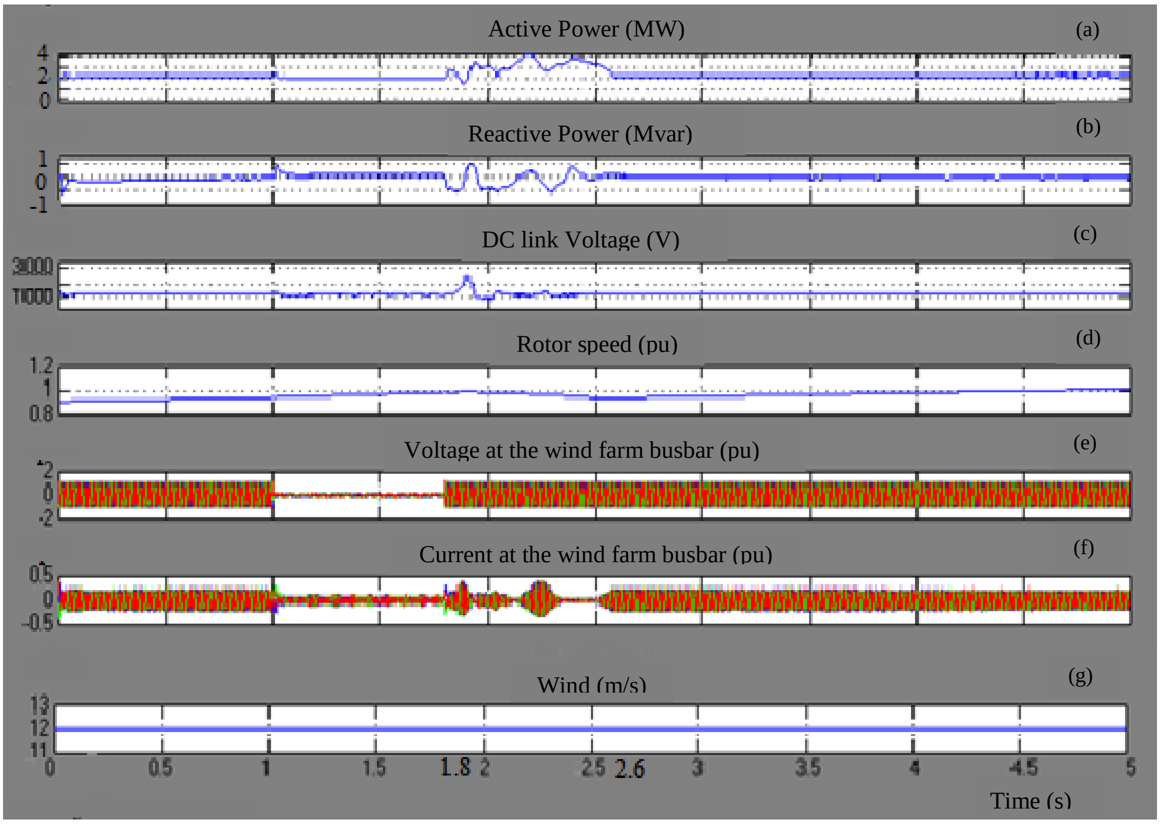

Fig. 8. LVRT capability for wind turbine using the proposed strategy

A. *Test For Power Smoothing*

The performance of the DFIG was tested with the proposed methodology by varying (randomly) the wind speed every one second over a 5 seconds period. Initially, the 10 mF SC was used as an optimum energy storage device. From Fig. 9 it can be observed that the fluctuation of the grid active power (Fig. 9 “a”) in the range of (+/– 0.3) MW, whereas reactive power (Fig. 9 “b”) in the range (+/– 0.15) and DC link voltage (Fig. 9 “c”) fluctuation is +/– 15 V. In the second test, the wind turbine system was simulated with 1000 mF SC, where the voltage sag and wind speed values are kept the same as in the first case. The obtained results are shown in Fig. 10. Compared to the results as depicted in Fig. 9, the fluctuations of the active power (Fig. 10 “a”), reactive power (Fig. 10 “b”) and DC link voltage (Fig. 10 “c”) are decreased. As seen from Fig. 10, the active and reactive power fluctuate in the range of +/–0.25 MW and +/– 0.1 Mvar respectively, while the DC link voltage in the range of +/–0.1 V.

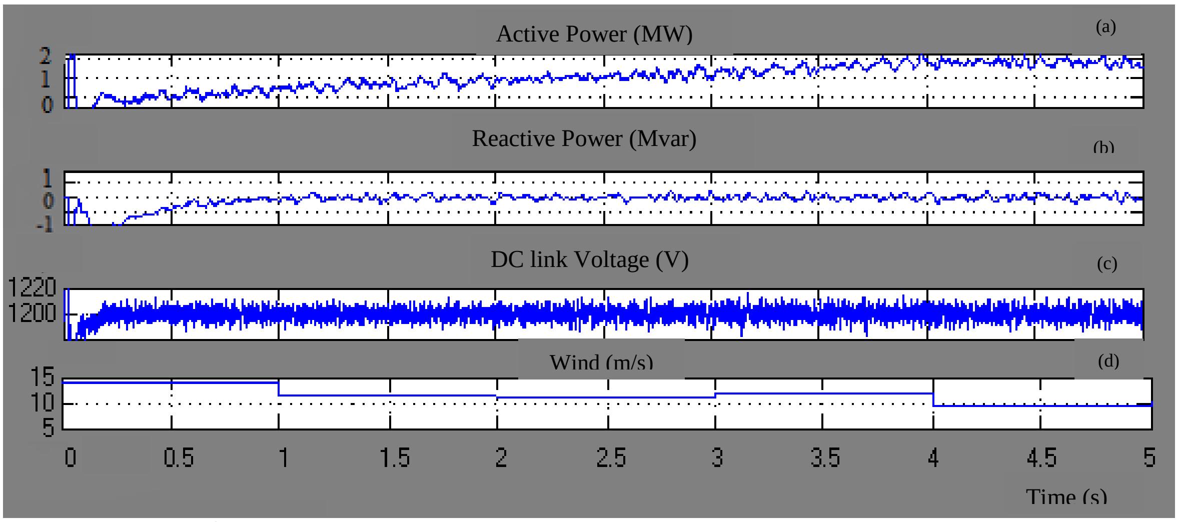

Fig. 9. Power smoothing capability for 10 mF DC

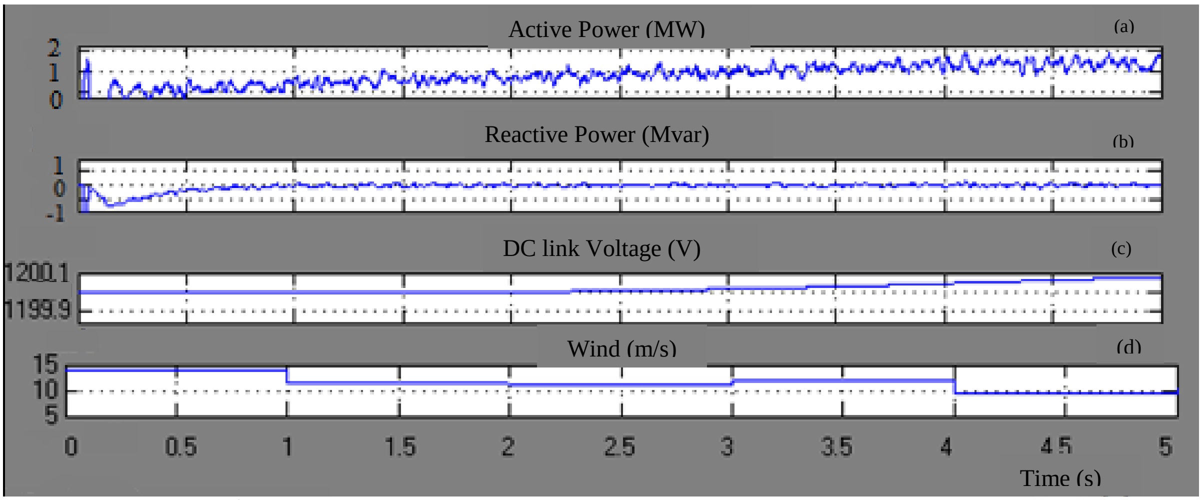

Fig. 10: Power smoothing capability for 1000 mF DC

V. CONCLUSION

The proposed simple methodology to improve the LVRT capability of DFIG has proven to be more effective during system disturbances than wind turbine with crowbar technique. Results show that with larger energy storage, wind turbine can stay connected to the grid during voltage sags and faults for longer time. This will help reducing the DC link voltage, and real and reactive power fluctuations. Furthermore, in the propose methodology, the SC can be charged during the high wind speed, and this stored energy can be used as an extra energy supply for DFIG to overcome low voltage sags during faults in the grid side. Finally, to design an optimal DC side super capacitor of wind turbine, two factors should be considered which are cost and physical size of super capacitor. In the future research, the cost-benefit analysis will be carried out to determine the optimal size of the super capacitor.

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