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Research Article

# Improvement FRT Capability of DFIG Wind Energy based on Three Level Converter

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***Abstract***

*This paper investigates the dynamic behavior of wind farm based on DFIG wind turbines during three phase to ground fault at wind farm terminals using different types of protection. Also, it schemes to improve fault ride through (FRT) capability for keeping the machine connected to the grid during fault period without destroying the machine, which is important to avoid a cascading effect due to lack of power and instability of the system. First, the system is tested using only crowbar protection scheme with varying of its resistance, then using only DC-chopper with different values of its resistance. Finally, the system is evaluated using both crowbar and DC-chopper. The transient behavior of DC-link voltage, electromagnetic torque, reactive power, stator voltage and rotor speed during fault is evaluated and compared with proposed types of protection schemes.*

***Keywords:*** *Crowbar, DC-chopper, Doubly fed induction generator (DFIG), Fault ride-through (FRT), Rotor current, Electromagnetic torque, Reactive power.*

## 1. Introduction

According to the numbers and studies talking about start entering the circle of running out of conventional energy and fossil fuels of petroleum and its derivatives, and due to the increasing of $CO_2$ emissions, the frantic search comes by countries and companies, scientists and researchers to obtain so-called "alternative energy", or renewable and clean energy. It is energy available, durable, and low cost, risk and damage, what keeps the economy, the purity of the earth and the human life. Wind power is the fastest growing renewable energy source. It is forecasted that the cumulative wind capacity growth rate will be between 11% - 16% and the cumulative installed wind capacity will reach about 666 GW in the 2019. According to the global wind energy outlook, by green peace international and the global wind energy council (GWEC), wind energy could provide between 17-19% of global electricity by 2030 and 25-30% by 2050.

Nowadays, the variable-speed wind turbines based on DFIGs are the most widely used technology for wind farms due to some advantages such as the rating of the power electronic converter is only 25–30% of the generator capacity, which makes this concept attractive and popular from an economic point of view, does not need either a soft starter or a reactive power compensator, reduced losses with an improved efficiency, and the stator active and reactive power can be controlled independently in four quadrants.

However, wind turbines based on the DFIGs are very sensitive to grid disturbance especially to voltage dips. A sudden short circuit on the grid, lead to large fault currents in the stator due to the direct connection of its stator to the grid. Because of the magnetic coupling between the stator, the rotor and the laws of flux conservation, the stator disturbance is further transmitted to the rotor. Therefore, the rotor current can exceed to more than 2-3 times its nominal value. In addition, as the grid voltage drops in the fault moment, the grid side converter (GSC) is not able to transfer the power from the rotor side converter (RSC) further to the grid. Therefore, the additional energy goes into charging the dc-bus capacitor and thus dc-bus voltage rises rapidly, (Anca D. Hansen, Gabriele Michalke, 2007), (Tamer Kawady, N. Mansour, A. Osheiba, A. E. Taalab and R. Ramakumar, 2007), (Omar Noureldeen, 2012), (Maged N. Nashed, and Mona N. Eskander, 2012). This obviously is not acceptable, and it may cause damages to rotor windings, converters, DC-link capacitors or induce drive train mechanical stress due to torque fluctuations. Therefore, to satisfy the fault ride-through (FRT), keeping the machine connected to the grid without destroying the machine, both of the crowbar and DC-link chopper are used in this paper for the wind farm protection. The operation principle of these protection schemes for FRT of the DFIG are presented in the next sections.

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## 2. Crowbar protection scheme

To protect the rotor winding of DFIG and its converter circuits against over-current or/and DC-link over-voltage, a rotor over current protection called crowbar is connected between the rotor of DFIG and rotor-side converter, coupled via the slip rings (V. Vanitha and K. Santhosh, 2014),(M. B. C. Salles, K. Hameyer, J. R. Cardoso, A. P. Grilo, and C. Rahmann, 2010). The crowbar circuit could uses diode rectifiers with a semiconductor switch or anti-parallel semiconductor switch pairs as shown in Figure 1. The crowbar is forced to active if the DC-link voltage or the rotor current exceeds their thresholds.

The threshold of the rotor current hysteresis comparison unit is 1.3 pu.-1.5 pu., while the threshold of DC-link voltage is 1050-1100V (the reference DC-lin/k voltage is 1000V).

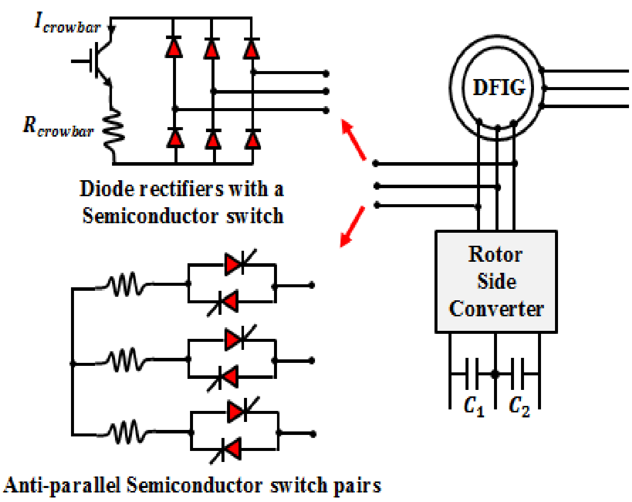


**Fig.1** Crowbar circuit

The crowbar limits the voltages and provides a safe route for the currents by passing the rotor by a set of resistors. When the crowbar is activated the rotor side converter pulses are disabled, short-circuit current will flow through this crowbar instead of the converter and the machine behaves as a squirrel cage induction machine directly coupled to the grid. The magnetization of the machine that was provided by the RSC in nominal condition is lost and the machine absorbs a large amount of reactive power from the stator and thus from the network (J. Morren and S. de Haan, 2007). When the crowbar is removed, the RSC is enabled again to control independently the active and reactive power.

Several principles and guidelines should be considered in designing crowbar protection. Crowbar technique is a useful way to solve FRT capability of WEG (V. Vanitha and K. Santhosh, 2014). When a crowbar protection was applied in this thesis, it was noted that FRT capability of DFIG could be improved by using a proper value of crowbar resistance. The crowbar resistance must be carefully chosen:

- If a very low value is chosen, the short-circuit current will be very large. The crowbar switch should then be oversized and the electromagnetic torque will have a big peak. In addition, the reactive power demand of the generator at a certain speed will be increased.
- The rotor current can be reduced by using a higher resistance. However, if the resistance is too large, the voltage on the crowbar will be too high and it may give a rise to the DC-link voltage of the RSC. This may cause over-voltage on the switching devices (Orłowska-Kowalska, Teresa Blaabjerg, and Frede Rodríguez, José, 2014). In this case, the rotor current will circulate across the rotor converter via its freewheeling diodes even if it is inactive. The dynamic stability of the generator is improved by increasing the resistance (Akhmatov V. 2003).

The crowbar mechanisms raise some problems. The crowbar ignition leads to the loss of the generator controllability through RSC, since the machine rotor is short-circuited through the crowbar resistors and RSC is blocked. During this time slot the, generator acts as a common single fed induction generator and consumes reactive power, which is not desirable. Additionally, it has a higher component count compared to DC-link chopper and cannot directly limit the DC-link voltage. Due to these disadvantages, nowadays, some countries are no longer use the crowbar scheme. Alternatively, they use DC-link chopper circuit as the protection device for FRT in the DFIG based wind turbines.

Two types of crowbar circuits are available (Miad Mohaghegh Montazeri, 2011):

- The passive crowbar which uses diode rectifier or a pair of anti-parallel thyristors to short the rotor side converter terminals. This type of crowbar has semi-controllable elements that can only be turned off when the valve current reaches zero, so it has no control on the deactivation process of crowbar operation. It leads to longer time of RSC connection to the rotor of DFIG and may delays the voltage recovery procedure.
- The active crowbar which uses fully controllable elements such as IGBT, IGCT, and GTO. Shorting rotor with this crowbar improves the dynamic of the crowbar operation by fast elimination of rotor transient and full control of crowbar deactivation.

## 3. DC-Chopper protection scheme

In order to avoid the over-voltage on the DC-link of the RSC, a breaking chopper is usually added on the DC-link. When the DC-link voltage surpasses the limit, the DC-chopper can be connected in order to consume the energy, as shown in Figure 2 (Orłowska Kowalska, Teresa Blaabjerg, Frede Rodríguez, and José, 2014), (I. Erlich, J. Kretschmann, J. Fortmann, S. M. Engelhardt, and H. Wrede, 2007). However, the chopper does not affect the dynamics of the rotor currents. The braking chopper is made up of a resistor that can be connected or disconnected by means of a switch. A freewheeling diode is also necessary to prevent over-voltages in the switch when it is turned off. In the three-level neutral point clamped (NPC) converter, the chopper circuit consists of two IGBTs, two freewheeling diodes and two breaking resistors as shown in Figure 2.

When the RSC is saturated and/or when the rotor EMF is too large for the RSC to handle, the DC-chopper can consume the power fed to the DC-link and thus avoid over-voltage on the DC capacitor. The safety operation is guaranteed under serious voltage dips. The control of the DC-chopper is activated when the DC-link voltage reaches 1.1 pu and is deactivated when reaches 1.05 pu. (Salles, M. B. C.; Cardoso, J. R.; Grilo, A. P.; Rahmann, C.; and Hameyer, K., 2009).

The DC-chopper is often associated with an active crowbar. This arrangement creates a synergy since both solutions complement each other:

- The active crowbar is activated at the beginning of the dip and prevents the initial over-currents from damaging the rotor converter.
- The DC-chopper makes it possible to disconnect the crowbar earlier and hence to accelerate injection of reactive power in to the grid.

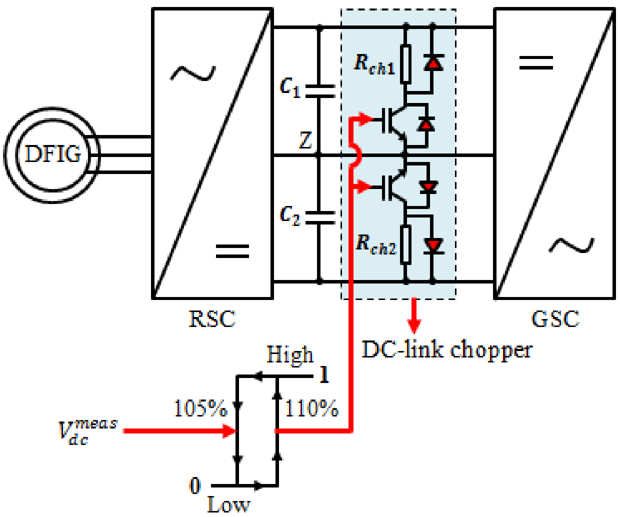


**Fig. 2** DC-link chopper circuit

## 4. Simulation results and discussions

DFIG wind farm consisting of six 2 MW wind turbines based on back-to-back NPC three-level offset addition pulse width modulation (OAPWM) converter is tested to evaluate its behavior during three-phase to ground fault at the wind farm terminals as shown in Figure 3. The fault is applied at t = 8s with a duration of 150 ms. The test farm is modeled and simulated in Matlab/Simulink environment and connected to a 132 kV/ 50 Hz grid through a step-up transformer 690 V/66 KV, 50 Km transmission line and step-up transformer 66 KV/ 132 KV. During simulation, the wind speed is constant at 10 m/s and DFIG wind farm is operating at super-synchronous mode. Before the fault, the DFIG wind system is in the steady operation at unity power factor with electromagnetic torque $T_{em}$ = -0.6 pu. And rotor speed 1.2 pu. Also, the DC-link voltage is constant at 1000 V. The following case studies investigate the dynamic performance of DFIG wind farm shown in Figure 3 during fault using different protection schemes discussed in above sections to improve FRT capability of DFIG system to achieve grid connection requirements.

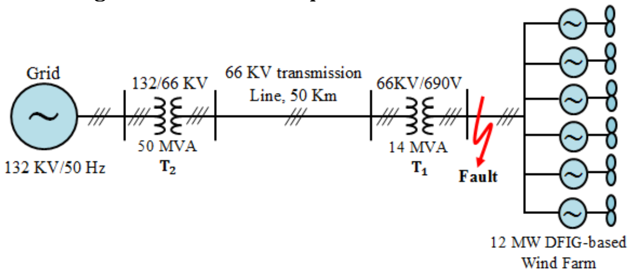


**Fig. 3** Simulation model of DFIG wind farm connecting to grid

### *4.1 Case (1)*

This case evaluates the dynamic performance of DFIG wind farm during fault with and without crowbar being activated, also studies the effect of varying the value of crowbar resistance on the FRT capability of DFIG wind power system. Five values of crowbar resistance are used, 0.1, 0.25, 0.5, 1, and 2 pu. The applied three-phase to ground fault at the wind farm terminals is started at t = 8 sec and cleared at t = 8.15 sec.

In case of using crowbar and once the rotor current or the dc-link voltage exceeds the threshold value after fault occurrence, the IGBT of the crowbar is activated and the RSC is blocked. The machine behaves like a squirrel cage induction machine directly coupled to the grid and absorbs a large amount of reactive power from the stator and thus from the grid. When the rotor current and dc-link voltage become within limits, the crowbar is deactivated with delay time of 10 ms. When the crowbar is removed, the RSC is enabled again to control independently the active and reactive power. Figure 4 shows a set of simulated waveforms for the DFIG wind power system during fault using crowbar resistance 0.5 pu.

Figure 5 illustrates DC-link voltage variations during fault with and without crowbar using different values of crowbar resistance. When the fault occurs, the grid voltage drops and the GSC is not able to transfer the power from the RSC to the grid, thus, the additional energy goes into charging the DC-link capacitor and hence DC-link voltage rises rapidly. However, using crowbar protection scheme with choosing small value of its resistance, the highest value of DC-link voltage during fault decreases from 1458 V in the case of without crowbar to 1030 V in the case of crowbar with resistance 0.1 pu. The highest value of DC-link voltage during fault decreases from 1515 V in the case of crowbar resistance 2 pu to 1434 V in the case of crowbar resistance 1 pu to 1313 V in the case of crowbar resistance 0.5 pu to 1156 V in the case of crowbar resistance 0.25 pu to 1030 V in the case of crowbar resistance 0.1 pu. This reveals that decreasing the crowbar resistance decreases the highest value of DC-link voltage during fault.

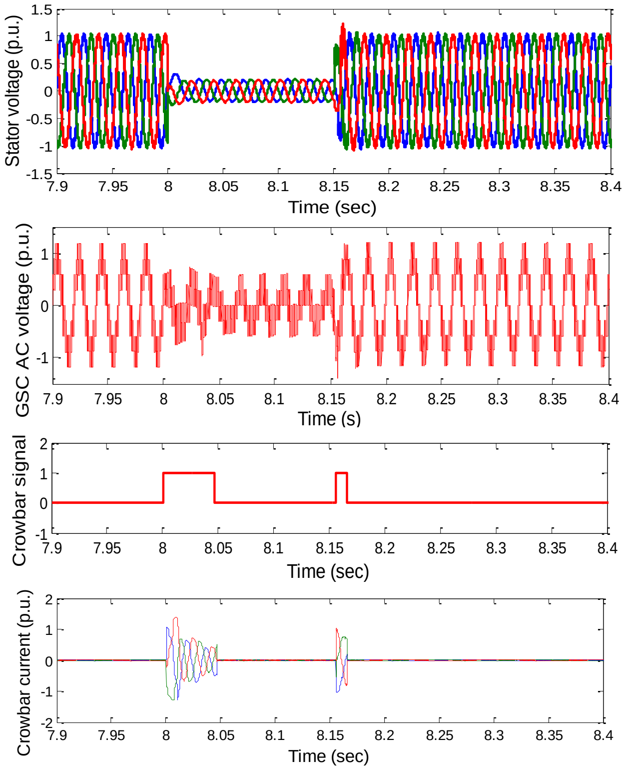


**Fig. 4** Simulated waveforms for the DFIG wind power system during three-phase to ground fault with crowbar resistance 0.5 Ω

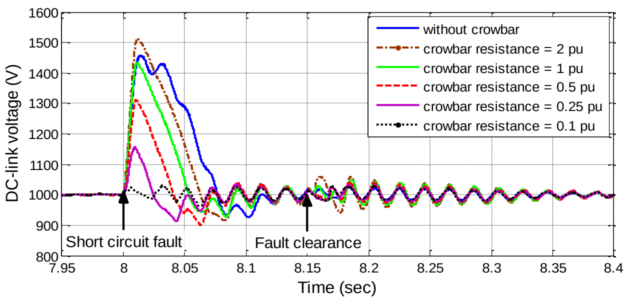


**Fig. 5** DC-link voltage variations during fault with and without crowbar using different values of crowbar resistance

Figure 6 depicts the variations of rotor speed during fault with and without crowbar using different values of crowbar resistance. By increasing the value of crowbar resistance, the maximum value of rotor speed during fault is increased. The maximum value of rotor speed is decreased from 1.254 pu in case of crowbar resistance 2 pu to 1.246 pu in the case of crowbar resistance 0.1 pu.

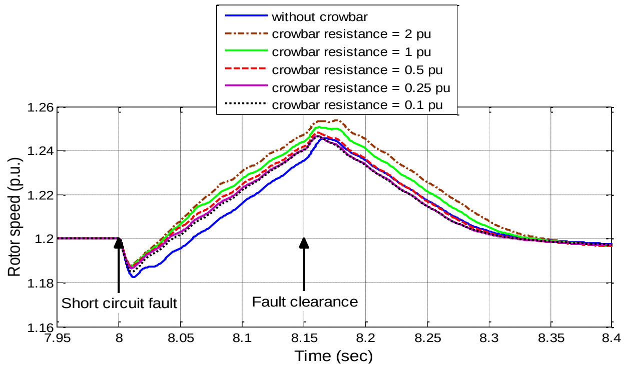


**Fig. 6** Rotor speed variations during fault with and without crowbar using different values of crowbar resistance

Figure 7 indicates the variations of electromagnetic torque during fault with and without crowbar using different values of crowbar resistance. After, the fault occurance the peak value of electromagnetic torque is decreased from -3.044 pu in the case of crowbar resistance 0.1 pu and without crowbar to -2.803 pu in the case of crowbar resistance 0.25 pu to -2.741 pu in the case of 0.5 pu to -2.711 pu in the case of crowbar resistance 1 pu to -2.689 pu in the case of crowbar resistance 2 pu. This reveals that increasing the crowbar resistance decreases the peak value of electromagnetic torque during fault.

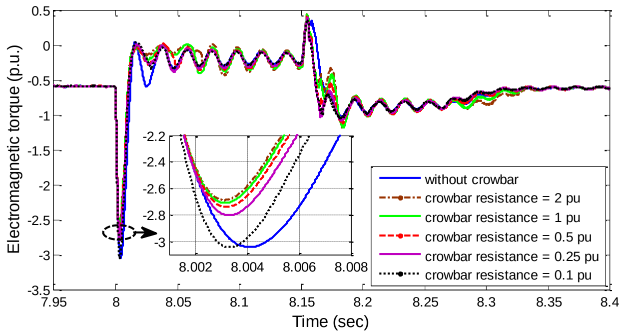


**Fig. 7** Electromagnetic torque variations during fault with and without crowbar using different values of crowbar resistance

Figure 8 describes the variations of rotor current during fault with and without crowbar using different values of crowbar resistance. After, the fault occurrence the peak value of rotor current is decreased from 4.288 pu in the case of without crowbar to 4.027 pu in the case of crowbar resistance 0.1 pu to 3.691 pu in the case of crowbar resistance 0.25 pu to 3.571 pu in the case of crowbar resistance 0.5 pu to 3.509 pu in the case of crowbar resistance 1 pu to 3.469 pu in the case of crowbar resistance 2 pu. This indicates that increasing the crowbar resistance decreases the peak value of rotor current during fault.

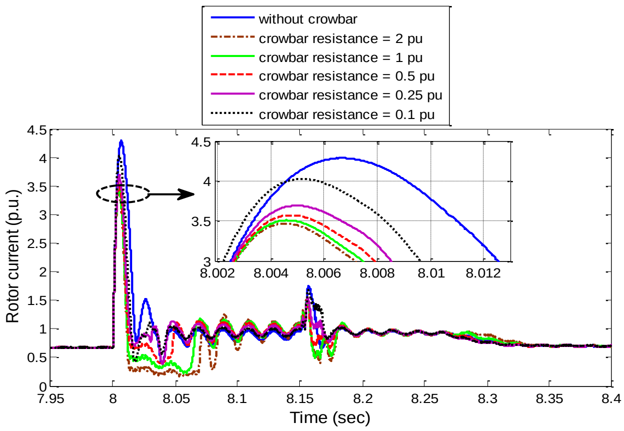


**Fig. 8** Rotor current variations during fault with and without crowbar using different values of crowbar resistance.

Figure 9 shows reactive power variations of DFIG wind farm during fault with and without crowbar using different values of crowbar resistance. After, the fault clearance the reactive power consumption by DFIG wind farm reduces from 0.6686 pu in the case of crowbar resistance 0.1 pu to 0.5308 pu in the case of without crowbar to 0.4664 pu in the case of crowbar resistance 0.25 pu to 0.3358 pu in the case of crowbar resistance 0.5 pu to 0.2586 pu in the case of crowbar resistance 1 pu to 0.222 pu in the case of crowbar resistance 2 pu. This reveals that increasing the crowbar resistance decreases the reactive power consumption by DFIG wind farm.

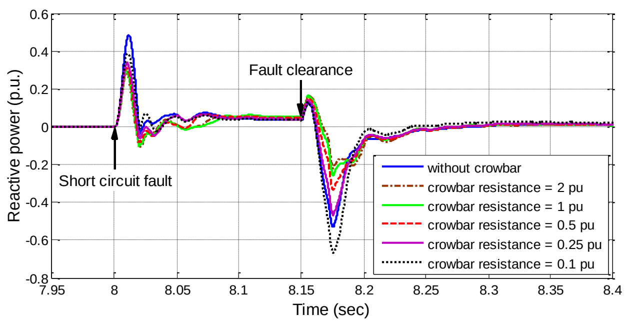


**Fig. 9** Reactive power variations of DFIG wind farm during fault with and without crowbar using different values of crowbar resistance.

Figure 10 represents the variations of stator voltage during fault with and without crowbar using different values of crowbar resistance. Recovery of voltage is faster with increasing the value of crowbar resistance and then enhance the stability of the DFIG.

As shown in Figures 5 to 10, a higher crowbar resistance can reduce the transient values of the rotor current, electromagnetic torque, and reactive power consumption by DFIG wind farm. Also, the recovery of voltage is faster and then enhance the stability of the DFIG. However, the voltage on the crowbar will be too high and it gives a rise to the DC-link voltage of the RSC.

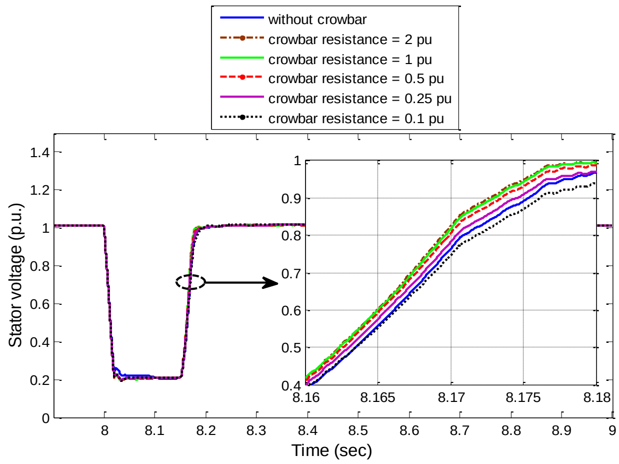


**Fig. 10** Stator voltage variations during fault with and without crowbar using different values of crowbar resistance

This may cause over-voltage on the switching devices or cause damage of DC-link capacitor. On the other hand, if a very low value of crowbar resistance is chosen, the DC-link voltage will be reduced. However, the transient values of electromagnetic torque and rotor current will have a big peak. Also, the reactive power consumption by the DFIG after the fault clearance will be increased. As a consequently, the crowbar resistance must be carefully chosen for improving the FRT capability of DFIG. All the simulation results illustrated in Figures 5 to 10 and obtained at different values of crowbar resistance have been compared to choose a proper value of crowbar resistance for this case study. Finally, the correct choice for this value in this case study is 0.5 pu.

### *4.2 Case (2)*

This case investigates the performance of DFIG with and without activating Dc-chopper during the three-phase to ground fault which is applied at the wind farm terminals for 150 ms duration starting from 8 sec, also studies the effect of varying the value of DC-chopper resistance on avoiding the DC-link over-voltage during the period of fault occurance.

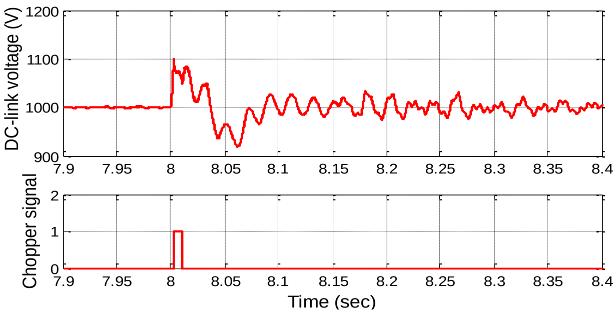


**Fig. 11** DC-link voltage variations and chopper signal during fault with chopper resistance $R_{ch1} = R_{ch2} = 0.5$ pu

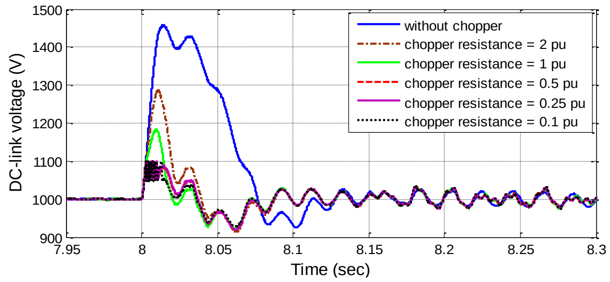


**Fig. 12** DC-link voltage variations during fault with and without DC-chopper using different values of chopper resistance

When the DC-link voltage surpasses the limit, the IGBTs of DC-chopper are switched on to consume the energy. Figure 11 illustrates the variations of the DC-link voltage and chopper control signal during fault with chopper resistance $R_{ch1}$ = $R_{ch2}$ = 0.5 pu. Also, the DC-link voltage variations during fault with and without DC-chopper using different values of chopper resistance are presented in Figure 12.

*4.3 Case (3)*

This case studies the dynamic performance of DFIG wind farm shown in Figure 3 with different protection schemes, namely, using only crowbar, using only DC-chopper, and using combination between crowbar and DC-chopper during three-phase to ground fault which is applied at the wind farm terminals for 150 ms duration starting from 8 sec. The values of crowbar resistance $R_{crowbar}$ and Dc-chopper resistance $R_{ch1}$ = $R_{ch2}$ are 0.5 pu.

Figures 13 and 14 show the variations of DC-link voltage and reactive power, respectively, during fault with different protection schemes. While, the variations of stator voltage and rotor speed during fault with different protection schemes are illustrated in Figures 15 and 16, respectively. Finally, Figures 17 and 18 depict the variations of electromagnetic torque and rotor current, respectively, during fault with different protection schemes.

As illustrated in Figures 13 to 18, using only crowbar protection scheme, the transient values of electromagnetic torque and rotor current are decreased. Also, the reactive power consumption by the DFIG wind farm after the fault clearance is reduced and the recovery of voltage is faster and then enhance the stability of the DFIG. However, the DC-link voltage have a big peak. When only DC-chopper protection scheme is used, the highest value of DC-link voltage is decreased. However, the transient values of electromagnetic torque and rotor current have a big peak and the recovery of voltage is slower. Also, The reactive power consumption by the DFIG wind farm after the fault clearance is increased. Finally, when a combination between crowbar and DC-chopper protection scheme is used, the transient values of electromagnetic torque and rotor current are reduced. The reactive power consumption by the DFIG wind farm after the fault clearance is decreased and the recovery of voltage is faster. Also, the highest value of DC-link voltage is decreased. This protection scheme combines the advantages of crowbar and DC-chopper. Therefore, the DC-chopper is often associated with crowbar. This arrangement creates a synergy since both solutions complement each other.

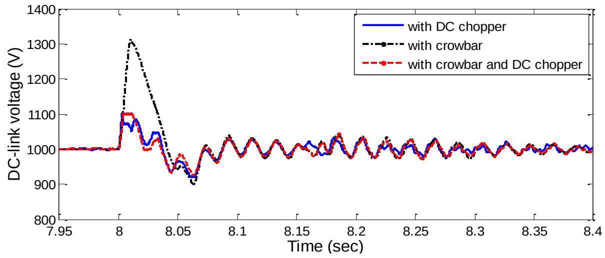


**Fig. 13** DC-link voltage variations during fault with different protection schemes

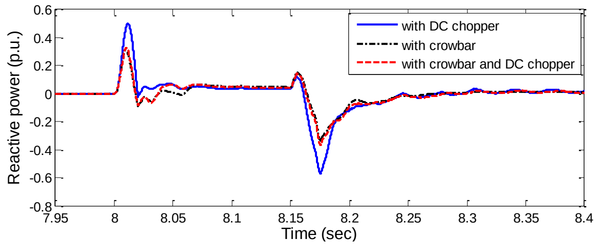


**Fig. 14** Reactive power variations of DFIG wind farm during fault with different protection schemes.

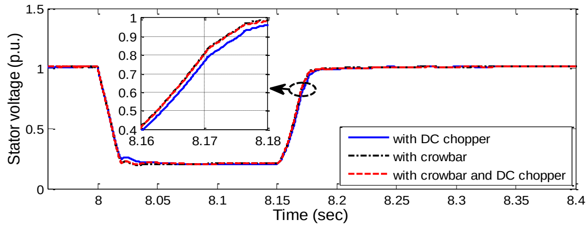


**Fig. 15** Stator voltage variations during fault with different protection schemes

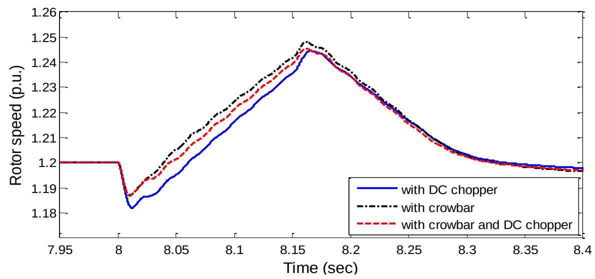


**Fig. 16** Rotor speed variations during fault with different protection schemes

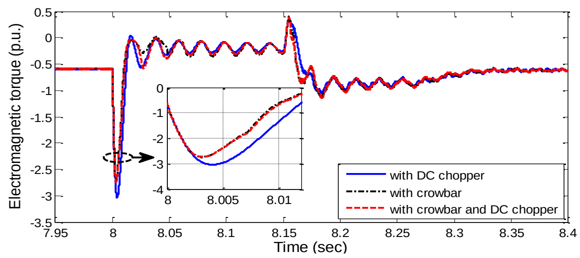


**Fig. 17** Electromagnetic torque variations during fault with different protection schemes

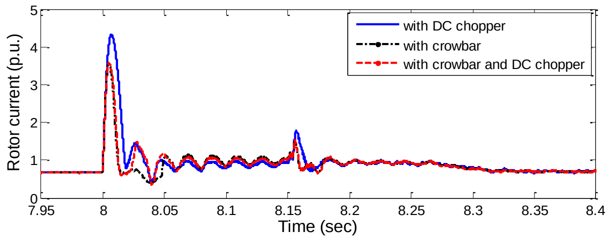


**Fig. 18** Rotor current variations during fault with different protection schemes

## Conclusions

The dynamic behavior of wind farm consisting of six 2 MW DFIG wind turbines based on three level NPC OAPWM back-to-back converter is investigated during three phase to ground fault at wind farm terminals using different types of protection schemes. The fault is applied with duration of 150 ms. The transient behavior of DC-link voltage, electromagnetic torque, reactive power, stator voltage and rotor speed during fault has been evaluated and compared with proposed types of protection schemes.

First, the system has been tested using only crowbar protection scheme with varying of its resistance. It's noted that a higher crowbar resistance can reduce the transient values of the rotor current, electromagnetic torque, and reactive power Consumption by DFIG wind farm. Also, the recovery of voltage is faster and then enhance the stability of the DFIG. However, the DC-link voltage will be too high. This may cause damage of DC-link capacitor. On the other hand, it's noted that a very low value of crowbar resistance is chosen, the DC-link voltage will be reduced. However, the transient values of electro-magnetic torque and rotor current will have a big peak. Also, the reactive power consumption by the DFIG after the fault clearance will be increased. As a consequently, the crowbar resistance must be carefully chosen for improving the FRT capability of DFIG.

Then the system has been tested using only DC-chopper with different values of its resistance. It's noted that its effect on only DC-link voltage which decreases with decreasing DC-chopper resistance. Finally, the system has been evaluated using both crowbar and DC-chopper. It is noted that the arrangement creates a synergy since both solutions complement each other.

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