Transient stability enhancement of DFIG based 10 MW wind farm by using of new inductive bridge type fault current limiter

Author
Md Emrad Hossain a*

a Department of ECT, Remington College, Memphis, TN, USA

ABSTRACT
Due to numerous advantages of the doubly-fed induction generator (DFIG), the application of DFIG based wind generator (WG) is increasing very rapidly. However, the transient stability is one of the major concerns of the DFIG based wind generator. Therefore to accomplish this goal, in this paper, an existing non-linear controller based new inductive bridge type fault current limiter (NC-NIBFCL) is proposed to augment the transient stability of the DFIG based wind farm (WF), and its performance is compared with the existing series dynamic braking resistor (SDBR). In this work all simulations were executed in Matlab/Simulink software and in simulation, a temporary three-line-to-line (3LL) fault, and double-line-to-line (2LL) faults were applied in the DFIG based tested model system to examine the transient stability improvement performance of the proposed NC-NIBFCL. After simulation results, it is proved that the proposed method can improve the transient stability of DFIG based WF and performed well compared to SDBR.

Article history:
Received : 17 April 2017
Accepted : 23 August 2017

Keywords: Doubly-Fed Induction Generators (DFIG), Non-Linear Controller New Inductive Bridge Type Fault Current Limiter (NC-NIBFCL), Series Dynamic Braking Resistor (SDBR), Wind Generator (WG), Wind Farm (WF).

1. Introduction
Last two decades, the application of renewable energy is becoming very popular and very effective in the power systems. Due to numerous advantages of wind energy in comparison to others available renewable energy sources, day by day the penetration level of wind energy conversion systems (WECS) into the power grids are increasing very rapidly, especially large-scale wind farms (WFs). In [1], it is reported that throughout the world total 760 Giga Watts (GW) of the wind power will be generated by the end of year 2020 and, only in China, total 150 GW power will be generated from the wind energy [2].

Recently, application of the variable speed based wind generators (VSWGs) is getting attractive in comparison to the fixed speed induction generator based wind generators and the application of DFIG-based WFs are widely used among the available of VSWGs, mainly for applications more than 1 MW. However, DFIG based WF is very sensitive during the grid faults. In the event of fault, the terminal voltage of DFIG decrease expressively from the rated voltage and the rotor side converter (RSC) is highly affected due to inject of high fault current and the
performance of the DFIG under these conditions can considerably affect the system stability [3].

Previously crowbar protection was used in order to protect the RSC of the DFIG from the excessive current in the event of a fault. But recently the application of crowbar protection is decreasing in the DFIG based WF because of its incapable to maintain the new grid codes as well as unable to maintain the transient stability of DFIG based WF during faults [4].

To overcome the problems of crowbar protection in the DFIG based wind generators, some research group’s proposed and discussed internal controllers in order to improve the transient stability of DFIG based WG in [5-7]. Besides crowbar solution and internal controllers for transient stability of DFIG based WG, some more solutions are found in literature, like as, superconducting magnetic energy storage (SMES) in [8], static synchronous compensator (STATCOM) in [9], series dynamic braking resistor (SDBR) in [10], superconducting fault current limiter (SFCL) in [11], non-superconducting fault current limiter (NSFCL) in [12], [13], thyristor switched series capacitor (TCSC) in [14], bridge type fault current limiter in [15]. These above can improve the transient stability of the DFIG based WG but they have some limitation. For example, some of the energy storage systems and reactive power compensators (RPC) require large capital investments; on the other hand, SFCL is very costly due to its superconductivity nature.

Therefore, based on the above mentioned reasons, this paper proposes an existing nonlinear controller based new inductive bridge type fault current limiter (NC-NIFCL) to improve the transient stability of the DFIG based 10 MW WF. To evaluate the transient efficiency of the proposed NC-NIFCL in enhancing the transient stability of DFIG based wind farm, its performance is compared with the existing series devices of SDBR. All simulation outcomes are proved that the proposed NC-NIFCL is very effective in enhancing the transient stability of the DFIG based WF and performed well in comparison to SDBR.

2. Wind turbine modeling

The mechanical power \( P_w \) by the turbine can be defined [9], [11], [16].

\[
P_w = 0.5 \rho C_p(\lambda, \beta) A_{wt} V_o^3 [\text{W}],
\]

where, \( \rho \) is representing the air density, \( V_o \) is representing the wind speed, \( A_{wt} \) is the area covered by the rotor of the wind turbine \( \left( A_{wt} = \pi R^2 \right) \), \( R \) is representing the radius of the turbine blade, \( C_p \) is the power coefficient and it is the function of both tip speed ratio, \( \lambda \), and blade pitch angle, \( \beta \). The tip speed ratio is defined as [9],[11],

\[
\lambda = \frac{\omega_r R}{V_o},
\]

where, \( \omega_r = \text{Rotational mechanical speed [rad/s]} \).

In order to design the wind turbine, \( C_p(\lambda, \beta) \), MOD-2 model is used in this work [9],[16]. That is,

\[
C_p(\lambda, \beta) = 0.5(\lambda - 0.022\beta^2 - 5.6)e^{-0.11\lambda}.
\]

3. Overview of DFIG modeling and controllers

3.1. DFIG Modeling

The DFIG itself a three-phase wound rotor induction machine, where its stator windings is directly connected to the grid [11-13]. The rotor side converter (RSC) and grid side converter (GSC) is based on voltage source converter (VSC) and these two converters capable to transfer both active and reactive power in both directions autonomously. A DC-link capacitor is connected between the RSC and GSC to keep variations of the voltage within a small range [11-13]. To control the RSC and GSC converters, vector control method is used in this work [17].

3.2. Rotor Side Converter (RSC) Controller

Figure 1(a) shows that the RSC with gain parameter values. The main objective of the RSC is to active and reactive power of the stator. In general, the RSC is a power electronic full bridge 2-level, 6-pulse converter, and electromagnetic torque of DFIG can be controlled with these the 2-level, 6-pulse converter [7], [12], [13]. In order to generate the appropriate reference signals for three phase pulse width modulation (PWM) signal block, the RSC is designed with the two set of proportional integral (PI) controllers. In this work parks model is selected for RSC converter, and the controller of RSC converter is well explained in [17], which is followed in this work.
3.3. Grid Side Converter (GSC) Controller

The main purpose of the GSC controller is to keep the fixed dc-link voltage and helps to keep a constant power factor \([12], [13]\). To achieve this goal, in this paper the vector control method is used. In this scheme, the d-axis current component is used to keep the dc-link voltage constant, and a q-axis current component is used to control the reactive

---

**Fig. 1.** Configurations of (a) RSC controller; and (b) GSC controller \([12], [13]\).
power of the DFIG [12], [13]. In order to design the GSC, two series PI controllers are used in this work. The gain parameter values of the GSC controller are shown in Fig. 1(b). The GSC controller also contains a 2-level, 6-pulse based full bridge power electronic converter [7], [12], [13]. It uses the dc-link voltage \( V_{dc} \) and the reactive power \( Q_s \) from the rotor line as inputs and sends the desired signal with the processing of the PI controller and carrier frequency of the GSC controller. In this paper, a 14000 \( \mu \)F power capacitor is used to smooth the dc voltage ripple of and maintain constant 1200 Volts and the carrier frequency of GSC and RSC are chosen 2700 Hz and 1600 Hz respectively.

4. Proposed Method (NC-NIBFCL)

4.1. NC-NIBFCL configuration and operation

The configuration of the proposed NC-NIBFCL is based on [19] and in this paper added one small value of inductor in the parallel path with the resistor to limit the instantaneous injected high current during fault, which is shown in Fig. 2. The NC-NIBFCL consists of four diodes \( D_1-D_4 \), with a small value of \( r_d \) and dc-reactive inductances \( L_d \) are considered in the bridge part, and a high impedance of shunt path of \( (R_{sh} \text{ and } L_{sh}) \) is connected in parallel with the fast response semiconductor IGBT switch.

![Fig. 2. Construction of: Proposed Single-phase new inductive bridge type fault current limiter](image)

The bridge part operation of the proposed device is similar to [12], [13], [19], but the parallel path is modified because of the inserted new inductor. The operation of the proposed device both in normal and abnormal conditions are explained here. In a normal condition the IGBT switch remains closed, and the bridge part of the NC-NIBFCL carries the line current. \( D_1 - L_d - r_d - D_4 \) for one half cycle, and other half cycle the line current is carried \( D_2 - L_d - r_d - D_3 \). Thus, the combination of the four diodes \( (D_1-D_4) \) of the proposed NC-NIBFCL operates in near dc condition \( (i_{dc}) \) in each phase and no current will flow thorough the parallel path \( (L_{sh} \text{ and } R_{sh}) \) as the impedance of the parallel path is high. In the event of fault the dc current \( (i_{dc}) \) becomes greater than the predefined maximum permissible current \( i_{ref} \) and the controller of NC-NIBFCL opens the IGBT switch from the closed mode. After opening the IGBT, the line current is bypassed to the parallel path \( (L_{sh} \text{ and } R_{sh}) \). Therefore, the high impedance parallel path limits the fault current and the shunt resistor \( (R_{sh}) \) consumes the excess energy from the DFIG, helping to ensure system transient stability.

4.2. NC-NIBFCL design and control Strategy

To design the NC-NIBFCL, a small value of \( (r_d = 0.0005 \Omega \text{ inoms}) \) and dc-reactive inductance \( (0.01 \text{mH}) \) are considered in the bridge part of the NC-NIBFCL to limit the instantaneous high injected fault current during the abnormal condition in the circuit. On the other hand to ensure the transient stability the parallel path of the NC-NIBFCL, the parallel inductor value \( (L_{sh} = 0.2 \text{mH}) \) and resistor value \( (R_{sh}) \) was selected 0.6255 p.u in trial basis in the tested model system.

The controller of this work is very simple and the configuration of the control algorithm is similar to [19] which are shown in Fig. 3. In this work some basic control parameters are chosen to operate the IGBT switch from closed-open-closed mode, for instance, dc current \( (i_{dc}) \), preset permissible reference current \( (i_{ref}) \), PCC voltage \( (V_{pcc}) \), and reference voltage \( (V_{ref}) \) [19]. The operation of the controller is explained in details in [19], which is followed in this work to operate the IGBT switch. Moreover, in this work a comparison is also done among the nonlinear controller and linear controller in order to show the effectiveness of the nonlinear controller based new bridge type fault current limiter. The conventional linear controller is explained in below subsection of 4.3.
4.3. Conventional Linear Controller

Figure 4 is representing the conventional linear controller. The concept of the conventional linear controller is found in [19], but in this work it is modified and explained in details. In conventional linear controller, the two basic parameters are used to operate the IGBT switch and they are PCC voltage ($V_{pcc}$) and permissible threshold voltage ($V_{th}$). During normal operation, the IGBT is closed until ($V_{pcc} > V_{th}$). But in the vent of fault the PCC voltage becomes less from reference voltage ($V_{pcc} < V_{th}$) and the fault is detected through the controller and therefore the IGBT is turned open from closed mode condition to force the fault current towards the high impedance of shunt path and ensure the transient stability. Therefore, we can say that only voltage profile is used to sense the fault in conventional linear controller, but in the nonlinear controller, both voltage and current responses are used to detect the fault and operate the IGBT switch. Moreover, in this work a comparison study is also considered among the linear controller and nonlinear controller which is explain with simulation outcomes in section 7.4.

5. Series dynamic braking resistor

5.1. SDBR Structure and Operation

Figure 5 is representing the model of the SDBR. It has two parts- one is resistor and another one is semiconductor IGBT switch [10]. In normal condition, the resistor of SDBR is deactivated as the IGBT switch is closed. During fault, the IGBT switch is activated and inserted the resistor of SDBR into the operation, which limits the high injected fault current into the systems.

5.2. SDBR Design and Control strategy

The operation of the SDBR is well explained in many literatures [10], [12]. In this work, SDBR operation is controlled by the sensing of PCC voltage. During normal operation the resistor of the SDBR has no function but in the event of fault the PCC voltage goes lower than the predefined reference voltage, and the controller turns the IGBT from closed mode condition to force the fault current towards the high impedance of shunt path and ensure the transient stability. After the fault clears, the IGBT switch closes to resume the normal condition of SDBR [12]. In this paper, to make the transient stability compatible among
the series auxiliary devices, the same value of resistor (0.6255 p.u.) is used in SDBR.

6. DFIG based wind farm model system

The concept of DFIG based double circuit transmission line model system is found in [9],[11],[19] which is also considered in this research work. The test system model is shown in Fig.6 and the DFIG based WF (10 MW) has been developed in MATLAB/Simulink environment. In this model 5 DFIG's (2 MW*5) are considered. All DFIG's are connected to the PCC as shown in the Fig.6. As the wind farms are based on many turbine generator systems, therefore this WF was constructed from five individual turbines. In order to improve the transient stability of DFIG based WF the series devices (SDBR and NC-NIBFCL) are connected between the PCC and double circuit transmission lines. The internal parameters of the DFIG with wind turbines are shown in Table 2 [18-20].

7. Simulation outcomes with discussions

7.1. Simulation Consideration

In this work, in order to analysis of the transient stability, variation of the wind speed is ignored for a short period therefore the wind speed is assumed constant 14 m/s at the moment of fault on the line [19]. For analysis of the systems performance, a 3LL, and 2LL temporary faults are applied to one of the transmission lines at point F1 at 0.1s. After applying fault, the faulted line circuit breakers CB1 and CB2 open at 0.2s successfully and re-close both circuit breakers at 1.2 s [12],[19]. To evaluate the case study, total duration of 2s is considered and simulation time step responses is used 10μs for the study. Three different cases are considered in this work in order to transient enhancement analysis among the series devices. The cases are as follows:

- Case A: Transient stability performance analysis without any controller.
- Case B: Transient stability performance analysis with SDBR.
- Case C: Transient stability performance analysis with proposed NC-NIBFCL.

7.2. Analysis the Transient Stability for 3LL fault

In Fig. 7(a), it shows that the DFIG terminal voltage goes near about zero right after 3LL fault without any auxiliary device. The voltage profile improves after inserting the series devices into the system. Although the SDBR can improve the terminal voltage, from the simulations it can be stated that the

![Fig.4. Conventional linear Controller [19].](image)

![Fig.5. Diagram of: SDBR [10],[12].](image)
performance of the proposed NC-NIBFCL is superior to SDBR in terms of voltage stability because by using of the NC-NIBFCL, the DFIG terminal voltage returns to its nominal value very quickly in comparison to SDBR.

Figure 7(b) is representing the DFIG machine speed responses for three cases. It can be stated that the machine speed of DFIG has lower oscillation by using of the proposed NC-NIBFCL, compared to others (SDBR and without controller). Figure 7(c) is representing the active power responses of DFIG for 3LL fault and it is seen from the simulation curve that the NC-NIBFCL performed well in comparison to the SDBR. The DC-link voltages for three cases are shown in Fig. 7(d). From this figure it is clear visualized that the performance of the NC-NIBFCL is better than the SDBR.

Therefore, from all responses it is noticed that the NC-NIBFCL provides better transient stability performance in comparison to SDBR in the event of 3LL fault.

![Fig.6. DFIG based Test model system [19].](image)

<table>
<thead>
<tr>
<th><strong>Table 2.</strong> Parameter of the wind turbine and DFIG [18-20].</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generator characteristics</strong></td>
</tr>
<tr>
<td>Turbine type (horizontal axis)</td>
</tr>
<tr>
<td>Rated wind speed (m/s)</td>
</tr>
<tr>
<td>Rated power of DFIG (MW)</td>
</tr>
<tr>
<td>Number of turbine Generators</td>
</tr>
<tr>
<td>Rated stator Voltage (V)</td>
</tr>
<tr>
<td>Rated frequency (Hz)</td>
</tr>
<tr>
<td>Stator resistance (p.u.)</td>
</tr>
<tr>
<td>Rotor resistance referred to the stator (p.u.)</td>
</tr>
<tr>
<td>Stator leakage inductance (p.u.)</td>
</tr>
<tr>
<td>Rotor leakage inductance referred to the stator (p.u.)</td>
</tr>
<tr>
<td>Magnetizing inductance (p.u.)</td>
</tr>
<tr>
<td>Lumped inertia constant (s)</td>
</tr>
</tbody>
</table>
7.3. Analysis The Transient Stability for 2LL fault

The DFIG terminal voltage responses for all cases in the event of 2LL fault is shown in Fig. 8(a). In Fig. 8(a), it is seen that the DFIG terminal voltage goes to 0.612 p.u. without any auxiliary devices. The voltage profile improves over 0.92 p.u and enhances the transient stability through the all series devices. However, the proposed NC-NIBFCL outperforms the SDBR by keeping the voltage level over 0.95 p.u, which indicates that the proposed NC-NIBFCL performance is better than SDBR in terms of voltage response.

The machine speed and active power responses for 2LL fault are depicted in Fig. 8(b)–8(c) respectively. It may be seen, from the simulation outcomes that the proposed NC-NIBFCL can improve the transient stability by maintaining the steady speed than the SDBR, as well as yielding superior performance, and by maintaining a small variations of output power than the SDBR during the 2 LL fault. The DC link voltage is shown in Fig. 8(d) for 2LL fault and NC-NIBFCL aids to keep maintain the variations of the dc-link voltage and more stable in comparison to SDBR. Finally we can say that proposed NC-NIBFCL performed well in comparison to SDBR in every aspect.

7.4. Controller Comparison

In this work, a comparison study is also considered among the proposed nonlinear controller (NC) and linear controller (LC) like as [19], and the dc link voltage for 3LL fault is considered which is shown in Fig. 9.

From Fig. 9, it can be stated that the performance of the nonlinear controller based series devices is better than the conventional controller based series devise, as the
Fig. 8. Simulation outcomes of DFIG for 2LL fault:
(a) Terminal voltage; (b) Speed response; (c) Output active power (d) DC link voltage

Fig. 9. DC-link voltages response curve for 3LL fault with nonlinear and linear controller
fluctuation of dc-link voltage is minimal when the series devices are equipped with the nonlinear controller.

7.5. Implementation feasibility of the Proposed device

The configuration of the proposed new bridge type fault current limiter is based on diodes, IGBT switch, inductor and resistor. In general, the diodes and IGBT/GTO switches are available in the global markets and therefore bridge type FCL can be implemented commercially [21], [22]. Moreover, it is possible to make the fast switching practically as the IGBT switch can switch at 50 KHz frequency [24] and therefore, it can be stated that proposed series device could be possible to implement in commercially in order to improve the transient stability of the DFIG based WF.

8. Conclusion

Finally, from above all explanation following points can be summarized from this research work.

- The proposed NC-NIBFCL is performed well and improved the transient stability of the DFIG based WF.
- The NC-NIBFCL can maintain the voltage level ±0.1 p.u. of the rated voltage both for balanced and unbalanced faults.
- Proposed NC-NIBFCL is capable to maintain the active power both for 3LL and 2LL faults.

The NC-NIBFCL maintains the DC-link voltage fluctuations in the event of fault and performed well in comparison to SDBR.

At the end, it can be stated that the proposed NC-NIBFCL performed well in comparison to SDBR and capable to improve the transient stability of the DFIG based 10 MW WF.

References


