Enhancement of Fault Ride-Through Capability during Symmetrical Fault of the DFIG Wind Turbine using Alternative Resistive-type SFCL

Umesh Chaudhary[1], Jyotishman Pathak[2]

[1]Department of Electronics & Electrical Engineering, Indian Institute of Technology Guwahati
Amingaon, Guwahati - 781039, Assam. INDIA.
c.umesh@iitg.ernet.in

[2]Don Bosco College of Engineering and Technology, Assam Don Bosco University
Airport Road, Azara, Guwahati - 781017, Assam. INDIA.
ieeejyoti@gmail.com

Abstract: ***In this paper, the resistive-type superconducting fault current limiter (RT-SFCL) with doubly-fed induction gen¬erator (DFIG) based wind turbine has been proposed to suppress the steady-state and transient fault current at stator side to improve the fault ride through (FRT) capability of the system. This fault current limiter utilizing the superconductor dc coil so there is not any power loss during both normal as well as faulty operation of system. The analytical analysis has been also presented. The simulation results of a 0.9 MW/0.69 kV, the DFIG-based wind turbine are obtained with and without proposed RT-SFCL using PSCAD/EMTDC software. Finally, it observed that the voltage sag at the generator terminal and consumption of reactive power from the grid has been reduced during symmetrical fault***

Keywords: Doubly-fed induction generator (DFIG), fault ride-through (FRT), resistive-type superconducting fault current limiter (RT-SFCL), renewable energy system, wind turbine.

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1. Introduction

In this era, the electricity has become an integral part of this modern technological civilization. With increasing demand of electricity in day to day life with minimal pollution, the wind energy as a renewable energy source plays important role due to its many aspiring prospects. Therefore, increases the high penetration of wind turbine in the modern power systems. The most popular doubly-fed induction generator (DFIG) based wind turbine are generally required to achieve an adequate fault ride-through (FRT) during grid faults [1]. However, the DFIG-based wind turbine is highly sensitive towards grid faults [2]. In case of without protection scheme, the large electro-magnetic transients due to grid disturbance may damage the core electrical and mechanical parts of the DFIG-based turbine and even result in failure of FRT [3].

Since, the discovery of superconductivity in 1911, by KamerlinghOnnes, it has come a long way. The SFCL have application in power systems, which includes transmission cables, transformers, magnetic energy storage, and electrical machines. In 1970s, the first superconducting fault current limiter (SFCL) were proposed and after discovery high temperature superconductors (HTS) in 1986 it became commercially viable. In the case of HTS materials liquid nitrogen is used for cooling which is less costly than liquid hydrogen. Recently, the several methods have been carried out to improve the FRT of the DFIG system. Different family of flexible ac transmission system (FACTS) devices have been discussed, which supports the large reactive power for recovering the flux of air gap after disturbance occurrence in modern power system [4]. The combinational dc chopper and crowbar system was previously studied [5]. The series dynamic braking resistor (SDBR) is generally connected at the generator terminal but it is cost effective [6]. The SFCL has been proposed to achieve FRT capability for the DFIG system is implemented [7,8]. Generally, the SFCL is divided in two families i.e. RT-SFCL (RT-SFCL) and inductive-type SFCL and its properties are during normal condition the superconducting elements has zero impedance and high impedance resistive during fault condition.

Due to continuous increasing of wind penetration to the grid, the probability of short circuit current has been increased. The main benefits of using SFCL are presented below:

i. Avoid equipment damaging and frequent replacement.
ii. Use of lower fault rated equipment.
iii. Waived series reactor, split buses, bus tie breakers.
iv. Reduce voltage dips at the generator terminal.
v. Finally, enhance the power system transient stability.

This paper has introduced a new application of the alternative RT-SFCL for FRT improvement applications in a 0.9 MW of the DFIG-based wind turbines. The proposed a new SFCL is connected inside the DFIG power circuit rather than connecting at terminal. The main properties of the proposed topology has not any considerable effect during normal condition operation and in the fault condition, the SFCL poses itself as a resistance between rotor of the DFIG and the RSC to improves the FRT capability of wind turbine.

This article is constructed as follows: Section 2 presents the modeling of the DFIG-based wind turbine. Section 3 is presenting the operation of the RT-SFCL. In Section 4 simulation results have been discussed. Section 5 draws the final conclusions.

2. The DFIG-based Wind Turbine Model

A schematic of the simulated DFIG-based system is illustrated in Figure 1.

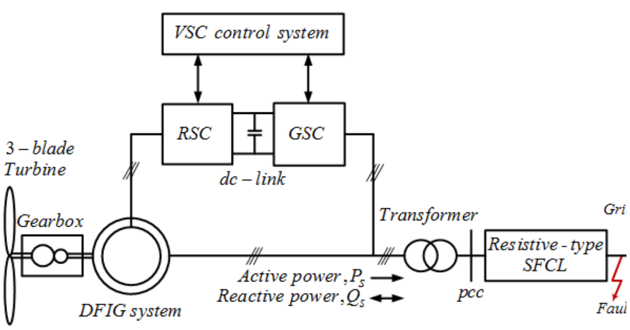


Figure 1: The DFIG-based wind turbine integrated with the grid.

The Wind Turbine Model

Aerodynamic blade pitch controlled wind turbines can extract more wind energy within the wide range of wind speed, by controlling the pitch angle of the turbine blade. The power harnessed by the turbine is defined as,

$$P_m = \frac{1}{2}\rho a_t \upsilon_o^3 c_p(\lambda, \beta) \qquad (1)$$

where the air density is ρ , a_t , at is the rotor swept area, area, and $\upsilon_0$is the wind speed. The power coefficient is a nonlinear function of tip speed ratio $\lambda = r\omega_t / \upsilon_o$ and pitch angle β ;wherer *and* ω_t and pitch angle ; where r and stands for turbine rotor radius and wind turbine rotor rotational speed respectively. When the wind velocity is above the specified value, then the rotational speed of the rotor is higher and the electromagnetic torque is not adequate to limit the additional speed of the rotor, thus resulting in overload on the generator and the converter. To prevent rotor rotational speed to be through very high so the extracted power from the incoming wind speed must be limited.

The DFIG Model

Dynamic model needs to be more realistic for actual behavior of the DFIG. From control purpose, (d, q) representation of machine leads to control flexibility [9]. The mathematical equations of the DFIG can be expressed in d-q reference frame which is given by the Park's equations. The d-axis and q-axis component of stator and rotor voltages are presented as

$$\upsilon_{ds} = r_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \qquad (2)$$

$$\upsilon_{qs} = r_s i_{qs} + \frac{d\psi_{qs}}{dt} - \omega_s \psi_{ds} \qquad (3)$$

$$\upsilon_{dr} = r_r i_{dr} + \frac{d\psi_{ds}}{dt} - (\omega_s - \omega_r)\psi_{qr} \qquad (4)$$

$$\upsilon_{qr} = r_r i_{qr} + \frac{d\psi_{qs}}{dt} + (\omega_s - \omega_r)\psi_{dr} \qquad (5)$$

where the equations of flux linkage of the stator and rotor is associated with their currents and are represented as follows.

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \qquad (6)$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \qquad (7)$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \qquad (8)$$

$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \qquad (9)$$

here $\upsilon_{ds}, \upsilon_{qs}, \upsilon_{dr}, \upsilon_{qr}$ are voltages i_{ds} , i_{qs} , i_{dr} , i_{qr} are currents and ψ_{qs} , ψ_{ds} , ψ_{qr} , ψ_{dr} are the stator and rotor flux linkages in d and q-axis. The r_s and r_r are the stator and rotor windings resistances. The L_s ,

L_r , L_m are the stator, rotor and mutual inductances, ω_s is the reference frame speed and ω_s is the generator rotor electrical angular velocity.

The apparent power is calculated in two parts i.e. real and imaginary part. The real part of the apparent power represents either the stator or rotor side active power, respectively.

$$P_s = \frac{3}{2}\left(\upsilon_{ds} i_{ds} + \upsilon_{qs} i_{qs}\right) \qquad (10)$$

$$P_r = \frac{3}{2}\left(\upsilon_{dr} i_{dr} + \upsilon_{qr} i_{qr}\right) \qquad (11)$$

Accordingly, the imaginary parts of the apparent power represent the stator or rotor side reactive power, respectively.

$$Q_s = \frac{3}{2}\left(\upsilon_{qs} i_{ds} - \upsilon_{ds} i_{qs}\right) \qquad (12)$$

$$Q_r = \frac{3}{2}\left(\upsilon_{qr} i_{dr} - \upsilon_{dr} i_{qr}\right) \qquad (13)$$

The mutual flux between rotor and stator windings produces an electromagnetic energy, which is stored in the form of magnetic field and that energy can produces electromagnetic torque. The expression for the torque is given as follow:

$$T_G = \frac{3}{2} p_n \frac{L_m}{L_s}\left(\psi_{qs} i_{dr} - \psi_{ds} i_{qr}\right) \qquad (14)$$

where, p_n is the pole pair number. With the help of above equations the DFIG has been be modeled.

3. The RT-SFCL Model

The RT-SFCL is the simplest and most obvious form of SFCL, because the superconductors are electrically in series with the phase conductors. It operates on the principle that passing a current, which is greater than the superconductorrated critical current, through a superconducting wire initiates “quenching” and results in a transition to a resistive state. Hence, there are virtually no electrical losses in the SFCL during normal operation, yet an the SFCL intrinsically inserts impedance into the fault current path during a fault, as long as the transition threshold conditions are satisfied. Figure 2 are shows this behavior of SFCL changes from superconducting state to quenching state, and its resistance increases exponentially.

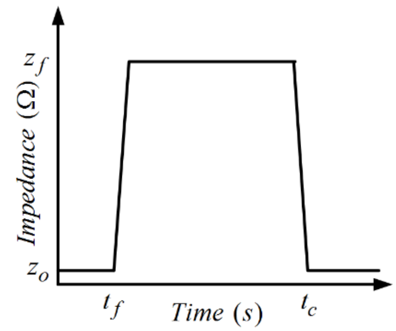


Figure 2: The basic characteristics of the RT-SFCL.

For analysis of the RT-SFCL, here consider the $E-J$ characteristic. This characteristic can be sub-divided into three parts on the basis of power laws so these are the normal conducting region. The electric field represented as flux flow region (E_n), electric field represented (E_f). The superconducting region of electric field represented (E_s). These regions are characterized by following equations are

$$E_n = \rho(T_c) J \qquad (15)$$

$$\frac{E_f}{E_o} = \left(\frac{E_c}{E_o}\right)^{\frac{\beta}{\alpha(77K)}} \left(\frac{J_c(77K)}{J_c(T)}\right)\left(\frac{J}{J_c(77K)}\right)^{\beta} \qquad (16)$$

$$\frac{E_s}{E_c} = \left(\frac{J}{J_c(T)}\right)^{\alpha(T)} \qquad (17)$$

Modelling of RT-SFCL

The model of the RSFCL using an inductor wound superconducting HTS wire, thyristor and variable resistor. Sequence of events:

- At $t < t_f$, the variable resistor is 0 as the thyristor is switched off.
- At $t = t_f + \Delta t_1$ (delay 1), the thyristors are fired andvalue of resistor increases like a ramp function.
- At $t = t_f + \Delta t_2$ (delay 2), current now is commutatedthrough the thyristor.
- At $t > t_f +$ time of fault, during this duration fault ispresent (3−phase fault occurs) in the system.
- At $t = t_f$, the fault is removed, and the value of theresistor decreases.
- At $t >> t_f$, the system.

First of all, measure the line current and calculate themagnitude of it. With the help of magnitude calculate, therate at which the line current is changing. These values ofmagnitude and rate are then used to detect if fault has occurred.If fault has occurred, then the value of impedance is changedfrom its initial value with a slope equal to maximum resistance Ω/s. Due to increase in the value of impedance the current islimited to a safe value. Then again, if the fault has been clearedthen the value of impedance is decreased to previous initialvalue with slope equal to maximum resistance Ω /s.

4. Simulation Results and Discussion

The RT-SFCL [8] is tested I n a single line system with the DFIG machine as shown in Figure 1. The test system [7] isconsidered for comparison between the RT-SFCL with the SDBRperformance and without an auxiliary controller. A 3-phaseto ground (3LG) fault has been considered at the integrationpoint of the wind turbine generator to the grid. The faultstarts at t = 3 s, and after 100 ms, the fault is cleared bya normal protection device. At that time, the wind turbineoperating at wind speed of υ_o = 11.5 m/s, and a currentlimiting discharging resistor of 10 Ω was considered.

In this present work, the DFIG-based wind turbine systemgrid (considered as an infinite bus) having a constant voltageof 20 kV with frequency of 50 Hz is considered. The DFIG-basedwind turbine is connected to the grid via a step-uptransformer of 0.69/20 kV. The DFIG-based wind turbinemachine parameters used in this paper are listed in Table I [10].The RT-SFCL and SDBR is connected after the transformerat PCC. The whole system simulation is analyzed utilizingPSCAD/EMTDC software.

The rms value of voltage response at PCC is shown in Figure 3. The fault occurred at t= 3s near at integration point,and it is found that voltage decreases to 0.4 pu, when noauxiliary controller has been considered with the grid. Afteradding the SDBR, the voltage reaches around 0.43 pu. Usingthe RT-SFCL, the voltage sag decreases to 0.59 pu. The RTSFCLkeeps voltage level higher than the SDBR during fault. It shows that the SDBR is less effective auxiliary devicecompared to the RT-SFCL.

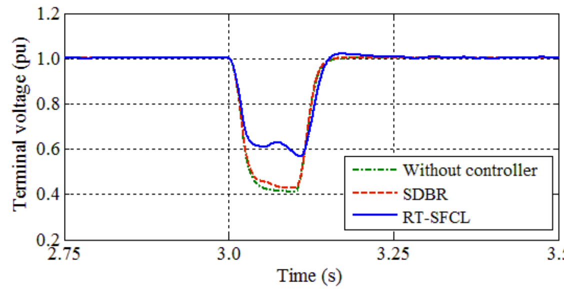
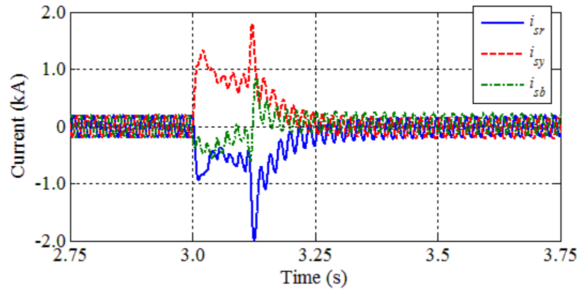


Figure 3: The voltage sag at PCC of the DFIG system.

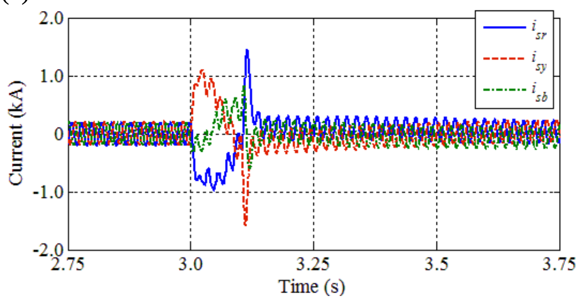
TABLE 1: SPECIFICATIONSDATA OF WIND TURBINE GENERATOR

DFIG wind turbine characteristic	***Specification***	**Unit**
Nominal power (P)	0.9	MW
Power factor (pf)	0.86	---
Rated voltage (V)	690	V
Stator resistance (r_s)	0.0054	pu
Stator leakage inductance (L_s)	0.1	pu
Rotor resistance (r_r)	0.00607	pu
Stator leakage inductance (L_r)	0.11	pu
Mutual leakage inductance (L_m)	6.75	pu
Inertia constant (H)	0.85	s
Number of pole pairs (p_n)	2	---
Stator connection	Star	---

The behavior of three phase stator current of the DFIG in thementioned fault is illustrated in Fig. 4. When without auxiliarycontroller has considered for the DFIG system as shown in Figure 4(a), the maximum value of the current goes upto 1.7 kA andinverse peak is about 1.9 kA. The current limiting capabilityfor the DFIG-based wind turbine with the help of the RT-SFCLas shown in Figure 4(b). After connecting the RT-SFCL at PCC,the stator current pick is limited to 1.48 kA and inverse peakis limited at 1.61 kA. It is observed that the inverse peak hasbeen limited after connecting the RT-SFCL. So, it seems tobe that as a whole dynamic performance of the system hasimproved.



(a)



(b)

Figure 4: Stator current behavior of the DFIG system (a) without auxiliary controller; (b) with the RT-SFCL.

The rotor swing response of the DFIG increases during faultas shown in Figure 5. The terminal voltage and the rotor speedboth are inherently related when the terminal voltage decreasedue to a fault, and rotor speed should increase. It shows thatthe RT-SFCL with discharging resistor can provide an effectivedamping after fault oscillations. The RT-SFCL is very effectivein controlling the rotor swing after fault.

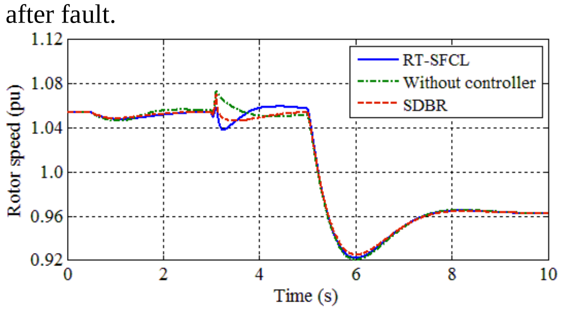


Figure 5: Rotor rotational speed of the DFIG system.

The dc-link voltage of the DFIG wind turbine in both casesis shown in Figure 6. It shows that, using the RT-SFCL, thedc-link voltage has been effectively reduced. It gives betterresponse of dc-link voltage compared to without auxiliarycontroller consideration for the DFIG-base wind turbine during fault. If dc-link voltage is high during fault, back-to-backconverter may collapse.

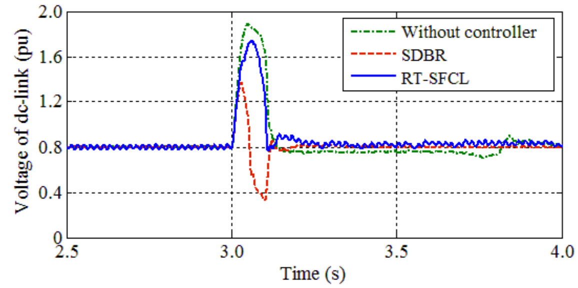


Figure 6: The dc-link voltage of the DFIG system.

The active power of the DFIG based WECS (without auxiliary controller and with the RT-SFCL) is shown in Figure 7. It is observed that the RT-SFCL consumes active powerfluctuation, only when the IGBT switch in the FCL is open andenables the DFIG wind turbine to perform better. In normal operating region, active power consumption is zero and steady state situation is unaffected.

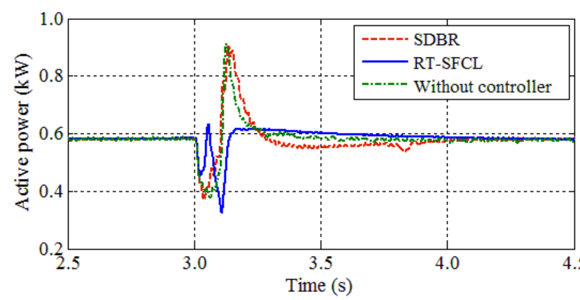


Figure 7: Active power output of the DFIG system at the PCC.

The interchange of the reactive power between the DFIGsystem and the grid for without auxiliary controller andwith the RT-SFCL as shown in Figure 8. After connecting theRT-SFCL, the reactive power is improved, and has limitedthe reactive power fluctuation during fault situation. Also,the absorption of reactive power from the grid under faultycondition regime is also limited and enhances the overallsystem stability.

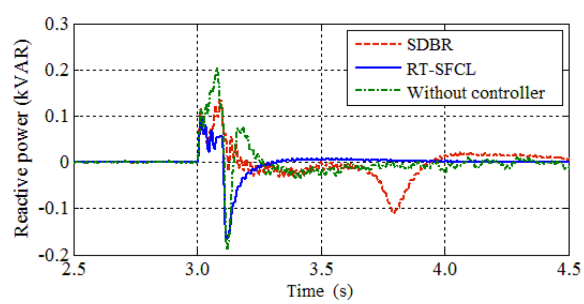


Figure 8: Reactive power output of DFIG system at the PCC.

The evaluated effectiveness of the RT-SFCL for the active power of the DFIG wind turbine has been observed. When the RT-SFCL is used, the DFIG delivered more active power to the grid and reactive power absorption by the DFIG has decreased. This helps to avoid other problem such as voltage collapse and recovery process, and improved the FRT capability.

5. Conclusion

This paper deals the RT-SFCL protection device for theDFIG-based wind turbine integrated into the grid to enhancethe FRT capability. Those auxiliary devices *i.e.* the RT-SFCLand SDBR integrated with grid that whole simulation systemis built utilizing PSCAD/EMTDC software. The rms voltagein per unit (pu) at the terminal has been verified by comparingwith the RT-SFCL and without auxiliary controller, and it wasfound that the resistive-type works better than SDBR auxiliarydevice. The simulation modeling for the stator current, dc-linkvoltage, electromagnetic torque, active and reactive power. TheRT-SFCL resistance have formed a new methodology for theDFIG protection to enhance the FRT capability. The simulationresults obtained from a 0.9 MW DFIG-based wind turbinecase have demonstrated the feasibility and practicability ofthe RT-SFCL based protection scheme under symmetrical faultscenarios. Therefore, the RT-SFCL based protection device isfavored to improve the overall FRT performance during fault,which is represented from both the DFIG system side and grid side waveform, and it can be expectedto apply in the practicalDFIG-based system and wind farms.

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Author Profile

Umesh Chaudhary

He received the B.Sc. (Eng.) degree in Electrical Engineering from the Bhagalpur College of Engineering, Bhagalpur, Bihar, India, in 2009, and the M.E. degree in Electrical Engineering from the Indian Institute of Science, Bangalore, India, in 2011. He is currently working toward the Ph.D. degree in the Department of Electronics and Electrical Engineering from Indian Institute of Technology Guwahati,India.He has published more than 30 papers in areas of the applications of power electronics in renewable energy especially wind turbine, wind turbine blade modeling, fault current limiter, and grid integration etc.

Jyotishman Pathak

He received the B.E. in Electrical Engineering from Bineswar Brahma Engineering College, Assam. He is currently working toward the M. Tech degree (Power Electronics and Power System)in the Department of Electrical and Electronics Engineering from Assam

Don Bosco University,India. His research interest towards the power semiconductor device, design of power converters design,battery design and fabrication, renewable energy conversion system, and applied nanotechnology.