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A Novel of Flux coupling Type Superconducting Fault Current Limiter in DFIG Based Isolated Wind Energy system

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Abstract : Nowadays renewable energy based energy generation and distributed generation, conventional electric power system. A fault current limiter (FCL) appears as excellent solution to above mentioned problem by limiting the fault current level. The aim of socioeconomic research is the development of fault current limiter which has following features is improved performance in terms of current limitation, higher reliability and lifetime and reduced material requirement. Superconducting fault current limiter (SFCL) appears as an excellent FCL which tends to satisfy above features. There are various types of SFCLs are in development process in order to have better performance. Resistive type SFCL is being commercialized soon. In this paper, a novel of flux coupling type SFCL is designed for limiting the fault current in isolated wind turbine generation system. The SFCL consisted of the primary and secondary coils, which were wound in series each other through an iron core. The primary coil and secondary coil with serially connected superconducting unit were connected in parallel in a flux-lock type SFCL. The major benefit obtained by limiting fault current is that we can avoid the up-gradation of existing switch-gear, protective scheme and substation equipment such as circuit breaker (CB). The whole research work and analysis has been carried out in MATLAB/SIMULINK environment.
Key words : Fault current limiter, Flux coupling SFCL, Wind, Resistive SFCL, Superconducting fault current limiter.

1. Introduction

Nowadays renewable energy resources to fulfil the gap between electrical power generations and its demand, is leading to continuous enhancement of short circuit current [1]-[2]. The increasing fault current is conventionally handled by upgrading the rating of power system utilities to higher value. Due to enormous cost and associated technical limitation in up-gradation of power system devices, development of SFCL seems to be the most promising solution. Fault current limiter can be superconducting, solid state and inductive devices. Due to high speed switching and technology associated with its operation, power electronic switches are extensively used in high voltage transmission system. In addition to this, it has ability to provide high reliability during fault current limitation. The transient behavior of flux-coupling SFCL has presented [3]. They have utilized a resistive SFCL in a micro-grid. It comprises of a usual power plant, solar-farm and wind-farm as source of renewable energy and five loads. Resistive SFCL can be connected directly in series to the line and it is extremely effective in limiting prospective fault current in a micro-grid [4]. The Resistive SFCL may not be work effectively with circuit breaker having auto-reclose feature. While installing an SFCL, magnetizing inrush of transformer and other transients must be taken into considered so as to forbid the false operation of the SFCL under these non-fault conditions. To satisfy with the fault ride through (FRT) requirements from the grid side and the operation requirements from the DFIG simultaneously, author has presented a novel FRT scheme by adopting a resistive-type SFCL connected in series with the rotor of DFIG [5]-[7]. The short-circuit behaviour a crowbar-protected DFIG. It has been shown that the difference between these results were lie within 15% [8]. The effect of hybrid SFCL on the performance of the over current relay was also presented. The implementation of hybrid SFCL is done with help of high switching speed power electronic components such as MOSFET and IGBT. Fault has been created in the above specified system so as to determine performance of current limiter [9]-[10]. The Inductive type of FCLs is installed PCC, the FCL is taken as an optimization parameter in the protection coordination problem and it affects the admittance matrix of system which allows for variations in the magnitude of fault current. Thus, from the solution of this optimization problem, one optimal relay setting is obtained that satisfies both modes of micro-grid operation [11]-[12].

2. Wind Energy System

The wind energy conversion system (WECS) is environmentally clean source of energy and it is large source of renewable energy. Though wind is perennially available but its exact availability is unpredictable. So its availability around the day for different month is predicted for past data collected from several years. Concept of probability and statistics are applied for the forecasting of wind's availability [13]-[19].

Table.1: Top ten producers of wind power (cumulative capacity in MW) [13].

Country	MW	% Share
China	145,104	33.6
USA	74,471	17.2
Germany	44,947	10.4
India	25,088	5.8
Spain	23,025	5.3
United Kingdom	13,603	3.1
Canada	11,200	2.6
France	10,358	2.4
Italy	8,958	2.1
Brazil	8,715	2.0
Rest of world	66,951	15.5
Total Top 10	365,468	84.5
World Total	432,419	100

2.1. Classification of wind turbine (WT)

Classification of WT is necessary in order to determine which type of WT is suitable for of a particular site based on historical wind data of concerning site. Different types of WT are classified in following figure.

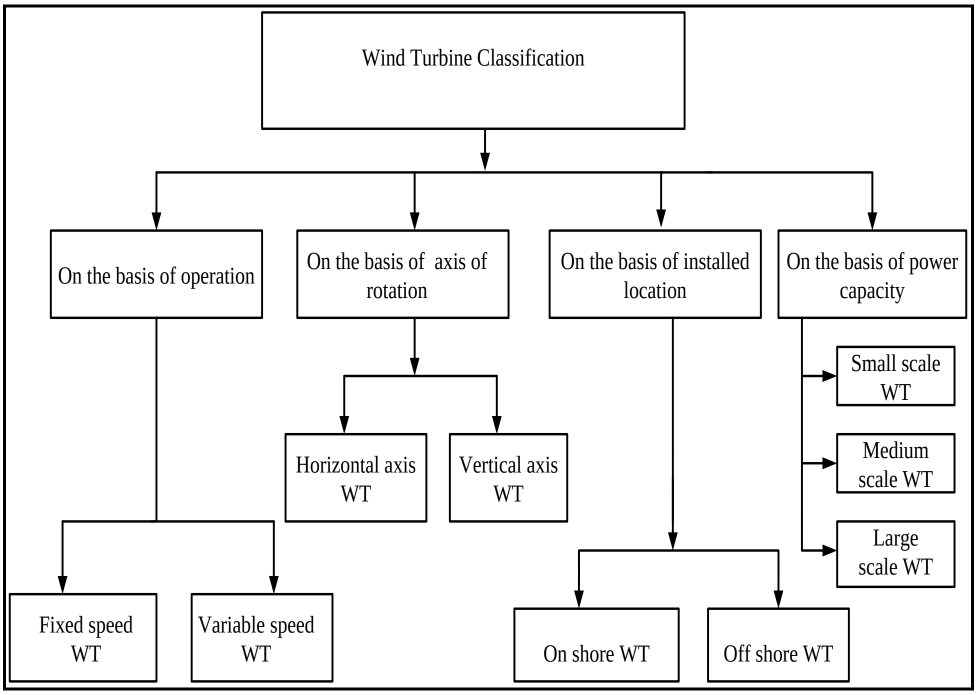


Fig. 1: wind turbine classification

Small scale wind turbine has power rating less than 10kW; medium scale WT has power rating between 10kW-500kW while large scale wind turbine has rating above 500kW.

2.2. Wind energy Fundamentals

The fixed speed and variable speed operation is possible. In fixed speed operation of WT, there is direct interconnection between wind generator and grid. Power electronic converters are used to control the generator for variable speed operation. Kinetic energy associated with a moving mass (air in this case) is given by [15]

$$E = \frac{1}{2}mv^2 \quad (1)$$

Where, E is energy contained in air, m is mass of air and v is velocity of air. Now, the wind power of can be calculated by derivation of wind energy (assuming wind velocity to be constant).

$$\frac{dE}{dt} = P_a = \frac{1}{2}v^2\frac{dm}{dt} \quad (2)$$

$$dV = A.dl \quad (3)$$

$$v = \frac{dl}{dt} \quad (4)$$

$$\frac{dm}{dt} = \frac{d(\rho V)}{dt} = \rho\frac{dV}{dt} = \rho A\frac{dl}{dt} = \rho Av \quad (5)$$

Now power contained in air is given by following equation

$$P_a = \frac{1}{2}\rho Av^3 \quad (6)$$

Where P_a: the power carried in wind in watts, ρ: density of air (assumed to be constant), A: swept area in ($meter^2$), V: volume of air and v: velocity of air (or wind) without any interference in rotor. The Power coefficient is given

$$C_p = \frac{P_{wind\ turbine}}{P_a} \quad (7)$$

$$P_{wind\ turbine} = \frac{1}{2}\rho C_p A V^3 \quad (8)$$

The maximum value of C_p is 16/27 i.e. 0593 as per Betz limit, and hence no wind turbine. The tip speed ratio is defined as below,

$$\lambda = \frac{v_{rotor}}{v_{wind}} = \frac{r_b w}{v_{wind}} \quad (9)$$

Here, some of the characteristics of wind turbine are listed for better understanding of wind turbine operation.

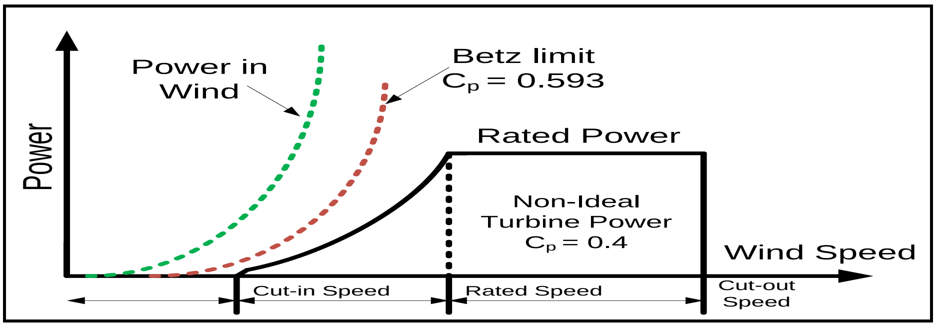


Fig. 2: Power vs. turbine speed

2.3. Fixed speed wind turbine systems

These wind turbines are directly connected to utility grid without any power electronic converter. The active power control is limited aerodynamically by stall or pitch control. This configuration requires an induction generator with direct grid connection is known as the 'Danish concept'.

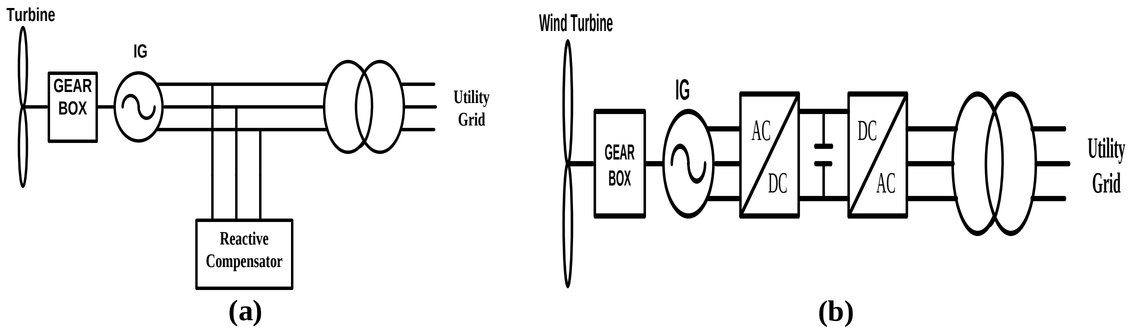


Fig. 3: (a) Fixed speed wind power system, (b) Variable speed wind power system IG.

2.4. Variable speed wind turbine system

These wind turbines are connected to utility grid with help of power electronic converters and hence in this system the generator operates absolutely independently because the DC-link uncouples the generator from grid. Hence, these wind turbine system offers the best dynamic system behavior. However, the generated power must pass the power converter and as a result there are higher losses compared to DFIG (doubly fed induction generator). But a higher performance can be achieved. So reactive and active power is controlled and reactive power can be provided even if there is no wind. In some application gear box is not used, instead of this multi pole synchronous generators are used. But in this paper wind turbine with induction generator is used to feed the local load demand operating in isolated mode.

3. Fault Current Limiter

A FCL is a device which is capable of limiting the fault current within the first half cycle without complete disconnection of electric power system. FCL can be superconducting, solid state and inductive devices. This requires that the large fault currents must be detected and disconnected by even the smallest circuit breakers. Because this increases the amount of power flow in power system network, hence all of the bus bars and their circuit breakers are required to be upgraded in order to handle the new higher fault current level. The prospective fault current surpasses its rated peak current and short time withstands current. Ideal FCLs are assumed to have the characteristics that it does not offer any impedance during normal operation.

3.1. Fundamentals of fault current limiter

When a short circuit takes place in a power system, there is abrupt increase in current level. This current is generally called fault current and it is several (approximately 15 to 20) times of normal operating current. Since the voltage level of power system is fixed (once designed), the rate of rise of current mainly depends on impedance of power system network. In Figure 4, the fault current would eventually be interrupted by a conventional circuit breaker. If the first peak of the fault current is higher than the rating of the device in the power system network, then it may be leads to damage of device. The simplest way to reduce the fault current,a FCL must be inserted directly into the system in order to reduce the first several peaks of fault current level under this situation.

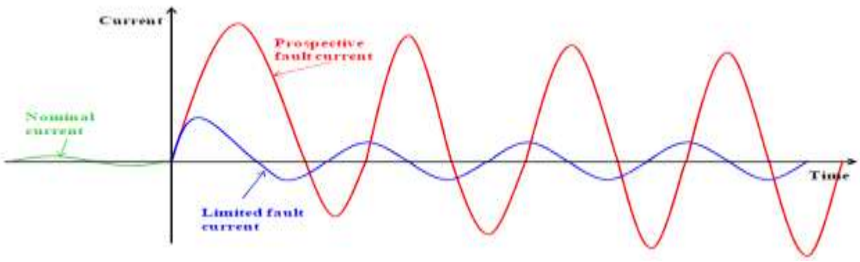


Fig. 4: Typical fault current waveforms with and without fault current limiting.

4. Superconducting Fault Current Limiter (SFCL)

SFCL is one of the important properties of superconductors. The operation of a SFCL is based on the sudden transition from the superconducting state to the normal state when actual current flowing through superconductor exceeds its critical value Ic. In normal operation, when current flows through the SFCL, it does not offer any impedance as superconductor is in superconducting state. During fault, current rises up to reach the critical of transition which causes superconductor to quench and hence its resistance increases abruptly, and current is diverted to a parallel circuit with the desired impedance of higher value.

4.1. Operating principle of SFCL

In Fig. 5 a simplified phase characteristics of a superconducting material is shown. This characteristics has been divided into three regions namely, “superconducting region ($\rho = 0$)”, the “flux-flow region ($\rho = \rho(j, T, B)$), and the “normal conducting region (ρ = constant). The easiest concept of SFCL is resistive type SFCL, in which the superconducting unit is directly connected in series with line The cross section of superconducting unit is selected in such a manner that superconducting unit remains in superconducting state, even at the peak value of current during normal operation and hence it does not offer in impedance to power system network [16]. When fault occurs in the system, there is increase in current density *j*, which drives the superconducting unit into flux-flow region. The abruptly increasing resistance limits the short circuit current to a value which is less than prospective fault current [16].

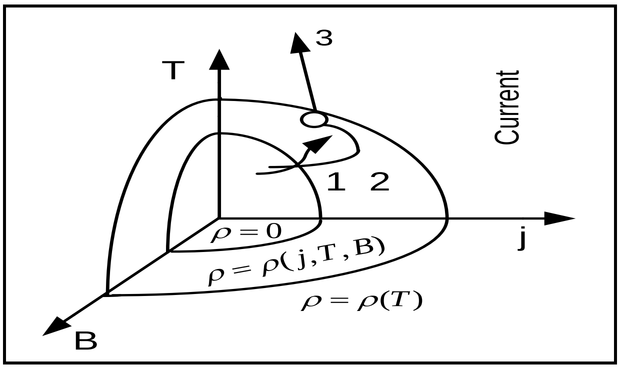
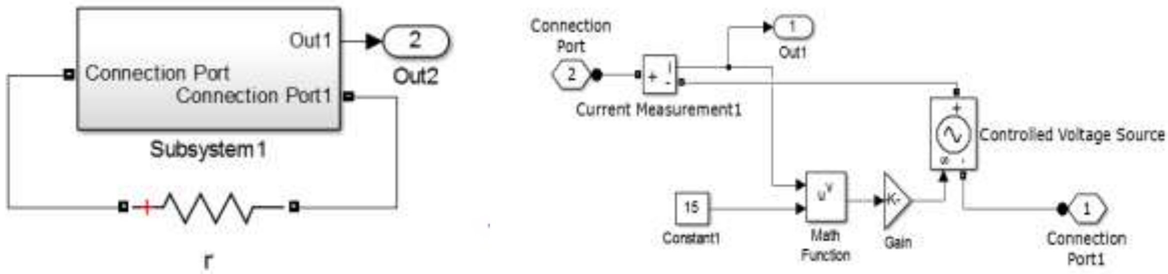


Fig. 5: T-B-J characteristics of Superconducting material.

Basically SFCL can be classified into two major categories: R-types (Resistive) and L-types (Inductive). Principle of operation of resistive SFCL [2, 3, 10] and inductive SFCL [1, 11] is same as of SFCL provided the fact that limiting impedance is resistance in case of resistive SFCL and it modifies as inductance in case of inductive SFCL [12]. Fig. 6 represents Matlab model of resistive SFCL [17].



(a) **(b)**

Fig. 6: (a) Matlab model of resistive SFCL, (b) Parameters inside subsystem1of resistive SFCL.

In Fig. 7 a three phase system is represented which have a three phase source supplying to a three phase load. Phase to phase rms voltage of source is 25kV and parameters of load are: 8MW active power and 6 MVAR reactive power. A three phase fault take place at t = 0.04 sec in the system. Current waveforms are shown in Fig. 7 and 8 without and with resistive SFCL respectively. The peak value of current under normal condition is 304.15 amp. But when three phase fault occurs, first peak of current abruptly increase to a value of 5075 amp. With help of resistive SFCL first peak of current is limited to 3627.6 amp and hence resistive SFCL efficiently limits fault current by 28.5%.

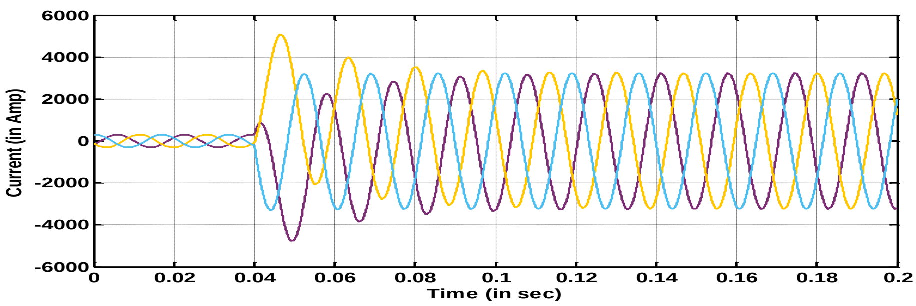


Fig. 7: Current waveform of simple three phase system without resistive SFCL.

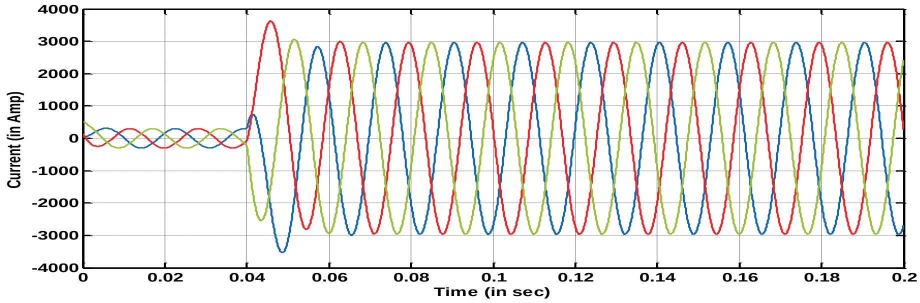
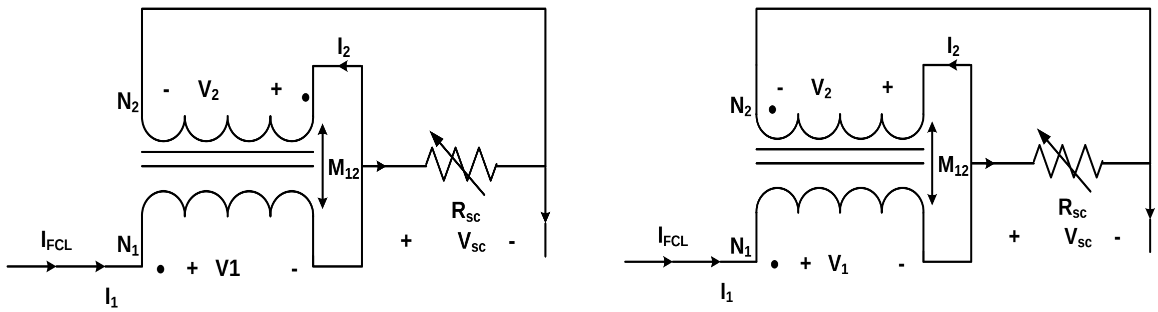


Fig. 8: Current waveform of simple three phase system with resistive SFCL.

The concentrated towards application of flux coupling type SFCL for protection of isolated wind-generation system.

5. Principle of Operation Flux Coupling Type SFCL

The evolution of flux-coupling type SFCL (SFCL) is being done with help of transformer. In flux-coupling type SFCL, primary and the secondary coils of transformer connected in series, and a superconducting unit is connected in across the secondary coil [1]. In Fig.9 flux-coupling type SFCL is represented with its simplified electrical equivalent circuit. Fig. 9 (a) shows the additive polarity winding and (b) represents subtractive polarity winding [1].



(a) **(b)**

Fig. 9: Equivalent circuits of flux-coupling type SFCL. (a) Additive polarity winding. (b) Subtractive polarity winding.

In Additive polarity winding, primary coil and secondary coil are wounded in the same direction. On the contrary, primary coil and secondary coil are wounded in opposite direction in subtractive polarity winding. Primary and secondary coils of flux-coupling type SFCL are connected in series and wounded on iron core. As shown in Fig.10 the superconducting unit is connected across secondary coil. N_1 and N_2 represent turn ratio of primary and secondary coils. V_1, V_2 and V_{SC} represent voltages of a primary coil, a secondary coil and a superconducting unit [1].

5.1. Mathematical equation

The operation and mathematical equation dealing with modeling of flux-coupling SFCL are shown below:

$$V_1 = \frac{d\psi_1}{dt} = N_1 \frac{d\Phi}{dt} \tag{10}$$

$$V_2 = \frac{d\psi_2}{dt} = N_2 \frac{d\Phi}{dt} \tag{11}$$

Where, Φ represents the mutual flux, $\psi_1 = N_1\phi$ is flux linkage of coil 1 and $\psi_2 = N_1\phi$ is flux linkage of coil 2.With equations (10) and (11), total voltage V is given by

$$V = (N_1 \pm N_2).\frac{d\Phi}{dt} = V_1 + V_2 \qquad (12)$$

Equations (13) and (14) described the value of fault current as per winding direction. Equation (13) describes the fault current for additive polarity winding while Equation (14) describes the fault current for subtractive polarity winding.

$$I_{FCL} = I_2 + I_{SC} \qquad (13)$$

$$I_{FCL} = I_2 - I_{SC} \qquad (14)$$

Resistance (R_{SC}) of superconducting is zero under normal condition as it is in superconducting state and hence the voltage (V_{SC}) across superconducting unit is also zero. If we neglect the leakage flux, voltage across secondary coil (V_2) is also zero since it is connected in parallel to superconducting unit. From equation (11), $\frac{d\Phi}{dt}$ is zero as N_2 is non-zero. Therefore, the voltage of a primary coil (V_1) is also zero. So, total voltage (V) is also zero in normal operation. Therefore it clear that under normal operating condition flux coupling type satisfies its characteristics i.e. it does insert any impedance in system or we can say that it does not interfere with system. When a fault occurred in the system and prospective fault current exceeds its rated peak current, then superconducting unit comes out of superconducting state and therefore a resistance (R_{SC}) was generated by the superconducting. Flow of mutual flux between primary and secondary coils induces the current limiting characteristics, so that fault-current was efficiently limited. The value of standard resistance (R_{in}) and load resistance (R_L) are 1 and 50 ohms, respectively. When source voltage (V_0) is $200/\sqrt{3}$ volt and SW_2 is closed at t=0.5 sec to create fault in system then magnitude of prospective fault current is 115.26 amp in the absence of flux coupling type SFCL. Fault current was limited to 13.28 amp in case of additive polarity winding. Moreover, the current of the subtractive polarity winding was limited to 22.23 amp.

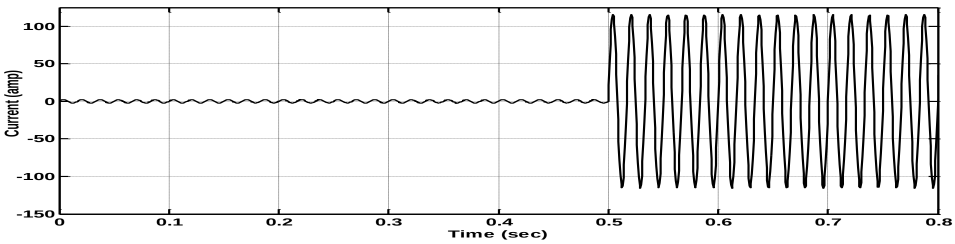


Fig. 10: Current waveform without flux-coupling SFCL.

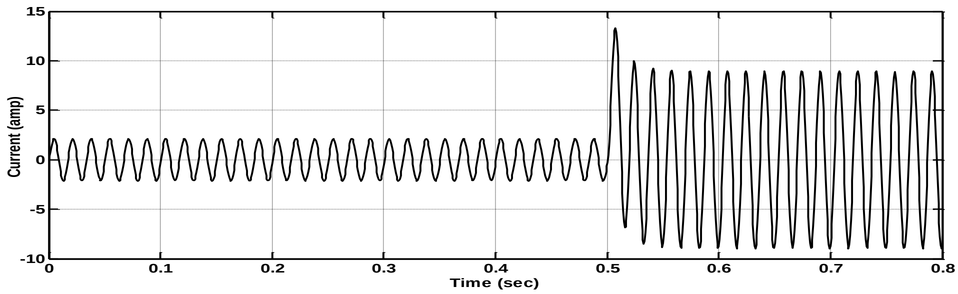


Fig. 11: Current waveform with additive polarity winding of flux-coupling SFCL.

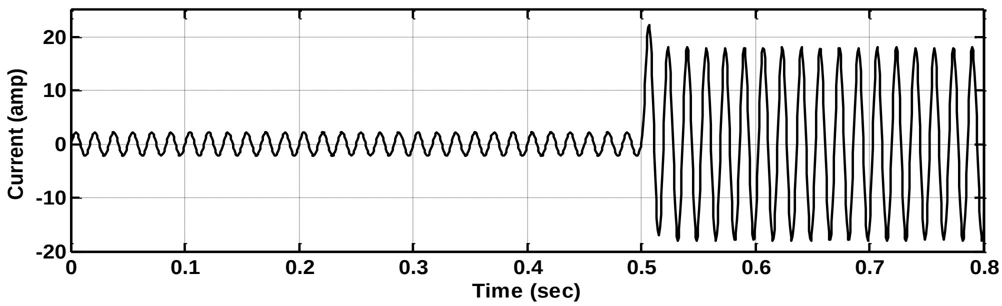


Fig. 12: Current waveform with subtractive polarity winding of flux-coupling SFCL.

6. Simulation and Results

As shown in Figure 13, there is a wind turbine with induction generator supplying power to load in an isolated network. A flux coupling SFCL is installed between load and wind turbine generator.

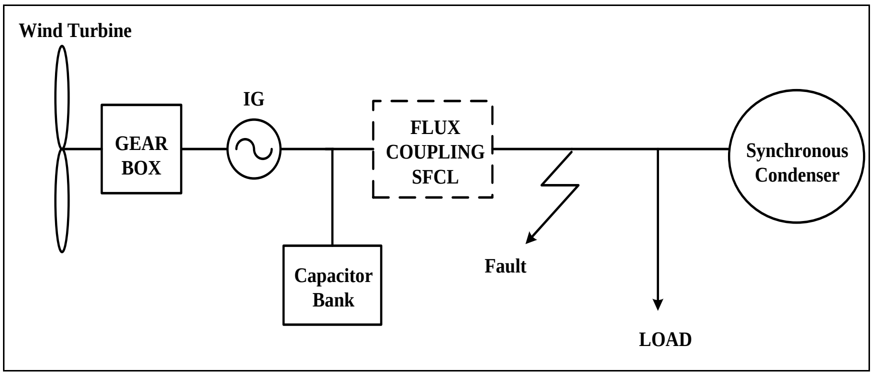


Fig. 13: Schematic diagram of isolated wind power system with Flux Coupling SFCL.

Table II Simulation Parameters

Parameters	**Values**
Rating of flux coupling SFCL	
Induction generator	275kVA, 480V
Synchronous condenser	300kVA, 480V
Load	50kW
Design Parameters of SFCL	
Self-inductance of primary coil	48.4 mH
Self-inductance of secondary coil	18.1 mH
Rated Frequency	50 Hz

6.1. Description of system presented and its simulation

Table II shows the rating of devices used in the system presented in this thesis. In addition to devices specified in table II, a variable secondary load (0 to 446.25 kW) is also used to regulate the frequency of isolated wind power system to its rated value, whenever load change takes place in the system. The variable Secondary Load is designed with of help three-phase resistors and power electronic switch GTO (gate turn off). GTO is simulated by ideal switch in Matlab environment and it is connected in series with three phase resistor. Both induction generator and synchronous machine feeds the load during low wind speeds. The synchronous machine used in this isolated wind power system is operated as a synchronous condenser at any condition of wind speed and its excitation system provides a very necessary voltage control of this distributed generation system so that voltage of the system is maintained at its nominal value. Here, induction machine operates in generating mode with super-synchronous speed of 1.011 pu. As per the characteristics of wind turbine, wind speed of 10 m/s corresponds to 0.75 pu turbine output power. Actual turbine output power can be obtained multiplying the per unit value to its base value. Here base kVA is 275 kVA so actual turbine output power is 206.25kW (.75*275=206.25). However, 200kW power is available on the output side of wind energy conversion system due to losses in induction generator. Since the main load requires only 50 kW so 150 kW must be absorbed by the secondary load in order to maintain a constant frequency (50 Hz) operation. Now, different characteristics of isolated wind power system are depicted in following figure. Fig.14, Fig.15 and Fig.16 represents the output wind power, voltage at load terminal and main load connected to the system, respectively. It is important to note that these three characteristics are independent of fault current limiter. So, their waveform does not change, with or without flux coupling type SFCL.

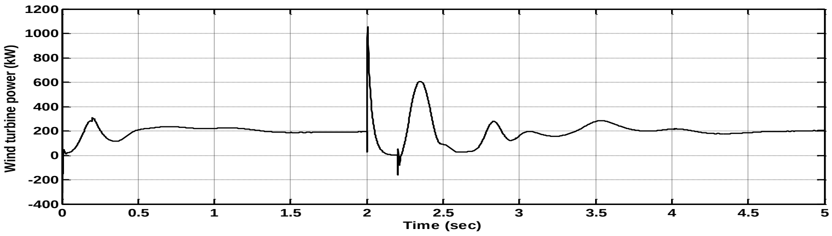


Fig. 14: Output power produced by wind turbine.

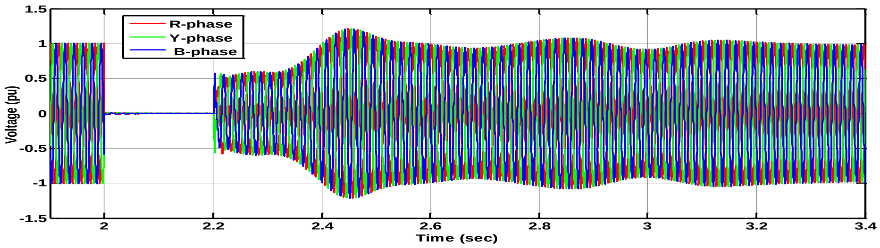


Fig. 15: Voltage waveform at load terminal of wind power system.

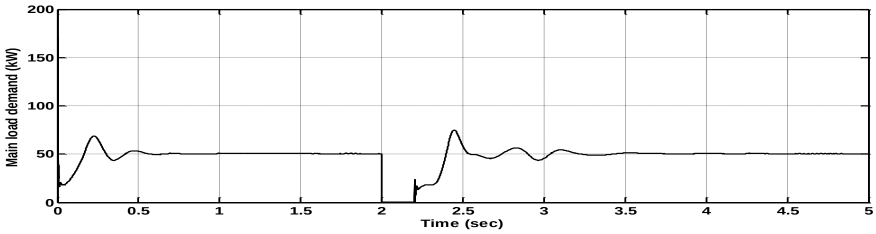
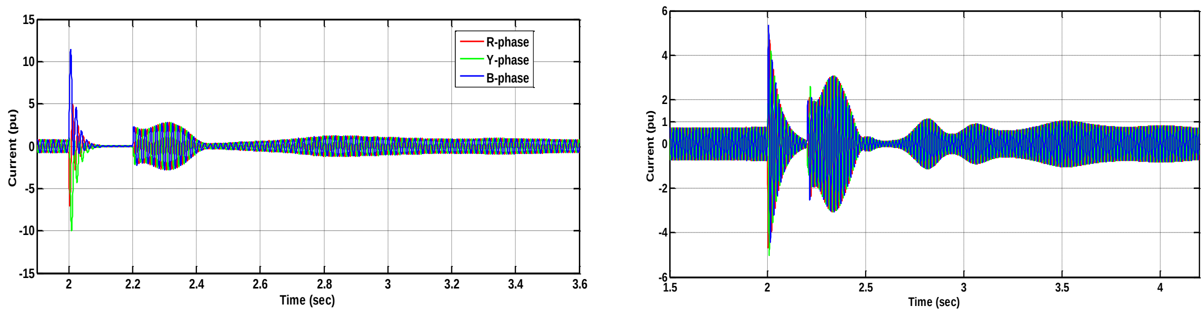


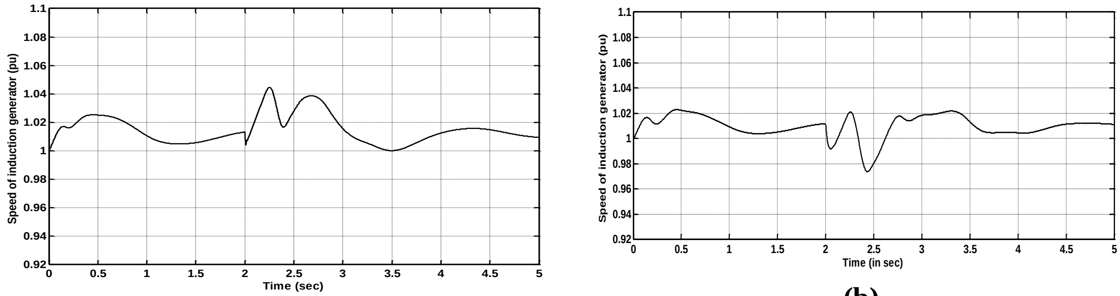
Fig. 16: Waveform of main load connected to wind power system.

Fig.17 shows the three-phase current waveforms without SFCL and with SFCL respectively. By comparing these three-phase currents , it could be noted that without SFCL the peak value of the fault current reaches about 11.4 pu, while with SFCL it is only about 5.367 pu. Therefore, a SFCL could effectively limit the peak value of the fault current by about 47.08 %.



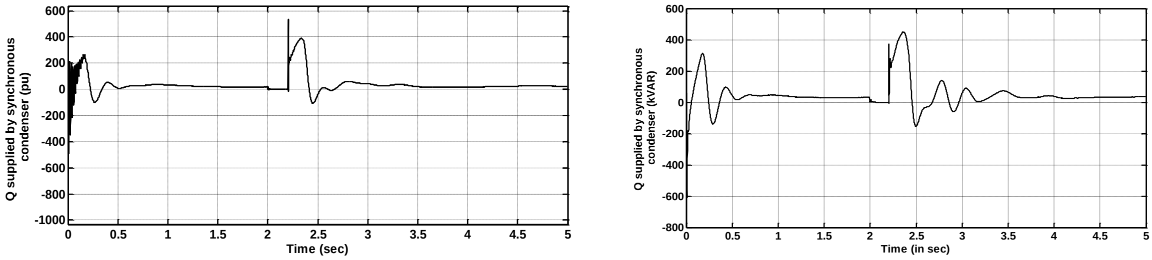
(a) **(b)**

Fig. 17: (a) Current waveform without Flux Coupling SFCL, (b) with Flux Coupling SFCL



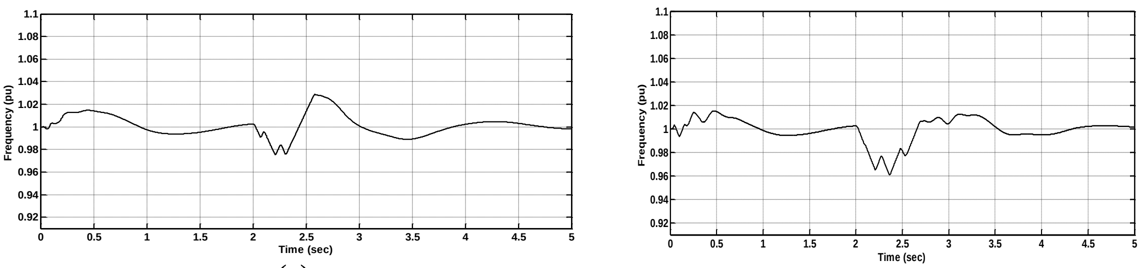
(a) **(b)**

Fig. 18: Speed of induction generator without Flux Coupling SFCL, (b) with Flux Coupling SFCL



(a) **(b)**

Fig. 19: (a) Reactive power (Q) supplied by synchronous condenser withoutFlux Coupling SFCL, (b) and with Flux Coupling SFCL.



(a) (b)

Fig. 20: Frequency of system in per unit without Flux Coupling SFCL, (b) and with Flux Coupling SFCL.

7. Conclusion

Current limiting characteristic of the flux-coupling type SFCL is investigated in isolated wind power system under faulty condition. According to the winding direction additive polarity winding is profitable for the current limitation. Flux coupling type SFCL could effectively limit the first peak value of the fault current by about 47.08 % and hence strengthens the robustness of wind power system against short circuit fault. So flux-coupling type SFCL appears as efficient device to reduce fault current to acceptable limits and hence avoids disconnection of wind energy generation from loads even under faulty conditions.Though flux coupling type SFCL works excellent to limit fault current and render its service properly in power system applications. but there may be further chance to design new kind of FCL on the basis of improved technology or anything that can further leads to better performance of existing FCLs so that FCL will be socio-economic, having fewer losses and reduced material or components requirement and also have high reliability, durability and lifetime.

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