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Voltage Stability Enhancement of Wind Generator System Using Superconducting Fault Current Limiter

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VOLTAGE STABILITY ENHANCEMENT OF WIND GENERATOR SYSTEM USING SUPECONDUCTING FAULT CURRENT LIMITER

by

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This thesis is dedicated to my family, friends and people who made "Memphis" home away from home.

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ABSTRACT

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Wind generator systems have stability problems during network faults. The superconducting fault current limiter (SFCL) has the ability to prevent the magnitude of short-circuit current from increasing. This work proposes the SFCL device to enhance the voltage stability of a fixed-speed wind generator system.

In this work the performance of SFCL is compared to that of the thyristor switched capacitor (TSC) method and the pitch control method. The comparison is done in terms of voltage stability enhancement, controller complexity and cost. The effectiveness of the proposed methodology is tested considering permanent and temporary, balanced and unbalanced faults in the power system model consisting of a wind generator and a synchronous generator.

From the simulation results it is evident that performance of SFCL is better. On comparison it can be concluded that SFCL performs better when compared to TSC or pitch control method. Simulations are performed through Matlab/Simulink software.

PREFACE

Two papers resulting from my thesis for my masters degree have been used as the manuscript in this work. The results from both these papers have been used in a combined way in Chapters 5 and 6. I have one conference paper published in the *Proceedings of the IEEE Innovative Smart Grid Technologies (ISGT) Conference 2013.* Another journal article is submitted and currently under review at the *"IEEE Transactions on Sustainable Energy."*

Following is the list of articles used in this document:

- A. Banik and M. H. Ali, "*Comparison between SFCL and TSC for voltage stability enhancement of wind generator system*", *Proceedings of the IEEE PES Innovative Smart Grid Technologies (ISGT) Conference,* Paper No. 169, Washington DC, USA, February 24-27, 2013.

- A. Banik and M. H. Ali, "*Transient Stability Enhancement of Wind Generator System Using Superconducting Fault Current Limiter"* (Under Review in the IEEE Transactions on Sustainable Energy)

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I. INTRODUCTION

Among renewable energies, wind is one of the most promising. In recent years, lots of research has been done on construction of the cost-effective, energy-efficient, reliable and stable wind energy conversion systems (WECS). There are mainly two types of wind generators available in the market. One is the fixed speed wind generator and the other is the variable speed wind generator. These days, variable speed wind generators are mostly used, but there are still many fixed speed wind generators that have been installed in the past ten years which are still in operation and they need to be integrated to the existing grid. Hence the study of the induction machine based fixed speed wind generator is considered here. Moreover, due to its rugged structure and low cost of maintenance, induction machines are the most common type of wind generators used. But the induction generator has stability problems, especially when integrated with existing power systems, making it a necessity to investigate the voltage stability of wind power stations with the existing power stations [1] [2] [3].

There are many stabilization methods available in the technological market today such as the pitch control method, the Thyristor Switch Capacitor (TSC), the static var compensator (SVC), the static synchronous capacitor (STATCOM), the dynamic braking resistor (DBR), the Thyristor switched series capacitor (TSSC), the crowbar, the superconducting magnetic energy storage system (SMES), the superconducting fault current limiter (SFCL). The static synchronous compensator (STATCOM), pitch angle control system, braking resistor (BR), and superconducting magnetic energy storage (SMES) are reported as stabilization methods for fixed-speed wind energy systems [4]. The superconducting fault current limiter (SFCL) causes no power loss in a steady-state condition and improves the voltage stability of a power system by suppressing the level of the fault current with the quick operation and auto recovery capability within 0.5 s [5]-[6]. The high temperature SFCL can be a solution to reduce the level of short-circuits currents during a fault. The level of short circuit currents is increased by the wind-turbine generator systems (WTGS). SFCL has been used with variable-speed wind generator system [7].

This work proposes the SFCL as a means to stabilize the fixed-speed wind generator system. There has been a study recorded for SFCL and its comparison with Superconducting Magnetic Energy System (SMES) [8]in case of wind generator system. The work [8] analyzed only the effect of temporary balanced fault on the wind generator system. However, this work performs a detailed analysis considering both balanced (three-line-to-ground) and unbalanced (single-line-to-ground) temporary and permanent faults in the system. Another salient feature of this work is that the exact cut off fault current level and the resistance needed for the SFCL modeling are studied.

In this work, in order to evaluate the effectiveness of the proposed SFCL methodology in detail, its performance is compared to that of the pitch angle controller and thyristor switched capacitor (TSC). The pitch controller is used to maintain a constant output power at the terminal of the generator when the wind speed is over the rated speed.

As far as TSC is concerned it is usually placed in series [9] and hence called Thyristor Controlled Switched Capacitor (TCSC). In this work, a capacitor is connected in parallel and switched using thyristor. Capacitors are known for supplying reactive power and connecting it in parallel ensures more compensation in case of faults.

The simulations are done using Matlab/Simulink software. The effectiveness of the proposed methodology is tested considering both permanent and temporary faults in the power system model consisting of a wind generator (IG) and a synchronous generator (SG). Various indices in terms of speed deviation of IG, terminal voltage deviation of IG, real power deviation of IG and terminal voltage deviation of SG are used for evaluating the system performance. The comparison between the SFCL with TSC and pitch controller is done in terms of voltage stability enhancement, controller complexity and cost.

A. Background Study for Various Technology Applications in Wind Energy Systems

Over the year plethora of methods has been adopted for safe and reliable operation of power systems. In recent times, the focus of study has been on renewable energy sources like wind, and lots of research and study have gone into solving the problem of successful integration of WECS system into the existing grid. Pitch control method was one of the most embryonic technologies used as long as control of wind turbines is concerned. Torque fluctuation of wind rotor and unbalanced load is caused due to irregular force of the wind rotor on the rotation plane due to presence of wind shear, tower shadow and other factors. Blade element theory is used to build the dynamic aerodynamic model of three-blade wind turbine applied to individual pitch control, and in accordance with wind model the wind rotor torque is simulated [10]. In [11] pitch control in terms of variable speed wind turbine is used. In this work a system has been considered by the authors who can generate maximum energy while minimizing loads. Maximization of energy is done based mostly on a static basis and drive train loads are considered as a constraint. Also in [12] a fuzzy logic pitch angle controller is developed. They have designed the fuzzy controller and compared it with the conventional pitch angle control. Fuzzy logic control is especially helpful in systems which contain strong non-linearity, such as wind turbulence is strong, or the control objectives where fatigue loads are considered. In [13] pitch control is used to enhance the fault ride through capability. In this work, it has been proved that an amalgamation of mechanical and electrical controllers design helps improve the fault ride through capability. In previous works it has already been established that pitch control provides good stability in terms of adverse conditions and for high value of speed. In [14] a new approach for control of the pitch angle of the wind turbine is represented in an unstable and noisy circumstance. It is established that with the help of the proposed control system the output power of the wind turbine can be efficiently controlled. This method amends the stability of the wind turbine as well as helps with the improvement the regulation of the output power.

In [15] a control strategy based on average wind speed and standard deviation of wind speed and pitch angle control using a generalized predictive control in all operating regions for a WTG is dealt with. For smoothing the power output and to measure its cost effectiveness, the work [16] has mentioned a novel approach for the study. In [17] a comparative study has been done between fixed and variable speed wind generators, and the effectiveness of the pitch control in both the cases has been studied. The variable speed wind turbine is based on Permanent Magnet Synchronous Generator (PMSG). The energy efficiency of the variable-speed wind turbines is widely improved relative to that with fixed speed wind turbines.

Having gone through all these studies, pitch control is still not very effective; there are other means which are better suited for the control strategy and stabilization. One such comparison has been done in [18]. A pitch controlled WTGS is used for stabilization of the wind turbine during grid faults.

Both STATCOM and a capacitor bank have been used to enhance voltage performance of grid connected pitch controlled wind farm. For STATCOM a simplified control strategy is employed, where only measurement of rms voltage at induction generator (IG) terminal is needed. A comparison study shows that STATCOM has better performance than capacitor bank. In [19], advanced form of SVC, named ASVC has been used and extensively researched and discussed. It has been debated quite often about the close resemblance of TSC and SVC. Both when used together have a huge impact on a system. One such study has been done in [20]. To have a correct compensation in case of rapidly changing load, a predictive control algorithm for TSC is deliberated. The proposed combined system can implement continuous reactive power and harmonic currents compensation cost-effectively. In [21], a combined study of SVC and TCSC for stabilizing a wind farm has been done. After performing the study it has been found that during the fluctuation of wind speed SVC offers reactive power for continuation of stability in the system. In addition to this, whenever there is a three line short circuit fault in the power grid which has a wind farm integrated in it, TCSC will help maintain the terminal voltage and efficiently improve the voltage ride through capability. In [22], SVC and another fixed series capacitor have been used to perform the steady state analysis. In addition to that, to improve the voltage profile of the system a SVC is used. The convergence characteristics of both methods show that a larger number of wind turbines can be accommodated in a Flexible Alternating Current Transmission System (FACTS) controlled network, maintaining a good voltage profile. In [23], a SVC is designed which consists of Thyristor Controlled Reactors (TCR) and Fixed Capacitor (FC). To simulate the symmetrical three-phase load bridge rectifier an L-R circuit has been used. The voltage and admittance double loop control strategy is adopted to maintain the stability of the client node voltage and satisfy the requirements of system power factor, and the well-behaved steady-state effect is obtained. In [24], it describes the grid-connected characteristics of wind power system. An SVC is proposed for betterment of the reactive compensation to improve the grid connected capacity and operation performance of the wind farms. This way grid connected quality of the wind farms can be maintained.

In [25], the SVC composed of the fixed excitation capacitor(FC) in parallel with the TSC and the TCR is applied to regulate and stabilize the generated terminal voltage of the single-phase self-excited induction generator (SEIG) for the passive load variations and the prime mover speed changes.

Another good FACTS device for reactive control used is STATCOM in its various forms. In [26], an isolated three-phase IG with fixed frequency and controllable output voltage using a three-phase four-switch STATCOM with space vector modulation (SVM) switching method has been shown. A squirrel-cage three-phase induction machine is used with two separate windings on the stator by a star connection. In [27], the performance of the wind turbine and thereby power quality is assessed on the norms followed according to the guidelines specified in IEC-61400 (International Electro-technical Commission). These are measured according to national/international guidelines. The existence of power quality problem due to installation of wind turbines with the grid is clearly mentioned here. The STATCOM is connected at a point of common connection (PCC) as a proposed method to rectify the power quality problems.

In [28], distribution static synchronous compensator (D-STATCOM) is used for operation and control for power quality improvement in asynchronous machine-based distributed generation because these kind of generators have poor voltage regulation specially, during peak load conditions. Using D-STATCOM as voltage controller helps improve the overall voltage regulation of the distribution system significantly.

Fault current limiter has a huge role to play in terms stability of a wind energy systems. It doesn’t control the reactive power but it controls the current and also helps maintain the active power drop in the system. In [29] [30], the effect of a SFCL on WTGS and its protection have been analyzed. Trying to connect WTGS into the existing grid, fault current has the tendency to increase. Increase in fault current can severely decrease the coordination time intervals between relays. By using SFCL fault current can be limited in the system which in turn will provide a chance to increase the maximum capacity of the WTGS. For selection of SFCL, selecting the impedance value is very important. In [31], a study of impedance of SFCL for improving the coordination between the protection devices is studied. In [32], a comparative study has been done between SFCL and SMES. SMES is known for its capability to damp out power swings after occurrence of faults. However, the energy absorbed by SMES during faults is not enough because the places where the SMES is installed bus voltage drops considerably. Hence in that paper a combined study of SFCL and SMES has been done. SFCL at first damps out the voltage power swing by not allowing the fault current beyond a certain point. SMES damps out the remaining power swing. A further comparative study between SFCL and SMES has been done in [8] which shows when working alone as far as wind generator system is concerned SMES works better than SFCL.

There is no doubt that SFCL will be used if the technical and economic benefits are high enough. Up to now, a number of studies have been carried out to show suitable applications of SFCL but very few reports have been published on their technical and economic benefits in existing networks. One such economic aspect of the SFCL has been discussed in [33].

II. WIND ENRGY CONVERSION SYSTEMS

There are different types of wind generators available in the market. Based on the rotational speed there are two types of wind generators. One is the fixed speed wind generator and the other is the variable speed wind generator. In this section both types of generators are discussed and then a few examples and references are discussed explaining the differences between these types of generators and what kind of technologies have been used in reference to both the generators.

A. Components of Wind Turbine

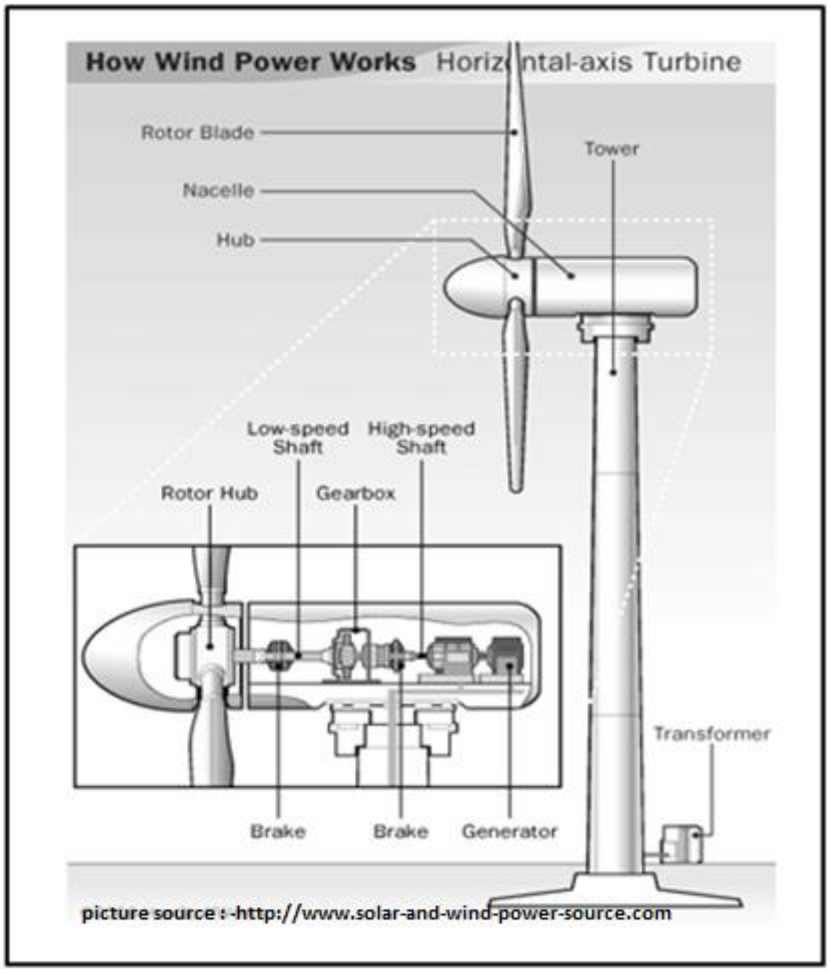

Figure 1: Horizontal Axis Wind turbine Components.

A typical wind turbine involves a set of rotor blades rotating around a hub. The hub is connected to a gearbox and a generator, located inside the nacelle which houses the electrical components. The basic components of a wind turbine system are shown in figure 1 [34].

The Nacelle: A nacelle is a cover housing for all of the generating components in a wind turbine, including the generator, gearbox, drive train, and brake assembly. It also has a direction monitor and yaw mechanism.

Rotor Blades: Diameter of the rotor blades are the most important part in a wind turbine because the longer they are the more they will sweep and they can squeeze more power out of the air. But their design and materials used are also very important.

Gearboxes and drives: Most wind turbines use a gear box whose function is to increase the rotational speed of the blades up to the level of speed of the generator installed. Lot of research is going on about how to get rid of the gear boxes and have the power electronic interface of drives installed to minimize certain effects of change in wind speed.

Brake: - Brakes are used before and after the gear box (as shown in figure 1). They are there in case of emergencies and in case the speed of the turbine blades gets out of control.

Controller: - Controller is usually used to start and stop the turbine below and above a certain level of the wind speed. In case the wind speed is too low as well as there is a wind gust, wind turbine is stopped. Right now usually it is stopped below 8-14 miles per hour (3.5 m/s -6.25 m/s) or above 55 miles per hour (24.6 m/s).

B. Types of Wind Turbines

1) Wind Turbines Based on Orientation of Rotational Axis

There are two types of wind turbines based on orientation of rotational axis: vertical axis and horizontal axis [34].

a) Vertical Axis Wind Turbine

Picture source http://tribes.tribe.net/sustainablepractices/photos/3e94df7c-b319-4355-bbf6-051c32dbb8bd

Figure 2: Vertical Axis Wind Turbine.

Vertical-axis wind turbines (VAWTs) are a type of wind turbine where the main rotor shaft is set vertically and the main components are located at the base of the turbine as shown in figure 2. Among the advantages of this arrangement are that generators and gearboxes can be placed close to the ground, which makes these components easier to service and repair, and that VAWTs do not need to be pointed into the wind. Also a yaw mechanism is not needed to turn the motor against the wind.

Major drawbacks for the early designs included the pulsatory torque that can be produced during each revolution and the huge bending moments on the blades. Another disadvantage is wind speed is very low on the lower part of the turbine which is closer to the ground.

b) Horizontal Axis Wind Turbine:

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which converts the slow rotation of the blades into a faster rotation that is more suitable to drive an electrical generator [35] .

Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its supporting tower. Turbine blades are stiff to prevent the blades from being pushed into the tower by high winds.

Downwind machines have been built, despite the problem of turbulence (mast wake), because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design [36].

2) Wind Turbines Based on Power Scale

Small Scale Wind Turbine: - Their range is 0.025 kw to 110 kw. Mean wind speed range is between 2.5-4.0 m/s. [34]

Medium Scale Wind Turbine: - Range is from 10kw to 100 kw. Speed range is 4 to 5 m/s. [34]

Large Scale Wind Turbine: - Mean Speed is more than 5 m/s and output power is more than 100kw to MW range. [34]

3) Wind Turbines Based On Location

a) On Shore Wind Turbine

Photo Source : http://en.wikipedia.org/wiki/Wind_farm

Figure 3: The Shepherds Flat Wind Farm is a 845 megawatt (MW) wind farm in the U.S. state of Oregon.

Onshore turbine installations in hilly or mountainous regions tend to be on ridgelines generally three kilometers or more inland from the nearest shoreline. This is done to exploit the topographic acceleration as the wind accelerates over a ridge. The exact position of each turbines matters, because a difference of 30m could potentially double output. This careful placement is referred to as 'micro-siting'. One such example is shown in figure 3 in US state of Oregon.

Advantages of onshore wind farms as compared to offshore wind turbines:-

i. Cheaper foundations.
ii. Cheaper integration with the electrical-grid network;
iii. Cheaper installation and access during the construction phase
iv. Cheaper and easier access for operation and maintenance.

Disadvantages of onshore wind farms as compared to offshore wind turbines:-

i. Objections based on their negative visual impact or noise.
ii. Restrictions associated with obstructions (buildings, mountains, etc.).
iii. Land-use disputes or limited availability of lands.

Hence there is another form of installation called offshore wind turbine discussed in next section.

b) Offshore Wind Turbine

Offshore wind power refers to the construction of wind farms in bodies of water to generate electricity from wind. Studies have shown that in some cases offshore wind turbine location may be a better option rather than other location on land. [37]. However, offshore wind farms are relatively expensive [38] .Figure 4 shows one such example of off shore installation near Copenhagen, Denmark.

Figure 4: Offshore wind turbines near Copenhagen.

Advantages of Offshore wind turbine are:-

i. Higher and more constant wind speeds.
ii. Offshore wind turbines sometimes have higher efficiencies because of more possibility of more wind speeds.
iii. Transporting the large components of wind turbines is much easier on ships, as they handle heavy loads far better than trucks or trains.

Disadvantages of Offshore wind turbines:-

i. The main disadvantage is that construction costs are high. The cost of building an offshore wind turbine can be twice as much as one on land of equal capacity.
ii. Maintenance is also very difficult in offshore wind turbines.

C. Wind Turbines Based on Type of Generator

1) Fixed Speed Wind Generator

In fixed speed WECS the speed is determined by calculating the generator's pole number, slip, frequency and gear ratio.

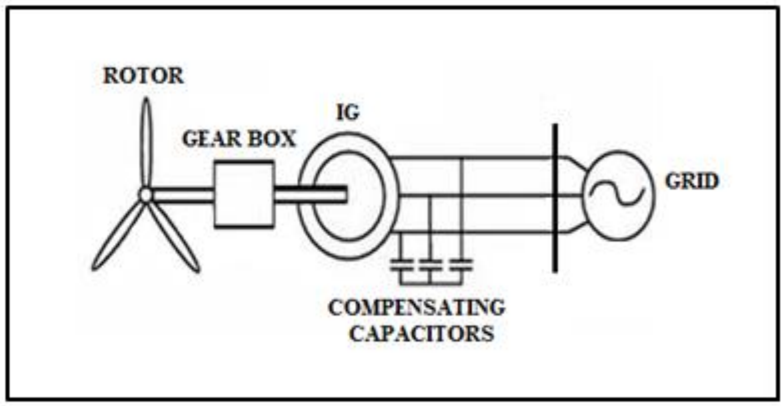

Figure 5**:** Fixed speed wind energy conversion system

Even though the generator is supposed to be fixed, wind speed is always varying. Although the variable wind speed doesn't affect the rotor speed, it definitely affects the electromagnetic torque and the electric output power. Hence it becomes very important to optimize the whole system by using auxiliary control means which increases the complexity and the costs related. The commonly used fixed speed wind turbine system is shown in figure 5.The power is usually limited by applying pitch control system. A soft starter is used in some cases to limit the value of high inrush current that may damage the machine. Gear box is used to increase the low speed from the turbine to make it up to speed required by the generator. The compensating capacitors are connected at the terminal of the IG to supply IG reactive power needed. IG absorbs reactive power from the system and supplies active power. Capacitors supply the required reactive power needed by the IG for its optimum operation. All these solutions amalgamated with IG low cost and rugged construction makes fixed speed wind generator a very attractive solution. But due to its limitation of not utilizing the variable nature of the wind, it is hindered of not extracting as much as energy from the wind as a variable speed generator does.

2) Variable Speed Wind Generator

Of late, the variable speed wind generator has been gaining popularity because of its ability to track the changes in wind speed. Variable speed wind generator uses different types of generators for example synchronous generator (SG), Doubly Fed Induction Generator (DFIG), Permanent Magnet Generators.

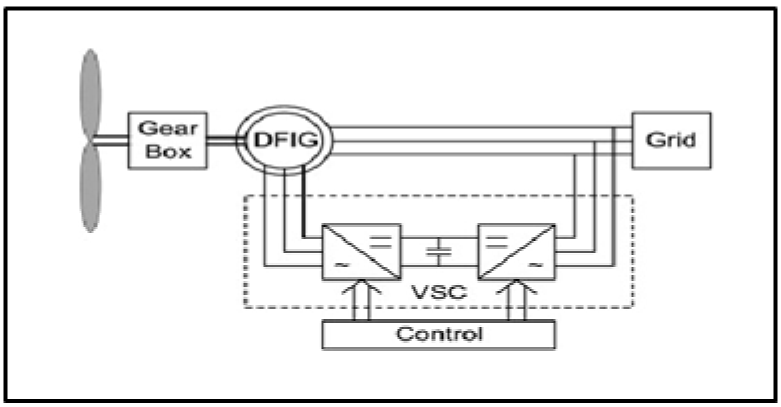

Figure 6: Wind Energy Conversion System Using DFIG

Figure 6 shows a wind energy conversion system which uses DFIG as the generator. In the figure above we can clearly see a power electronic interface between rotor and the grid. If the generator is running super synchronously, the power is delivered through both rotor and stator, whereas in case of sub synchronous operation power is delivered only through the rotor. These types of electronic converters will have some extra losses in power conversion, but provide better performance.

Synchronous generators (SG) are widely used in standalone wind energy systems. To ensure continuation of the power, back to back pulse width modulation (PWM) voltage source inverters are interfaced between the synchronous generator and the grid. The advantage of using multi pole synchronous generator is that it can avoid the installation of the gear box, but there will be a massive increase in the weight of the machine.

But the most appreciated solution these days is employing the permanent magnet synchronous generators as it gives a huge advantage to the small wind turbine industry but on the downside it cannot be extended to large scale wind energy power because of its weight.

D. Induction Generator

1) Introduction

In this study, an induction generator which is usually used with fixed speed type of wind generator is considered [39]. An induction generator or asynchronous generator is a type of AC electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotor faster than the synchronous speed, producing negative slip. A regular AC asynchronous motor usually can be used as a generator, without any internal modifications. Induction generators are useful in applications such as mini hydro power plants, wind turbines, or in reducing high-pressure gas streams to lower pressure, because they can recover energy with relatively simple controls.

To operate an induction generator must be excited with a leading voltage; this is usually done by connection to an electrical grid, or sometimes they are self-excited by using phase correcting capacitors [39] .

2) Principle of Operation

Induction generators and motors produce electrical power when their rotor is turned faster than the synchronous speed. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, synchronous speed is 1800 rotations per minute. The same four-pole motor operating on a 50 Hz grid will have a synchronous speed of 1500 RPM.

In normal motor operation, stator flux rotation is faster than the rotor rotation. This causes the stator flux to induce rotor currents, which create a rotor flux with magnetic polarity opposite to stator. In this way, the rotor is dragged along behind stator flux, at a value equal to the slip.

In generator operation, a prime mover (turbine, engine) drives the rotor above the synchronous speed. The stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, an active current is produced in stator coils, and the motor now operates as a generator, sending power back to the electrical grid.

Induction generators are not, in general, self-exciting, meaning they require an electrical supply, at least initially, to produce the rotating magnetic flux (although in practice an induction generator will often self-start due to residual magnetism). The electrical power can be supplied from the electrical grid or, once it starts producing power, from the generator itself. The rotating magnetic flux from the stator induces currents in the rotor, which also produces a magnetic field. If the rotor turns slower than the rate of the rotating flux, the machine acts like an induction motor. If the rotor is turned faster, it acts like a generator, producing power.

3) Required Capacitance

A capacitor bank must supply reactive power to the motor when used in stand-alone mode. The reactive power supplied should be equal to or greater than the reactive power that the machine normally draws when operating as a motor. Terminal voltage will increase with capacitance, but is limited by iron saturation.

III. MODEL OF WIND TURBINE AND SYSTEM

For performing the simulations and carrying out the experiment, a system is needed. A wind turbine equation also needs to be chosen from few of the equations present right now in the literature [9], [40].

The modeling of wind turbine rotor is complicated. According to the blade element theory [41], modeling of blade and shaft needs complicated and lengthy computations. Moreover, it also needs detailed and accurate information about rotor geometry. For that reason, considering only the electrical behavior of the system, a simplified method of modeling of the wind turbine blade and shaft is normally used. In general, the mathematical relation for the mechanical power extraction from the wind can be expressed as follows [41]:

$$\boldsymbol{P_\omega}=0.5*\rho*\pi*R^2*V_w{}^3*C_p(\lambda, \beta) \quad \text{(I)}$$

Where,

P_ω is the extracted power from the wind.

ρ is the air density [kg/m^3]

R is the blade radius [m]

V_w is the wind velocity [m/s]

C_p is the power coefficient which is a function of both tip speed ratio, λ , and blade pitch angle, β [deg].

There are few other equations right now, for example [40]

$$\boldsymbol{T_t = \frac{\rho A v_w{}^3}{2\omega_t} C_p(\lambda, \beta)} \quad \textbf{(II)}$$

Where,

T_t= Torque in N-m.

ρ = the air density [kg/m^3]

A=πR^2, R is the blade length in meter.

C_p = Performance coefficient of the turbine.

$$C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{\frac{-21}{\lambda_i}} - 0.0068\lambda \qquad \text{(III)}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\,\beta} - \frac{0.035}{\beta^3 + 1} \qquad \text{(IV)}$$

Further discussions about the equations III and IV and different parameters associated with it can be found in [40], [41] and [42] .

In another set of examples the basic equation is the same as mentioned in equation I. But the power coefficient, C_p is calculated in a different way as follows:

$$C_p(\lambda, \theta) = 0.73\left(\frac{151}{\lambda_i} - 0.58\theta - 0.002\theta^{2.14} - 13.2\right) e^{\frac{-18.4}{\lambda_i}} \qquad \text{(V)}$$

where

$$\lambda_i = \frac{1}{\frac{1}{\lambda - 0.02\theta} - \frac{0.003}{\theta^3 + 1}} \qquad \text{(VI)}$$

More discussion on equations V and VI and other parameters and details of calculations can be found in [9], [43], [44] and [45].

In this work, however, the MOD-2 model [9] , [45] is considered. This is because of the fact that MOD-2 equation is one of the basic and earliest equations used.

C_p - λ characteristics for the MOD-2 equation, is represented by the following equations and shown in Figure 7:

$$\boldsymbol{\lambda = \frac{Wr*R}{Vw}} \tag{VII}$$

$$C_p = \frac{1}{2}(\boldsymbol{\lambda - 0.022\beta^2 - 5.6})e^{-0.17\lambda} \tag{VIII}$$

Where Wr is the rotational speed [rad/s].

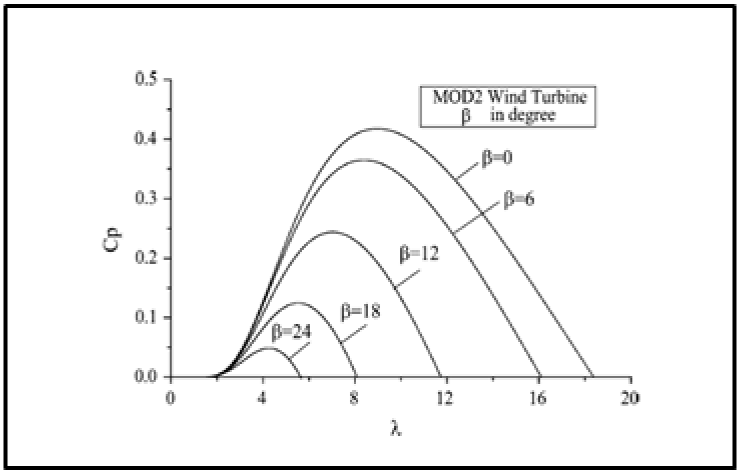

Figure 7: $C_p - \lambda$ Curves for different pitch angles.

Here in this work all the modeling has been done using equations I, VII and VIII.

IV. MODEL SYSTEM

The model system shown in figure 8 has been used in this work [46]. The model system consists of one synchronous generator (100 MVA, SG), and one wind turbine generator (50 MVA induction generator, IG), which are delivering power to an infinite bus through a transmission line with two circuits. Though a wind power station is composed of many generators practically, it is considered to be composed of a single generator with the total power capacity in this paper. There is a local transmission line with one circuit between the main transmission line and a transformer at the wind power station. The SFCL is placed in series just after the secondary windings of the transformer as shown in figure 8. The SFCL comes only in the picture when there is a fault current detected. When there is no fault, SFCL sits in the system almost being invisible and hence doesn't have any loss associated to it.

At the very same place a TSC has been connected on each phase but in parallel. The TSC acts as an additional support only and helps recover the system in cases of fault. The value of capacitor C and the firing angles for the TSC will be discussed in the subsequent sections. A fault position at F1 is picked as the location of the fault and for all the studies as shown in figure 8.

A capacitor C is connected to the terminal of the wind generator to compensate the reactive power demand for the induction generator at the steady state. This capacitor C is needed in case of induction generators, because when an induction machine is started it draws huge reactive power from the system and if the capacitor C is not there it will really hamper the power factor the system. Hence the capacitor is needed at that position.

The value of C has been chosen so that the power factor of the wind power station becomes unity when it is generating the rated power (P=0.5, V=1.0).

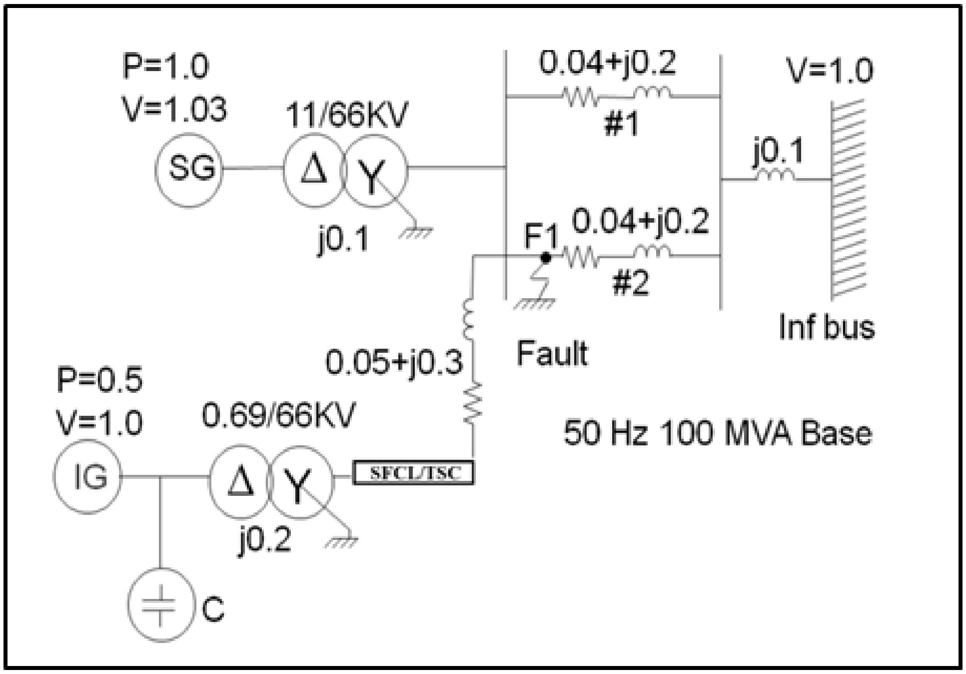

Figure 8 : Power system model.

In practical situations, there are different kinds of turbine shaft systems, like single mass system, three mass systems, and six mass systems. One such example of six mass inertia drive model system is discussed in [47]. The mechanical equivalent utilized in that study is shown in figure 9 and consists of a number of lumped inertias, elastically coupled to each other, as it is common in wind turbines [44], [48].

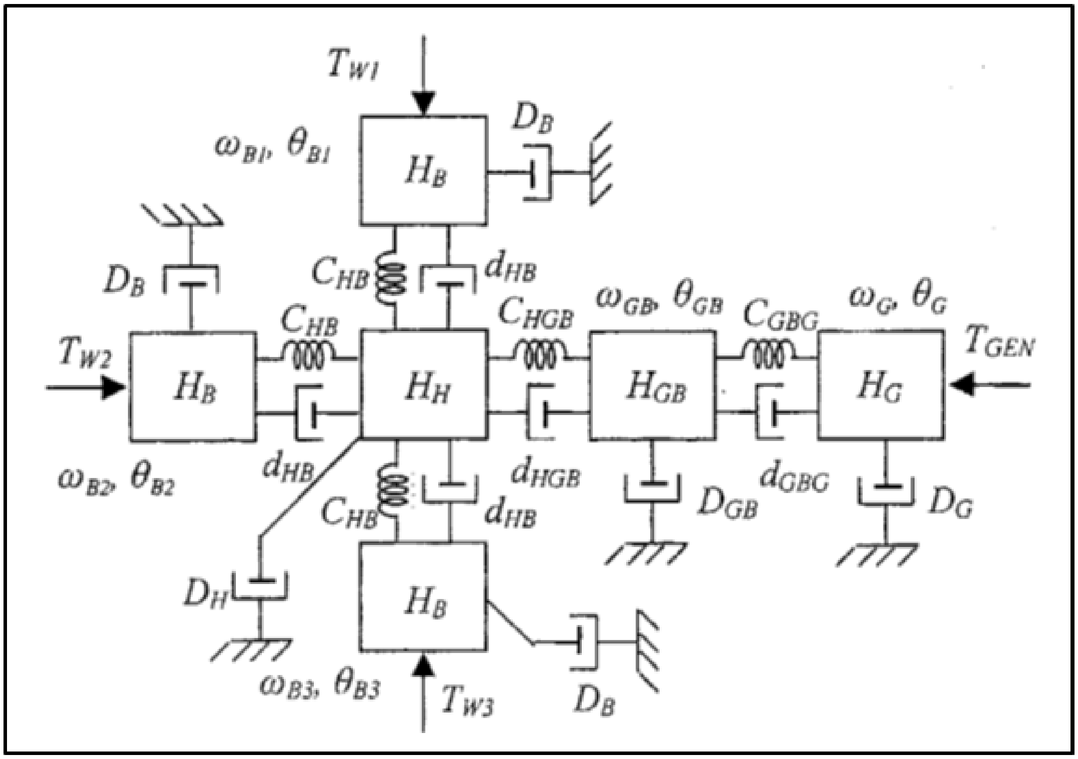

Figure 9: Drive train 6-inertia mechanical equivalent.

But in this study for simplicity and ease of calculation only single mass system has been taken into consideration. In this study the main aim was to first see the effect of SFCL on the fault current in case of integration with existing grid and hence six mass systems has not been considered.

A. Automatic Voltage Regulation (AVR) Model

A voltage regulator is designed to automatically maintain a constant voltage level. A voltage regulator may be a simple "feed-forward" design or may include negative feedback control loops. It may use an electromechanical mechanism, or electronic components. Depending on the design, it may be used to regulate one or more AC or DC voltages.

Figure 10 shows the AVR model used here with SG. The AVR model has inputs of terminal voltage and constant value of 1 p.u. After adjusting the value of the control systems in subsequent blocks, the output field voltage input for synchronous generator is obtained.

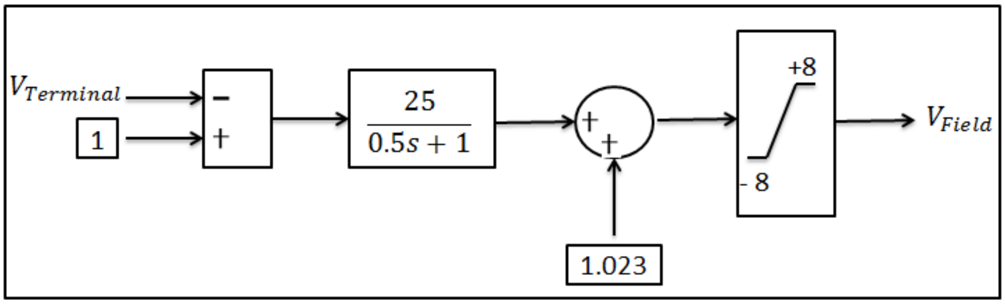

Figure 10: AVR Model

B. Governor (GOV) Model

A governor is a device used to control the speed of a prime mover. A governor protects the prime mover from over speeding and keeps the prime mover speed at or near the desired rotational speed. When a prime mover drives an alternator supplying electrical power at a given frequency (system frequency), a governor must be used to hold the prime mover at a speed that will yield this frequency. A governor regulates the speed of a prime mover by varying the flow of energy to or from it. In the case of gas and steam turbines and internal combustion engines, the fuel furnishes the energy to the prime mover. For such applications, the governor usually controls the speed of the unit by regulating the rate at which fuel, and hence energy, is furnished to the prime mover. The governor controls the fuel flow so that the speed of the prime mover remains constant regardless of load and other disturbances, or changes in accordance with such operating conditions as changes in speed setting.

Figure 11 shows GOV model used in this work with SG. It has input of rotor speed and after going through the control blocks the output power which is used as power input for synchronous generator is obtained.

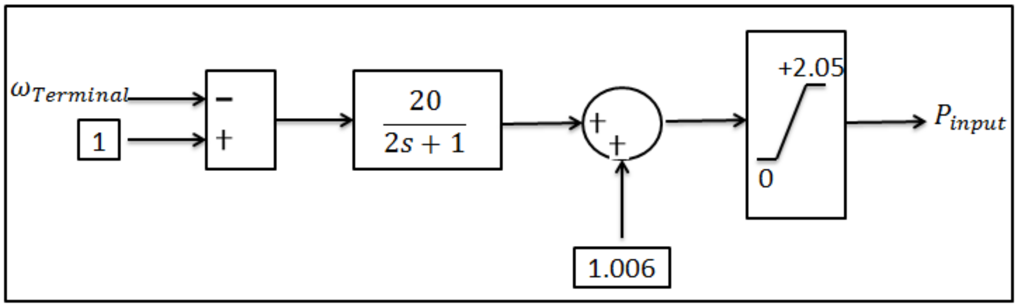

Figure 11: GOV Model

Table I shows the synchronous generator parameters [46] as well as induction generator parameters [49] used in this work.

Table I Generator Parameters

SG		IG	
MVA	100	MVA	50
r_a[pu]	0.003	r_1[pu]	0.01
X_a[pu]	0.13	x_1[pu]	0.18
X_d [pu]	1.2	X_{mu}[pu]	10.0
X_q[pu]	0.70	r_2[pu]	0.015
X'_d [pu]	0.3	x_2[pu]	0.12
X'_q [pu]	0.22	H[sec]	0.75
X''_d [pu]	0.22		
X''_q [pu]	0.25		
T'_{do} [pu]	5.0		
T''_{do} [pu	0.04		
T''_{qo} [pu]	0.05		
H [sec]	2.5		

V. CONTROL SYSTEM OF TECHNOLOGIES USED

A. Pitch Control Method

Controlling the power output from the turbine blades is a major issue in any wind turbine and it can be accomplished by two main technologies. One of those methods is pitch angle control and another is purely based on aerodynamic properties of the blade. In this thesis, concentration is given only on pitch control. The main purpose of using pitch control with wind turbine is usually to maintain a constant output power at the terminal of the generator when the wind speed is over the rated speed.

The pitch angle control is the most common means for adjusting the aerodynamic torque of the wind turbine when wind speed is above rated speed and various controlling variables may be chosen, such as wind speed, generator speed and generator power. A pitch controller with wind turbine can also enhance the voltage stability of wind generator by controlling the rotor speed.

The purpose of the pitch angle control might be expressed as follows [50], [51], [52] and [53]:

i) Optimizing the power output of the wind turbine. Below rated wind speed, the pitch setting should be at its optimum value to give the maximum power.

ii) Preventing input mechanical power to exceed the design limits. Above rated wind speed, the pitch angle control provides a very effective means of regulating the aerodynamic power and loads produced by the rotor.

iii) Minimizing fatigue loads of the turbine mechanical component. It is clear that the action of the control system can have a major impact on the loads experienced by the turbine. The design of the controller must take into account the effect on loads, and the controller should ensure that excessive loads will not result from the control action.

The pitch control system model of the wind turbine used in this work is shown in the figure 12. The time constant, T_d is 3.0 [sec]. Other parameters are K_p =1.5 and T_i =0.3, which are determined by the trial and error approach for optimizing the best performance of the system.

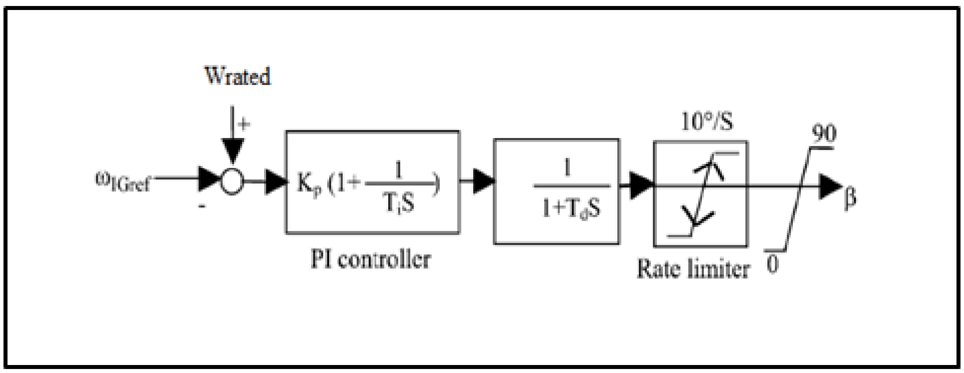

Figure 12: Pitch Control Method.

B. Control Scheme of Thyristor Switched Capacitor (TSC)

A thyristor switched capacitor (TSC) is a type of equipment used for compensating reactive power in electrical power systems. It consists of a power capacitor connected in series with a bidirectional thyristor valve and, usually, a current limiting inductor (reactor).

A TSC normally comprises three main items of equipment: the main capacitor bank, the thyristor valve and a current-limiting reactor, which is usually air-cored [54].

1) Capacitor Bank

The largest item of equipment in a TSC, the capacitor bank, is constructed from rack-mounted outdoor capacitor units, each unit typically having a rating in the range 500 – 1000 kilovars (kVAr).

2) TSC reactor

The function of the TSC reactor is to limit the peak current and rate of rise of current (di/dt) when the TSC turns on at an incorrect time. The reactor is usually an air-cored reactor, similar to that of a TCR, but smaller. The size and cost of the TSC reactor is heavily influenced by the tuning frequency of the TSC, lower frequencies requiring larger reactors. The TSC reactor is usually located outside, close to the main capacitor bank.

3) Thyristor valve

The thyristor valve typically consists of 10-30 inverse-parallel-connected pairs of thyristors connected in series. The inverse-parallel connection is needed because most commercially available thyristors can conduct current in only one direction. The series connection is needed because the maximum voltage rating of commercially available thyristors (up to approximately 8.5kV) is insufficient for the voltage at which the TCR is connected. For some low-voltage applications, it may be possible to avoid the series-connection of thyristors; in such cases the thyristor valve is simply an inverse-parallel connection of two thyristors.

In addition to the thyristors themselves, each inverse-parallel pair of thyristors has a resistor–capacitor “snubber” circuit connected across it, to force the voltage across the valve to divide uniformly amongst the thyristors and to damp the "commutation overshoot" which occurs when the valve turns off.

The thyristor valve for a TSC is very similar to that of a TCR, but (for a given AC voltage) generally has between 1.5 and 2 times as many thyristors connected in series because of the need to withstand both the AC voltage and the trapped capacitor voltage after blocking.

The thyristor valve is usually installed in a purpose-built, ventilated building, or a modified shipping container. Cooling for the thyristors and snubber resistors is usually provided by deionised water [55].

4) TSC Model Used in This Work

Here TSC is connected in parallel to the line as an additional support in cases of faults. It consists of a high value of capacitor which is usually switched with the help of back to back thyristors as shown in figure 13.This figure is only for one phase.Therefore for three phase we will have such arrangement on each phase. The value of the capacitor used is C=5.279Mvar. Here the TSC is connected in parallel and it is only operating in case the error percentage is more than 2% between the referece and terminal voltages. Thyristors work as a switching device for controlling the switching of the capacitor. Alpha is the switching pulse which is generated according to the control structure employed in figure 13.

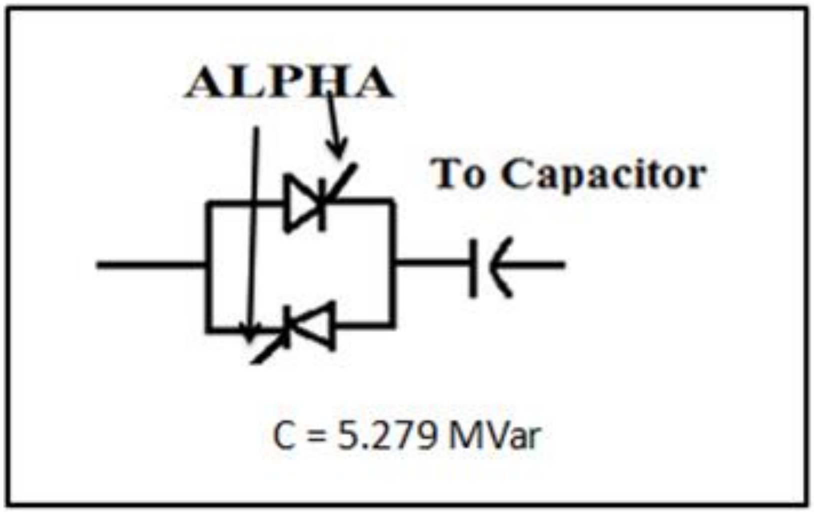

Figure 13 **:** Arrangement of TSC.

Figure 14 shows the arrangement for the generation of alpha. Here at first the reference voltage (1pu) and terminal voltage ($V_{terminal}$) of the IG is compared. It is then compared for an error of 2%. If the error percentage is more than 2%, only then alpha is generated; else alpha is kept zero or other full conduction takes place. After going through some time delays and PID (proportional-integral-derivative) controllers, switching pulse, "Alpha" is generated. Here the time constant T_d is 3 sec. Other parameters are T_i = 0.3 sec and K_p = 70 which are determined by trial and error method for optimizing the best system performance.

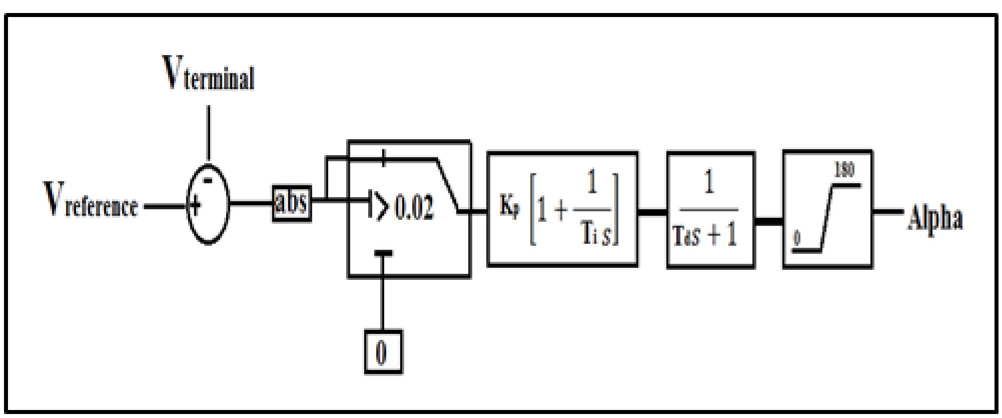

Figure 14: Control Scheme for "Alpha" Generation required for Switching of TSC.

C. Control Scheme of SFCL

1) Basics of SFCL

Being a promising application of superconductors, the SFCL is considered to be one of the innovative devices of Flexible Alternating Current Transmission Systems (FACTS) in electric power systems. The application of the SFCL would not only decrease the stresses on devices but also offer a secure network. This is a very effective means to enhance the system stability and power quality in terms of availability and voltage drop, which is a real need today [56]- [57]. Several types of SFCL have been considered which are based on different superconducting materials and designs. From the point of view of power systems, the resistive SFCL is preferable because it increases the decay speed of the fault current by reducing the time constant of the decay component of the fault currents, and can also make the system less inductive [58].

The integration of the SFCL could offer an effective solution to controlling fault current levels in distribution grids. However, the SFCL has no interrupting ability; a circuit breaker is required in series to interrupt the fault current which is limited upstream by the SFCL. To achieve a successful interruption, the circuit breaker must withstand the voltage recovery voltage (TRV) without re-igniting the arc between the contacts. The aim of the work is to examine the behavior of incorporating the resistive SFCL into the distribution grid and look at the potential beneficial effect of the SFCL in reducing the circuit breakers voltage recovery voltage (TRV) [5].

The reasons to choose a SFCL are as follows:-

i. When the fault current increases while integrating wind energy systems into the existing grids it raises the fault current level for the whole system. Hence the equipment used before like the transformers, circuit breakers etc., will have the threat of getting burned. So reducing the magnitude of maximum fault current will help protect these systems. [59]

ii. When the systems are protected, it also saves millions of dollars which otherwise would have been needed to replace the existing equipment.

iii. With fault current level kept in check, it also helps keep the coordination between the circuit breakers.

iv. The SFCL causes no power loss in a steady-state condition and it remains almost invisible to the system in steady state.

v. Improves the stability of power system by suppressing the level of the fault current with the quick operation and auto recovery capability within 0.5 sec

2) Control of SFCL

The simple structure of the resistive (non-inductive winding) SFCL unit is shown in figure 15. The unit consists of the stabilizer resistance of the n-th unit, R_{ns}, the superconductor resistance of the n-th unit, R_{nc} (t) which is connected with R_{ns} in parallel, and the coil inductance of the n-th unit, L_n. The subscript, n denotes the number of connected units [41], [49], [58]. The value of R_{ns} is not zero. However, the total resistance of parallel connection becomes zero because the value of R_{nc} is zero in the steady-state condition. The value of R_{nc} (t) becomes non-zero time-varying parameters during a fault depending on its unique characteristic. The value of total resistance of the SFCL during a fault depends on the total number of units in figure 15, which are connected in series. The value of L_n is determined by the wound coils. This should be as small as possible because the inductance causes AC loss under the normal condition. In practice, the coil is wound to have very small inductivity. Therefore, the value of Ln is so small that its effect can be ignored [7].

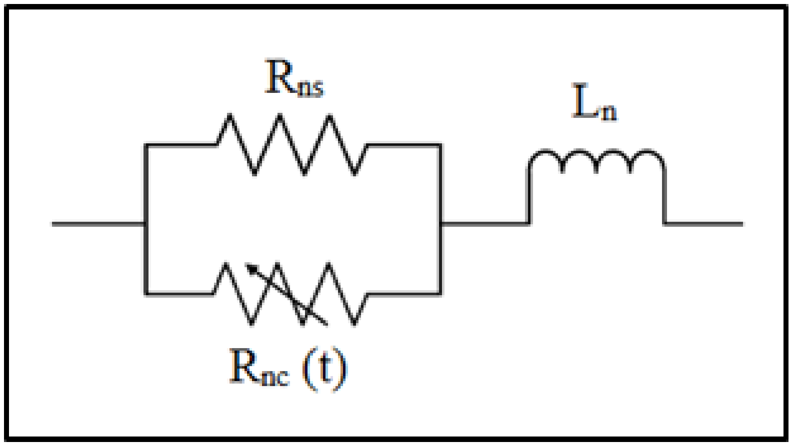

Figure 15 : The structure of a resistive SFCL unit.

However, in this work, for simplicity we have used a simplified version of the SFCL as shown in figure 16. Initially the switch, SW1 is closed, and the Inductor, L is in the circuit and its value is kept very low. The value of L is low and it is almost invisible to the system and doesn't contribute to the system and does not have any losses. In case of fault current above a certain value, the switch, SW2 is closed and switch SW1 is opened and high value resistance, R is brought in the circuit to limit the current. This R is in the circuit as long as the value of current is above the certain value. Once it's done, the R doesn't stay in circuit anymore and the SW2 is opened and SW1 is closed, which signifies that the SFCL has regained its superconductivity.

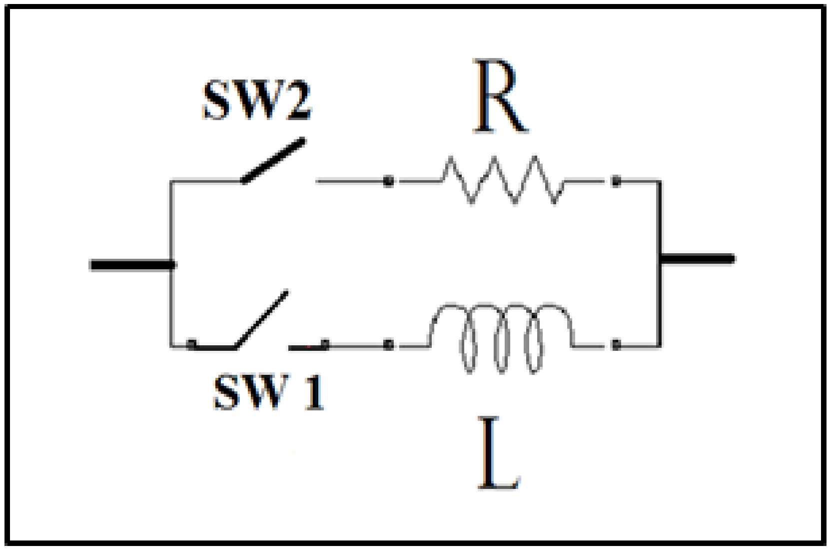

Figure 16 : Model for SFCL.

3) Determination of Fault Current Level and resistance value of SFCL

In this case the fault current level has been set at a particular value of 1.1 pu. When the fault current passes this value, a high value of resistance is inserted into the system. The values for the resistance and the fault current level have been determined by careful study in order to obtain the best system performance.

Figures 17- 19 show the responses for IG fault current with different values of resistance for a 3LG (three line to ground fault) fault. On careful study of the graphs we find that the performance for IG fault current is the best with 0.5 p.u resistance of the SFCL. Hence the optimum value of resistance as 0.5 p.u is chosen and used it for all the simulations performed in this study.

As discussed earlier, the SFCL helps in reducing the peak magnitude of the fault current and also the voltage sag in the system. This in turn helps the circuit breakers operate properly without any insubordination.

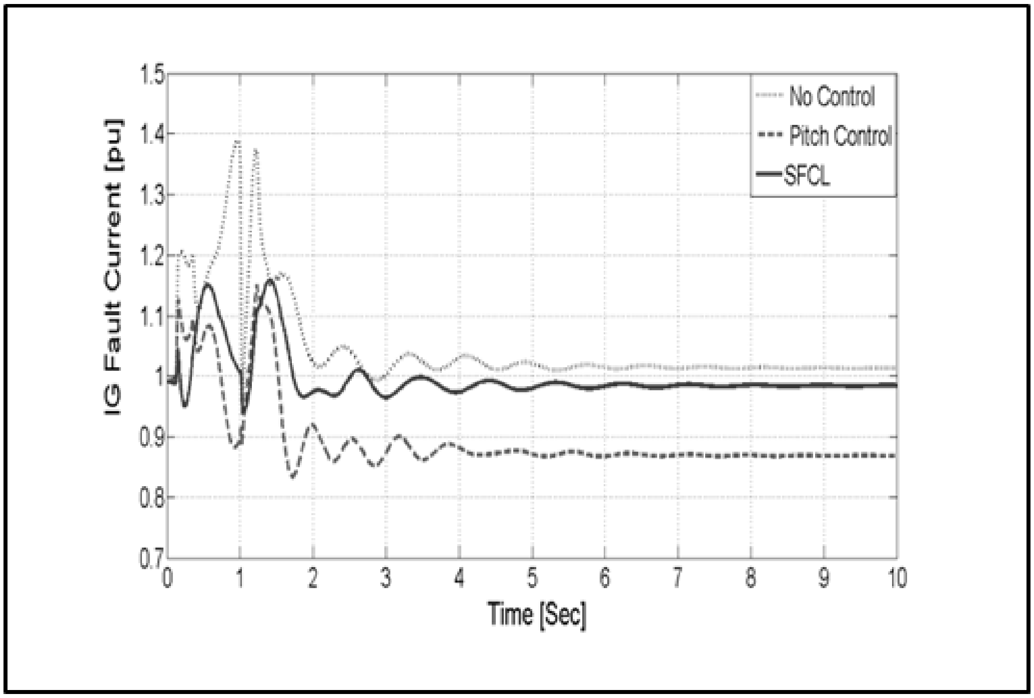

Figure 17: Response for IG fault current with 0.1 pu resistance.

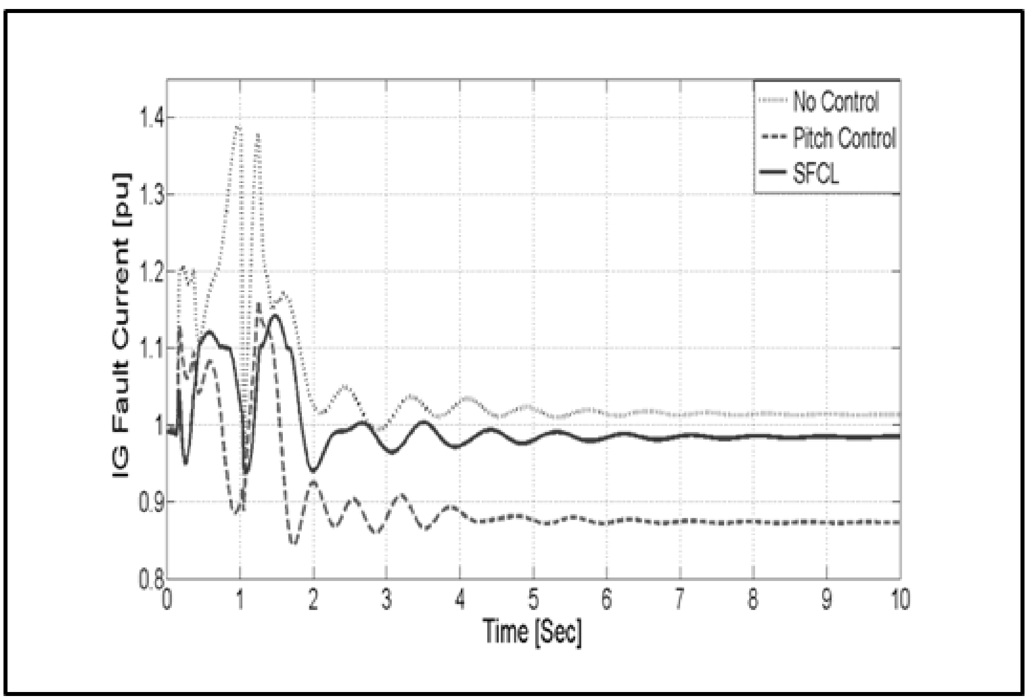

Figure 18: Response for IG fault current with 0.25 pu resistance.

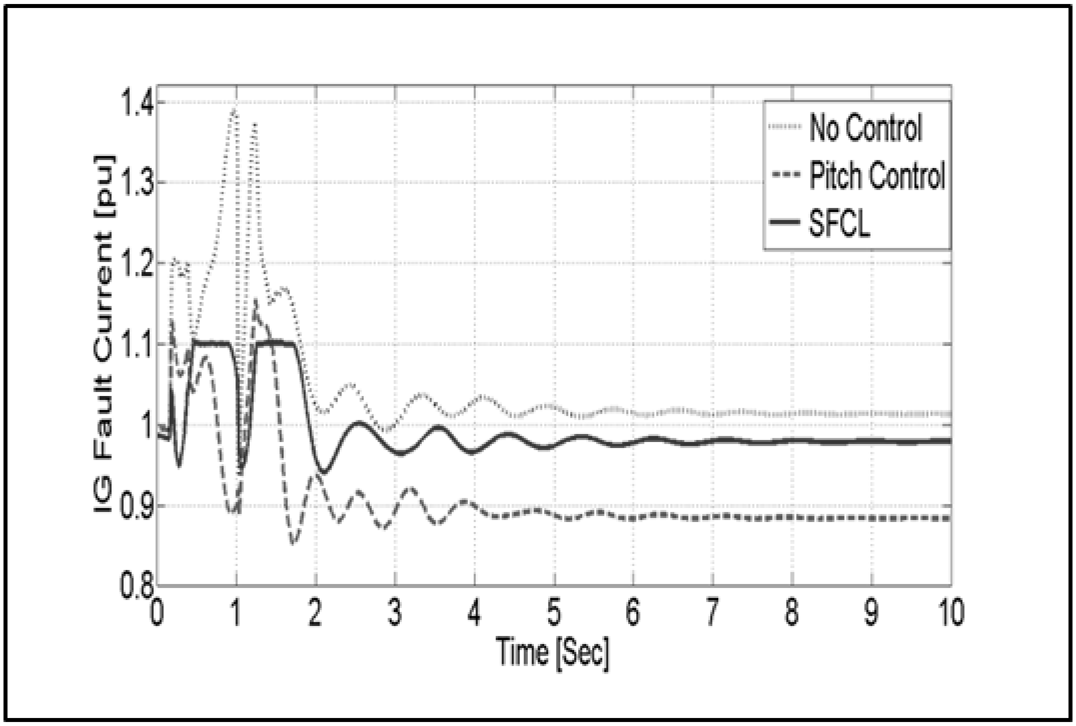

Figure 19 : Response for IG fault current with 0.5 pu resistance.

VI. SIMULATION RESULTS AND DISCUSSIONS

In this work, simulations are performed through Matlab/Simulink software considering the following cases: (1) temporary 3LG (Three-line-to-ground) and 1LG (Single-line-to-ground) fault and (2) permanent (both 3LG and 1LG) fault occur at a point F1 as shown in power system model of figure 4. The simulation time is 10 seconds and the mode is continuous.

To clearly understand the effect of the methods used for stabilization and to compare the effectiveness for various faults and to quantify the work, some of the performance indices has been used namely *vlt_sg (pu.sec), pow_ig (pu.sec)* ,*spd_ig(pu.sec)* and *vlt_sg (pu.sec)*.

They are calculated as follows:

$$\mathbf{vlt\_ig(pu.sec)} \quad = \int_0^T |\Delta V| dt \qquad \text{(IX)}$$

$$\mathbf{pow\_ig(pu.sec)} = \int_{0}^{T} |\Delta \boldsymbol{P}| \boldsymbol{dt} \tag{X}$$

$$\mathbf{spd\_ig(pu.sec)} \quad = \int_{0}^{T} |\Delta \boldsymbol{Wr}| \boldsymbol{dt} \tag{XI}$$

$$\mathbf{vlt\_sg(pu.sec)} \quad = \int_{0}^{T} |\Delta \boldsymbol{V}'| \boldsymbol{dt} \tag{XII}$$

In equations (IX)-(XII) , $|\Delta V|$, $|\Delta P|$ and $|\Delta Wr|$ denote the terminal voltage deviation, real power deviation and speed deviation of IG, respectively. $|\Delta V'|$ denotes the terminal voltage deviation of synchronous generator (SG). T is 10 sec, the simulation time of the system. The lower the value of the indices, the better the performance of the system is.

Another assumption made in this study is that during the short span of the analysis of the voltage stability, the variation in wind speed can be considered negligible. So, here a constant wind speed of 9 m/s is considered for the entire work.

A. Results and Discussions with SFCL and Comparison with TSC and Pitch Control Method

Firstly the performance and the results of the SFCL have been discussed. Also to have a proper comparison and effectiveness of SFCL, a comparison has been made with the most traditional form of control used with wind energy systems, i.e. pitch control system and also thyristor switched capacitor (TSC). Here both types of fault, successful reclosing (temporary fault) and unsuccessful reclosing (permanent fault) are discussed.

A successful reclosing is one where a temporary fault occurs in the line and the fault is successfully handled and diminished and circuit breakers are closed successfully. In case of unsuccessful reclosing, the fault is permanent and it is not possible to clear the faults and closing of circuit breakers is failed. Hence circuit breakers are opened again in the faulted lines to protect the system and the equipment from getting damaged.

In case of successful reclosing the fault occurs at 0.1 sec, circuit breakers are opened at 0.2 sec and circuit breakers are closed again at 1.0 sec. However as far as permanent faults are concerned they are opened again at 1.1 sec after the unsuccessful reclosing of circuit breakers.

1) *Voltage Stability Enhancement during Successful Reclosing*

a) Performance during three line to ground fault (3LG)

Table II tabulates the performance of SFCL and pitch control method in case 3LG fault. If the values in the table are looked upon carefully, it can be seen clearly that there is a definite improvement of performance as far as SFCL is concerned as compared with pitch control.

Also when compared to TSC, SFCL has lot of improvements, especially in case of voltage and power of induction generator the improvement is pretty evident. SFCL also helps in improving the overall stability as it is clear if a comparison is made for stability of voltage of synchronous generator.

Table II Values of Indexes during Successful Reclosing for 3LG Fault

INDEX PARAMETERS	VALUE OF INDICES			
	NO CONTROL	PITCH CONTROL	TSC	SFCL CONTROL

$spd\_ig(pu.sec)$	0.02	0.02	0.01	0.01
$vlt\_ig(pu.sec)$	1.38	1.11	0.34	0.15
$pow\_ig(pu.sec)$	1.36	0.83	0.37	0.17
$vlt\_sg(pu.sec)$	0.19	0.16	0.10	0.09

The figures 20- 24 show the responses for successful reclosing in case of 3LG fault. Figure 20 shows the response for terminal speed of the IG. Although SFCL shows a definite improvement we see that in terms of speed the difference is not much as far as temporary fault is concerned when compared to either pitch or TSC method.

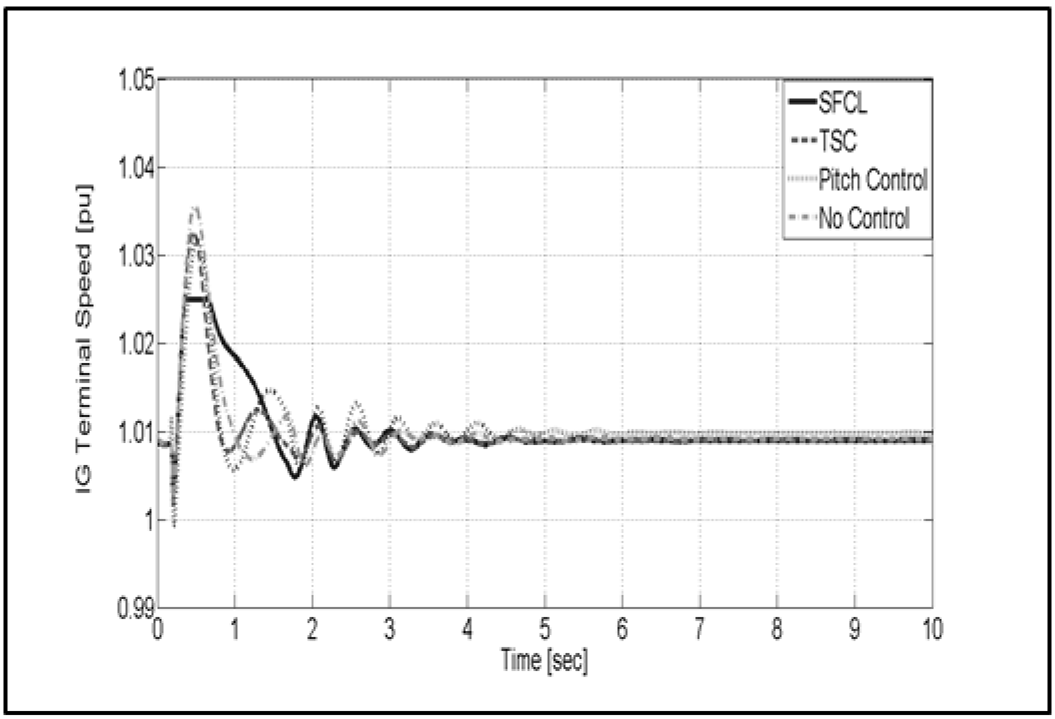

Figure 20 : Responses for Terminal Speed for IG.

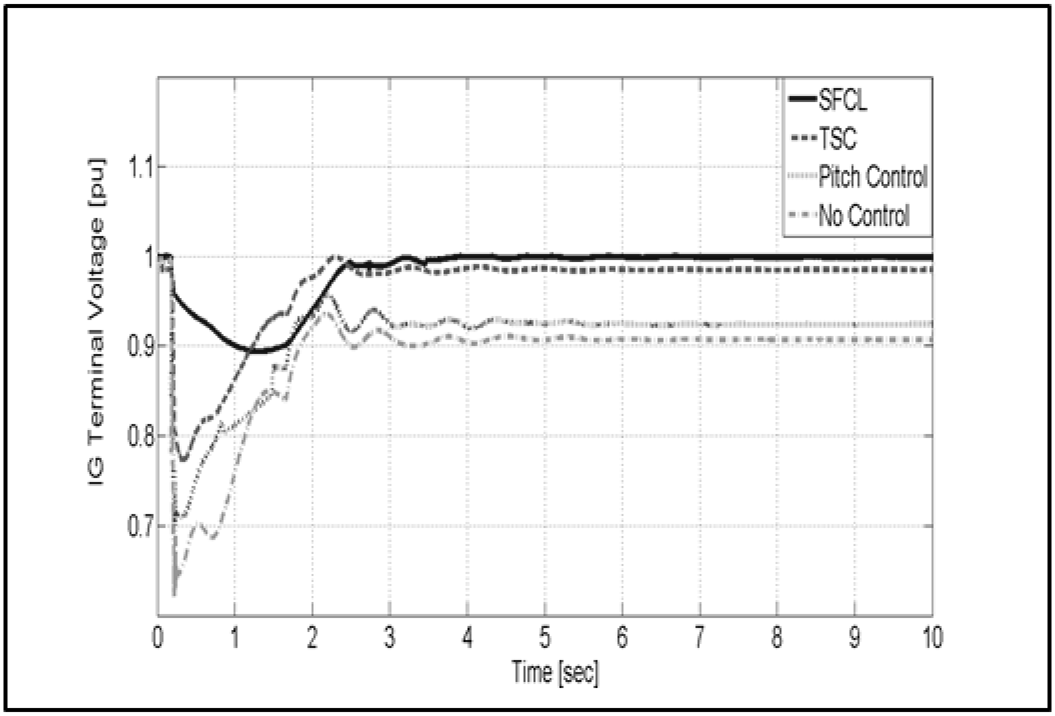

Figure 21: Responses for Terminal Voltage of IG.

Figure 21 shows the responses for IG terminal voltage. It is seen here that the SFCL can enhance the voltage stability of the wind generator the best when compared to pitch control or TSC. Although TSC and pitch control is able to recover the system, the SFCL exhibits the lower voltage sag and also it recovers the system quickly as compared to the other two methods.

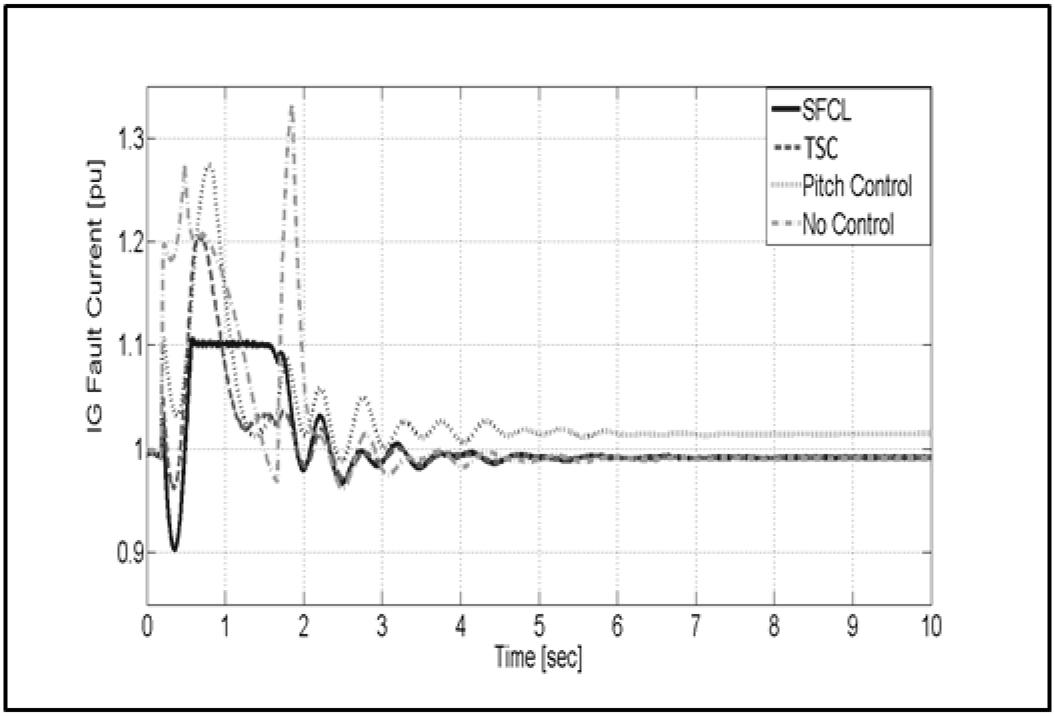

Figure: 22 Responses for IG Fault Current.

Figure 22 shows the responses for fault current from the IG. The magnitude of the fault current in case of the SFCL is less as compared with the pitch control method and TSC. SFCL restricts the magnitude of the fault current at 1.1 pu and also helps recover the system quickly when compared for the same with other two methods.

Figure 23 shows the responses for the IG real power. Upon careful examination of the graph response it can be seen that the voltage sag in case of no fault is very severe and goes down to as low as 0.75 pu of voltage and never recovers properly to 1 pu. But in case of pitch control the value is low only up to around 0.8 pu and it also helps recover the system but again to 0.95 pu. The response is slow but it definitely improves the performance. TSC and SFCL have comparable performances but in case of TSC recovery is slower as compared to SFCL. But in case of SFCL, the voltage dip is only up to 0.88 which is acceptable and it also helps restore the stability of the system very fast.

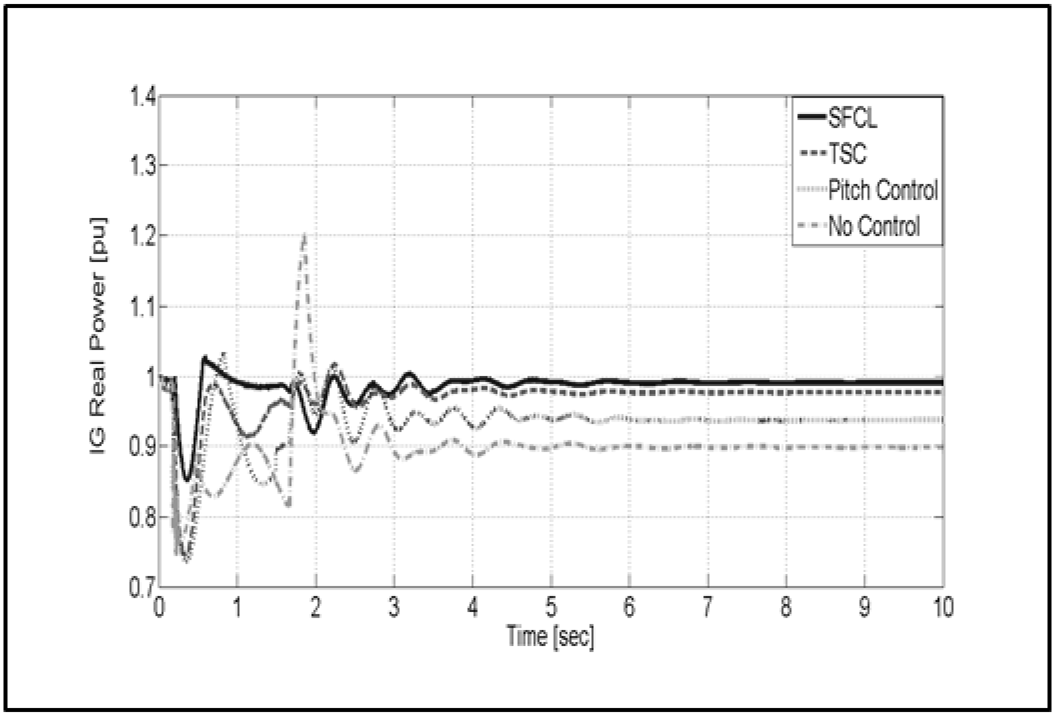

Figure 23 : Responses for Real Power for IG.

Figure 24 shows the responses for SG terminal voltage. It is seen that both the SFCL and TSC method quickly maintain the SG terminal voltage. However, the performance of the pitch method is worse when compared to SFCL or TSC in case of maintaining the stability of SG.

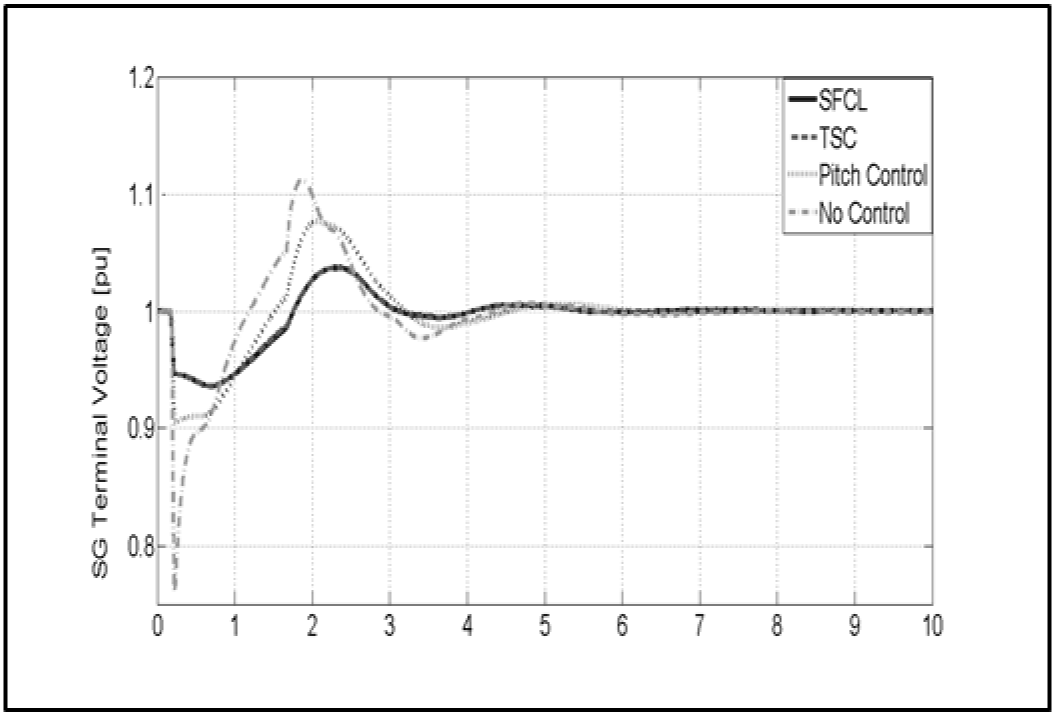

Figure 24: Responses for Terminal Voltage of SG.

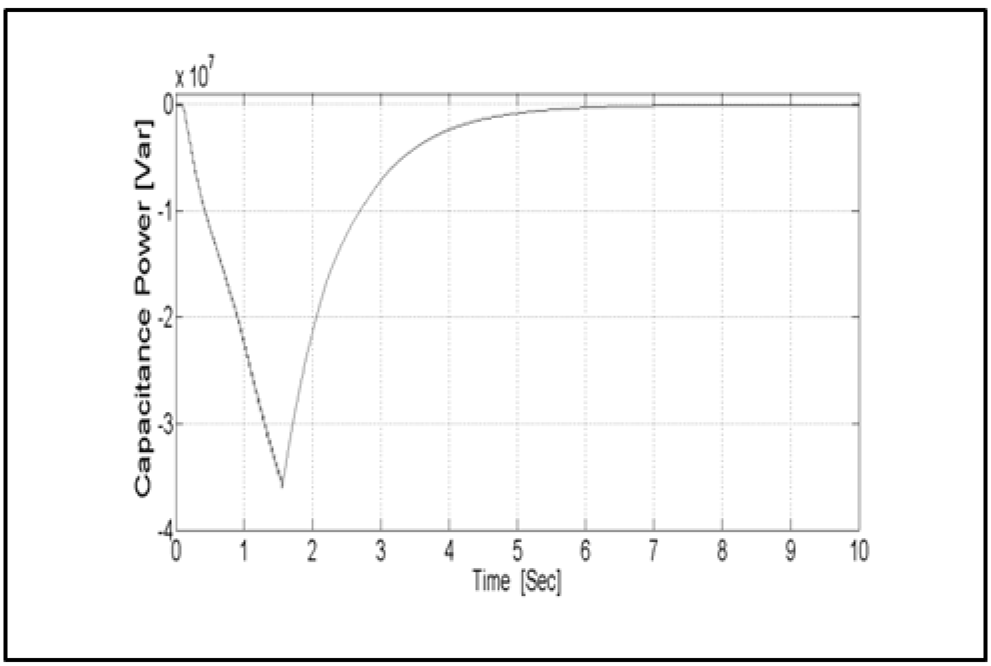

Figure 25: Responses for capacitance power.

Figure 25 shows the responses for capacitance power. During the fault it is seen that it switches on and supplies the system with reactive power and thus helps the system recover.

The response of figures 20-24 clearly demonstrate that for 3LG in case of successful reclosing of breakers the SFCL method improves the stability of the system much more than the conventional pitch control method or TSC method. Also by employing the SFCL method the value of the peak magnitude of the fault current is not allowed to go beyond 1.1 pu.

b) Performance during single line to ground fault (1LG)

Table III tabulates the performance indexes for successful reclosing in case of 1LG fault. From the table it is clear that both the SFCL and TSC can improve the voltage stability of the system. To some extent even pitch control is not a bad choice but comparing the indexes SFCL has the best values. Only in case of voltage of SG, the performance of TSC and SFCL are both comparable.

Table III Values of Indexes during Successful Reclosing for 1LG Fault

INDEX PARAMETERS		VALUE OF INDICES		
	NO CONTROL	PITCH CONTROL	TSC CONTROL	SFCL CONTROL
$spd\_ig(pu.sec)$	0.010	0.010	0.006	0.005
$vlt\_ig(pu.sec)$	1.256	1.050	0.233	0.040
$pow\_ig(pu.sec)$	1.282	0.882	0.323	0.150
$vlt\_sg(pu.sec)$	0.070	0.060	0.040	0.040

In the following pages the figures 26-31 show the responses for successful reclosing in case of 1LG fault.

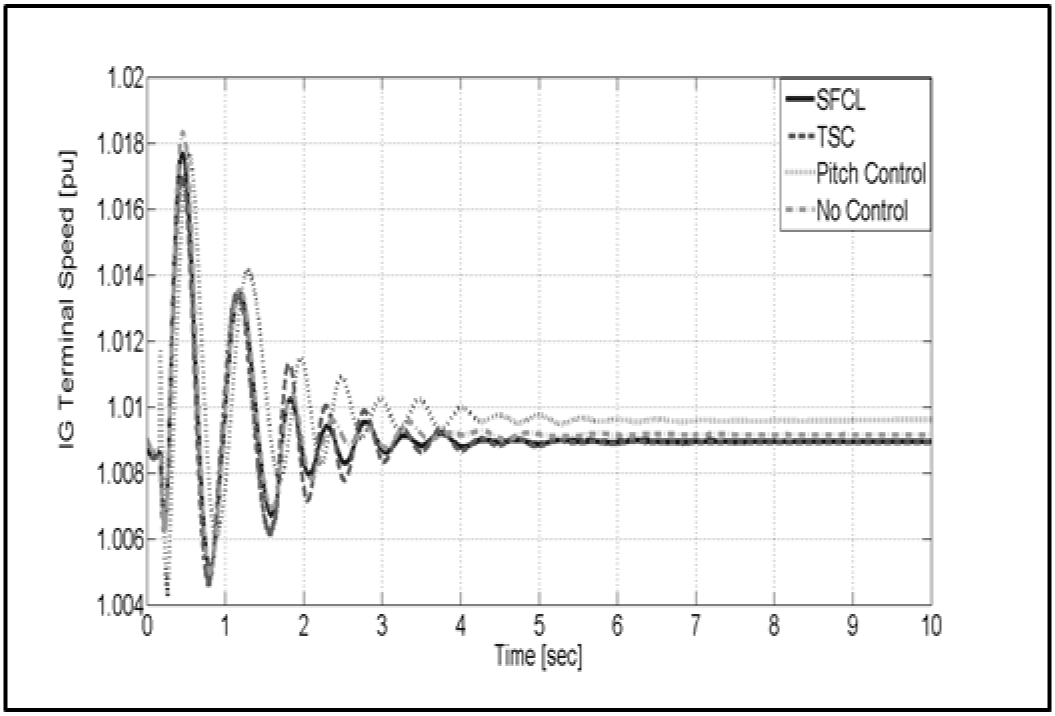

Figure 26 : Responses for Terminal Speed of IG.

Figure 26 shows the response for terminal speed for IG. As it is seen from the graphs there is not much difference in speed response when using different corrective techniques in case of 1LG fault.

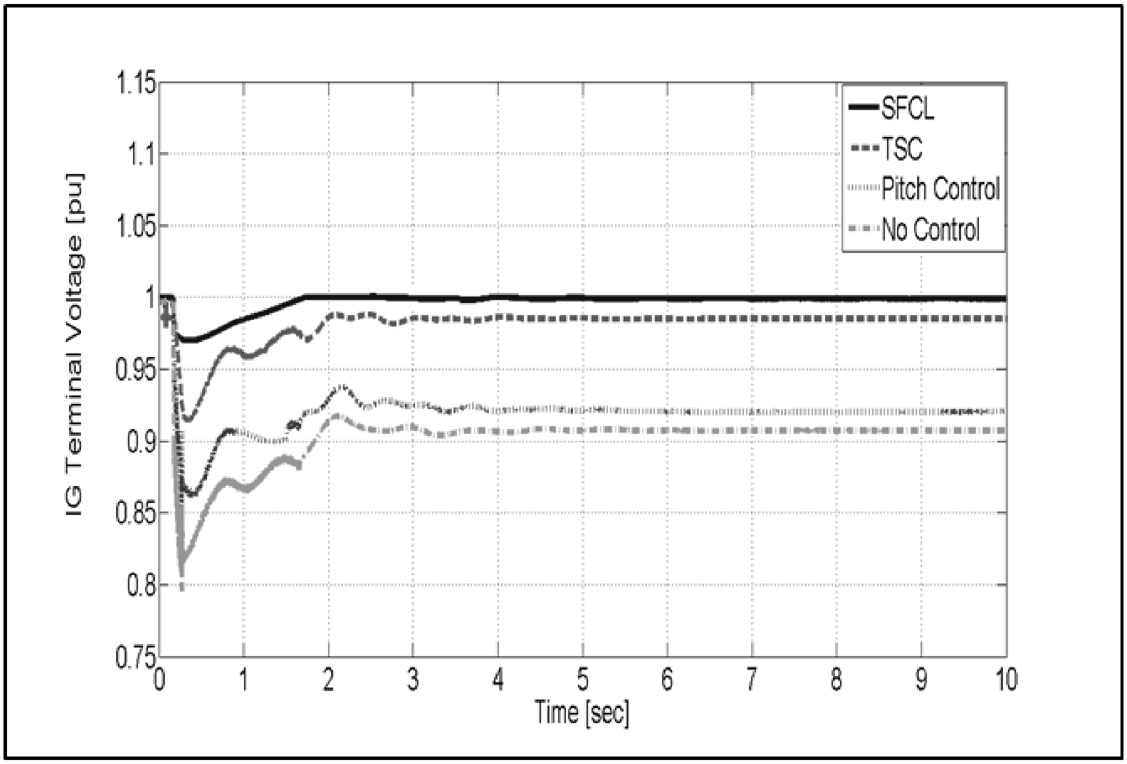

Figure 27: Responses for IG Terminal Voltage.

Figure 27 shows the responses for IG terminal voltage. It is clearly visible that the SFCL not only holds the system with the lowest voltage sag, but also helps regain its steady state quickly. Pitch control system and TSC method help recover the system, but it is not as effective as the SFCL.

Figure 28 shows the responses for fault current from the IG. The SFCL reduces the peak magnitude of the fault current much and restricts it go beyond the value of 1.1 pu. Both the pitch control and TSC methods fail to reduce the peak magnitude of the fault current. The performance with no control is the worst and provides no improvement for the system.

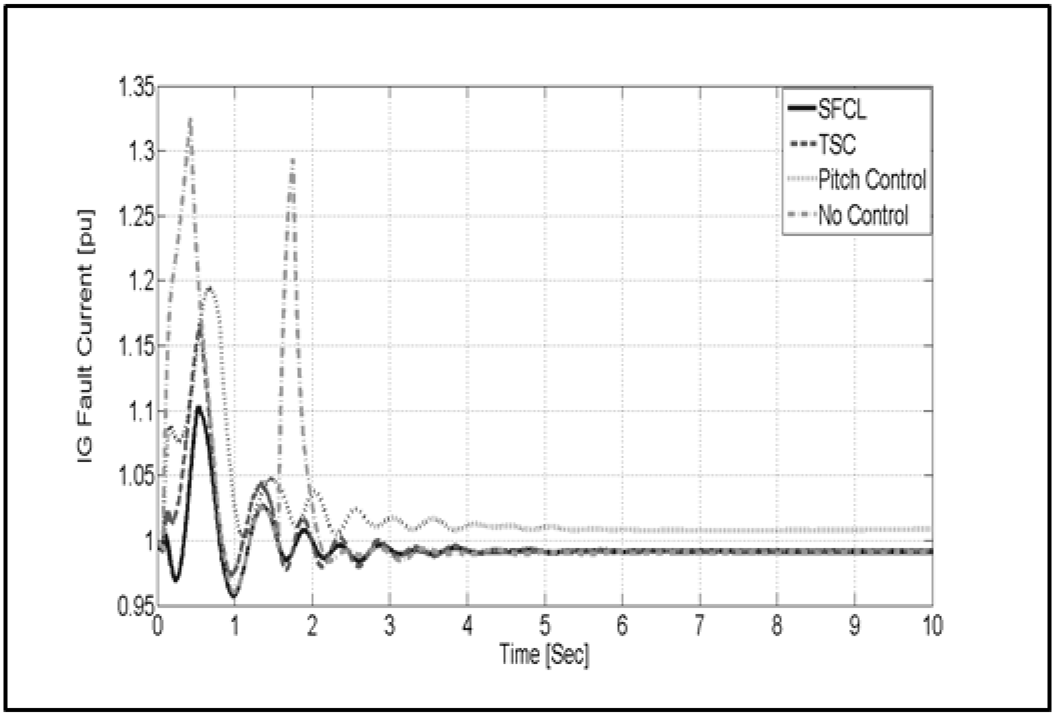

Figure 28: Responses for IG Fault Current.

Figure 29 shows the responses for IG real power. The SFCL helps maintain the original rated power, and the performance of the SFCL is better when compared with other methods.

Figure 30 shows the response for SG terminal voltage. It can be seen that the SFCL and TSC has almost the same response for SG. However, the pitch control method is very slow in maintaining the stability of the system and getting it back to steady state.

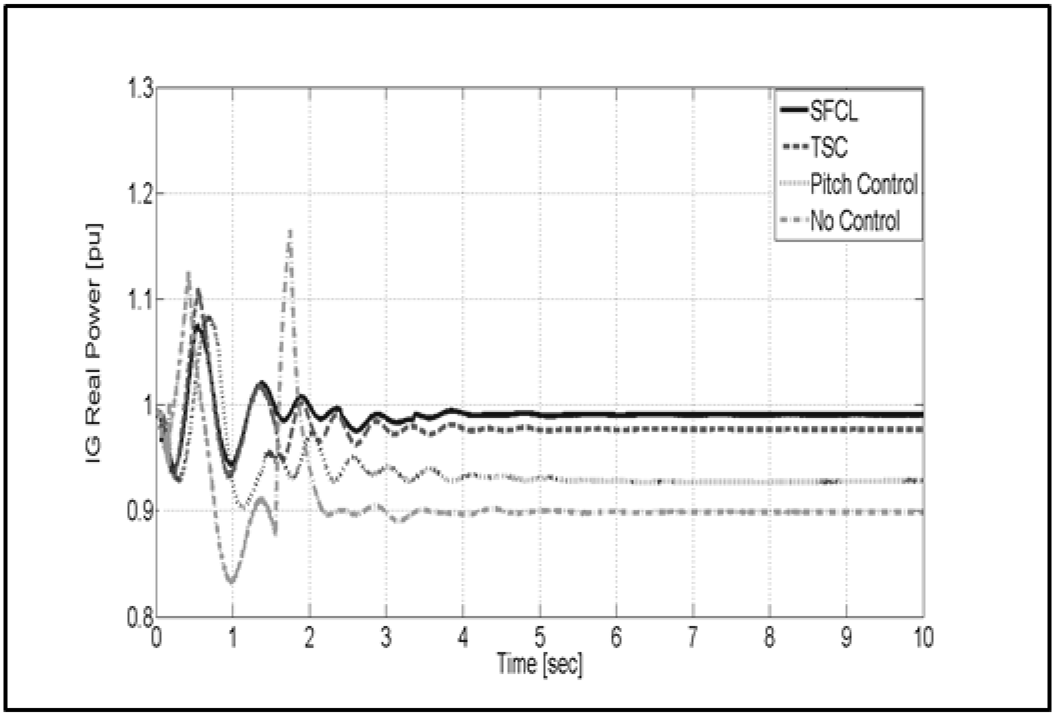

Figure 29: Responses for IG Terminal Real Power.

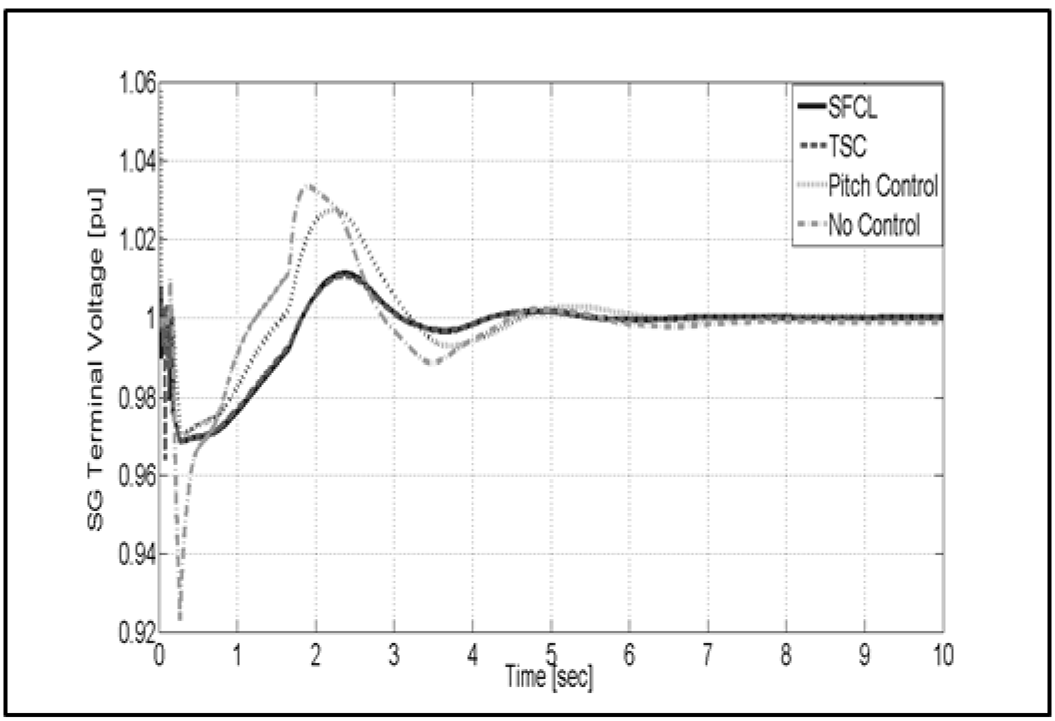

Figure 30 : Responses for SG Terminal Voltage

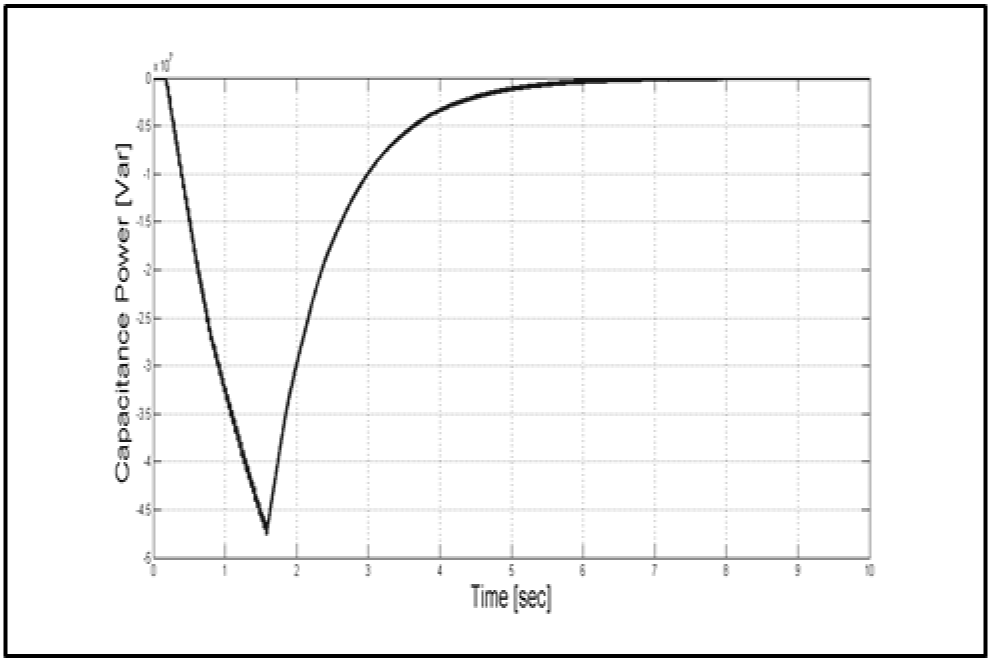

Figure 31: Responses For Capacitive Power.

Figure 31 shows the response for capacitive power and the reactive power it supplies to the system in case of fault.

2) Voltage Stability Enhancement during Unsuccessful Reclosing

a) Performance during three line to ground fault (3LG)

Table IV tabulates the performance indexes for unsuccessful reclosing for 3LG fault. Both the pitch control and TSC method have positive effects on the voltage stability of the system, but the SFCL performance is much better than the other two methods.

Table IV Values of Indexes during Unsuccessful Reclosing for 3LG Fault

INDEX PARAMETERS		VALUE OF INDICES		
	NO CONTROL	PITCH CONTROL	TSC CONTROL	SFCL CONTROL
$spd\_ig(pu.sec)$	12.2	0.05	0.05	0.05
$vlt\_ig(pu.sec)$	7.76	2.04	1.48	1.2
$pow\_ig(pu.sec)$	7.52	1.91	1.5	1.22
$vlt\_sg(pu.sec)$	0.23	0.14	0.08	0.08

Figure 32-37 show the responses for unsuccessful reclosing in case of 3LG fault. Figure 32 shows the response for terminal speed for IG in case of permanent 3LG. As it is very clear from the graph that the fault is very severe and without any control the machine gets out of control, making the system unstable.

Figure 33 shows the response for IG terminal voltage. It can be seen here that with the use of SFCL the voltage sag is the lowest and also it recovers very quickly as compared to the pitch control or TSC method. TSC also helps recover the system but the voltage sag and recovery is slow. In pitch control, voltage sag is even lower and hence its performance is worse than TSC.

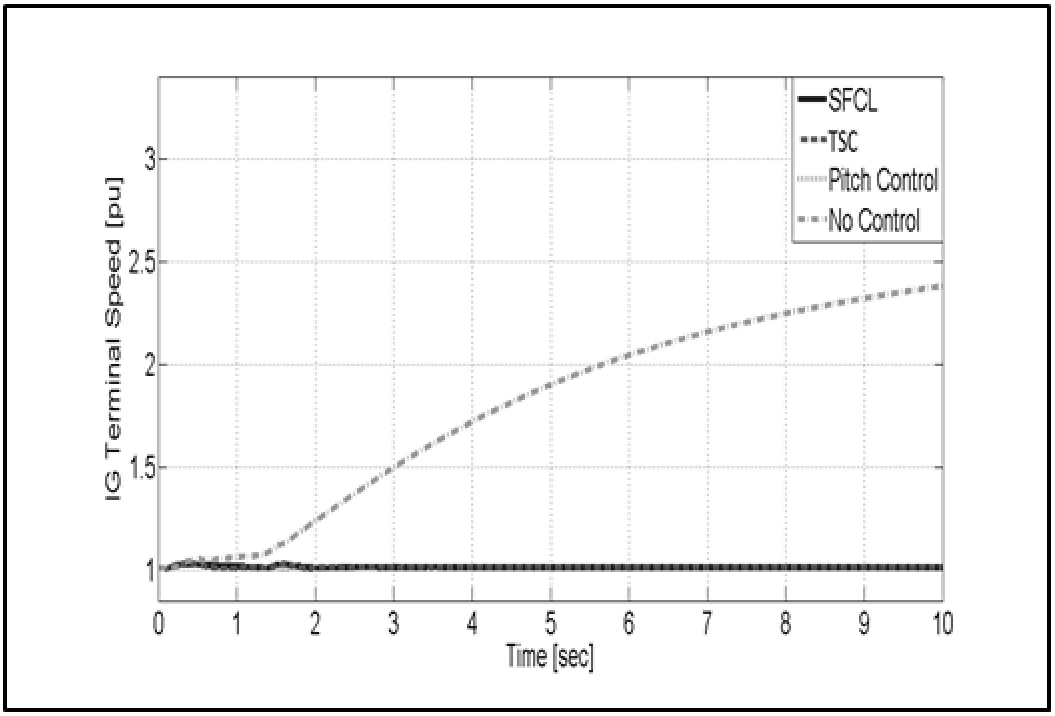

Figure 32: Responses for Terminal Speed of IG.

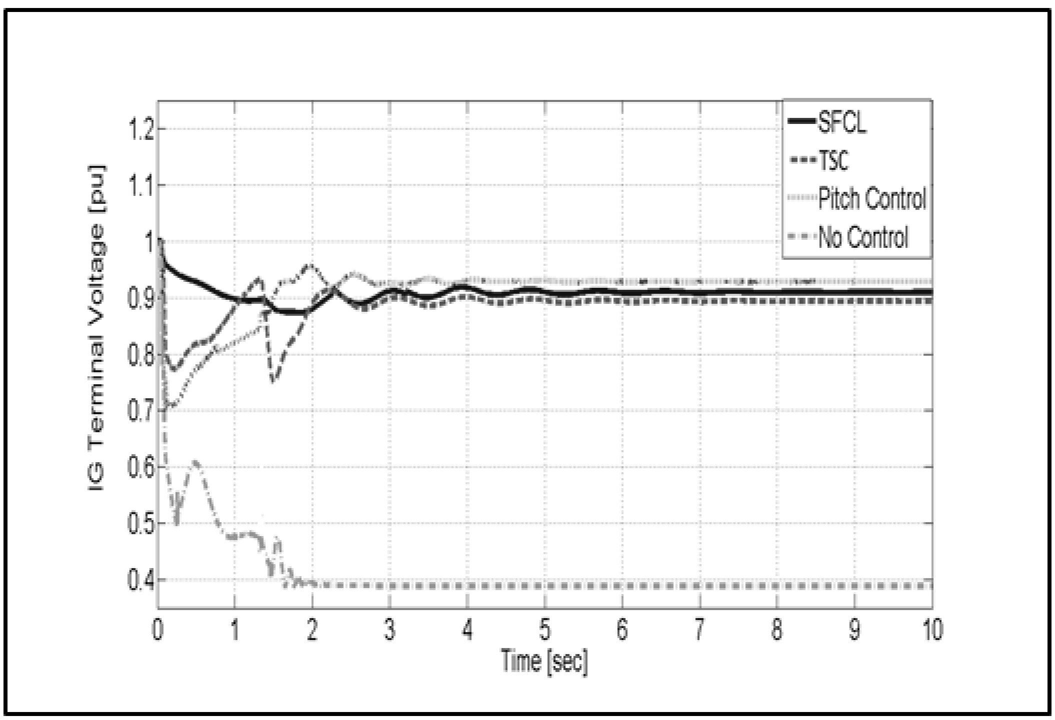

Figure 33: Responses for IG Terminal Voltage.

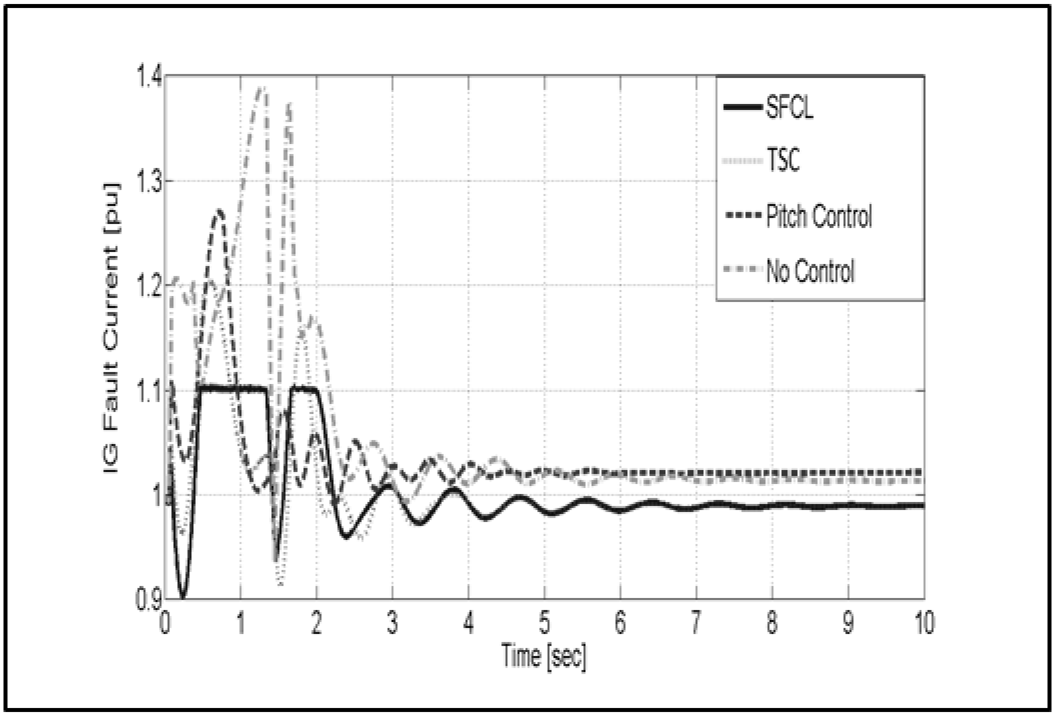

Figure 34: Responses for IG Fault Current.

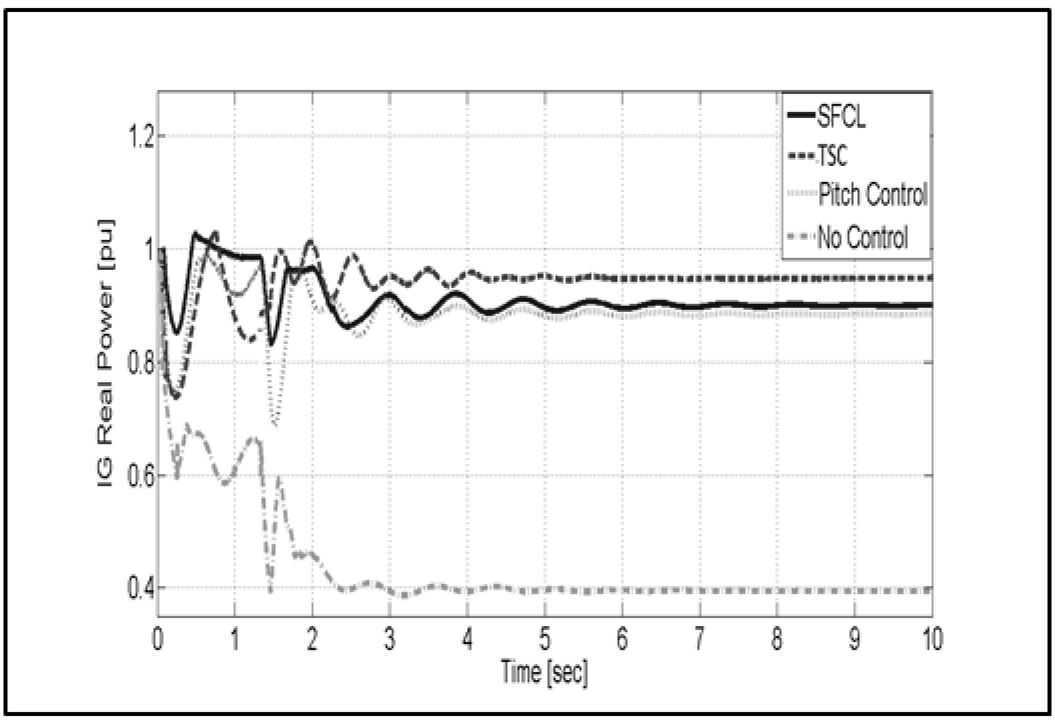

Figure 35: Responses for IG Real Power.

Figure 34 shows the responses for fault current from the IG. The SFCL restricts the fault current value at 1.1 pu. Both the TSC and pitch control method are unable to restrict the fault current level. In case of no control, the fault current level is very high exposing the system to potential risk.

Figure 35 shows the responses for the IG real power. It can be inferred from the figure that because of the use of SFCL, the system is able to recover from the fault and it does so in quick time. In case of TSC, although the system recovers but the voltage sag is higher and it takes more time to stabilize. However in this case the pitch control is not very effective. It is not able to help recover the system to its original state and the recovery is also very slow. With no control it is the same, when the system collapses to very low voltage level and system is unstable.

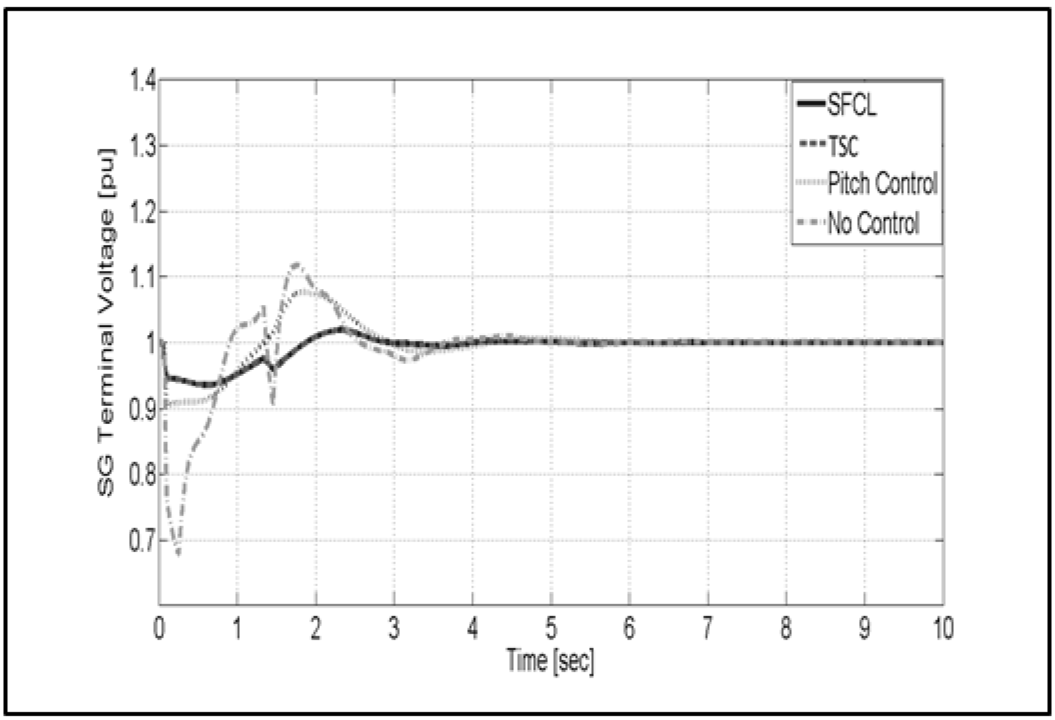

Figure 36: Responses for SG Terminal Voltage.

Figure 36 shows the responses for terminal voltage of the SG. It can be seen from the figure that by using SFCL and TSC the systems remains very stable and recovers very quickly from the fault. In case of pitch control, voltage dip is higher and it takes more time to stabilize the system.

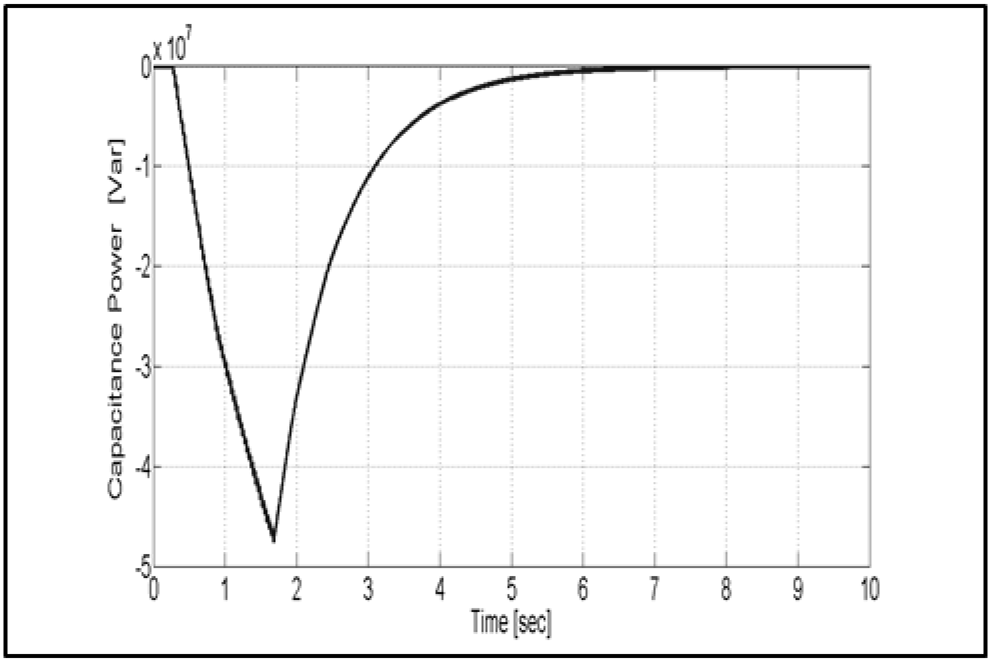

Figure 37: Response for Capacitive power.

Figure 37 shows the response for the capacitive power. It gives us an idea about how much power was delivered by the capacitance during the fault.

b) Performance during single line to ground fault (1LG)

Table V tabulates the performance indexes for unsuccessful reclosing for 1LG fault. Both the pitch and SFCL controls have positive effects on the voltage stability of the system, but the SFCL performance is much better than the pitch method. Although the value of voltage of synchronous generator and speed of induction generator doesn't show much improvement but there is certainly some change when a comparison is made between the voltage and power of induction generator.

Table V Values of Indexes during Unsuccessful Reclosing for 1LG Fault

INDEX PARAMETERS	VALUE OF INDICES			
	NO CONTROL	PITCH CONTROL	TSC CONTROL	SFCL CONTROL
$spd\_ig(pu.sec)$	0.020	0.010	0.010	0.009
$vlt\_ig(pu.sec)$	1.63	1.00	0.60	0.37
$pow\_ig(pu.sec)$	1.61	0.77	0.71	0.52
$vlt\_sg(pu.sec)$	0.07	0.06	0.04	0.04

Figure 38-43 show the responses for unsuccessful reclosing in case of 1LG fault.

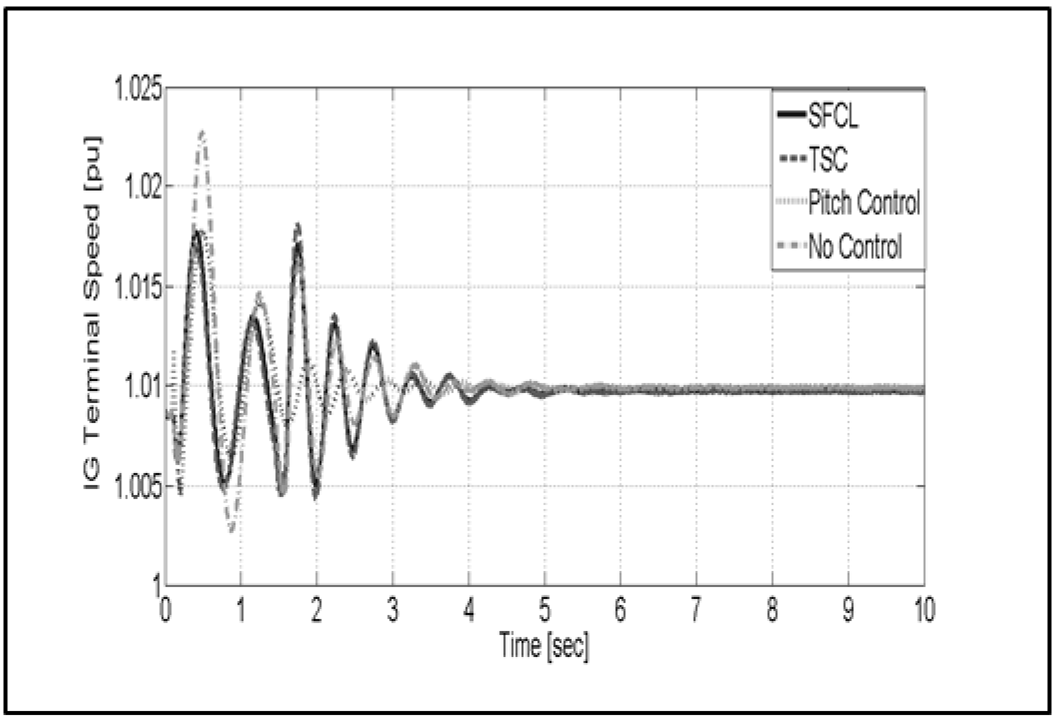

Figure 38: Responses for Terminal Speed for IG.

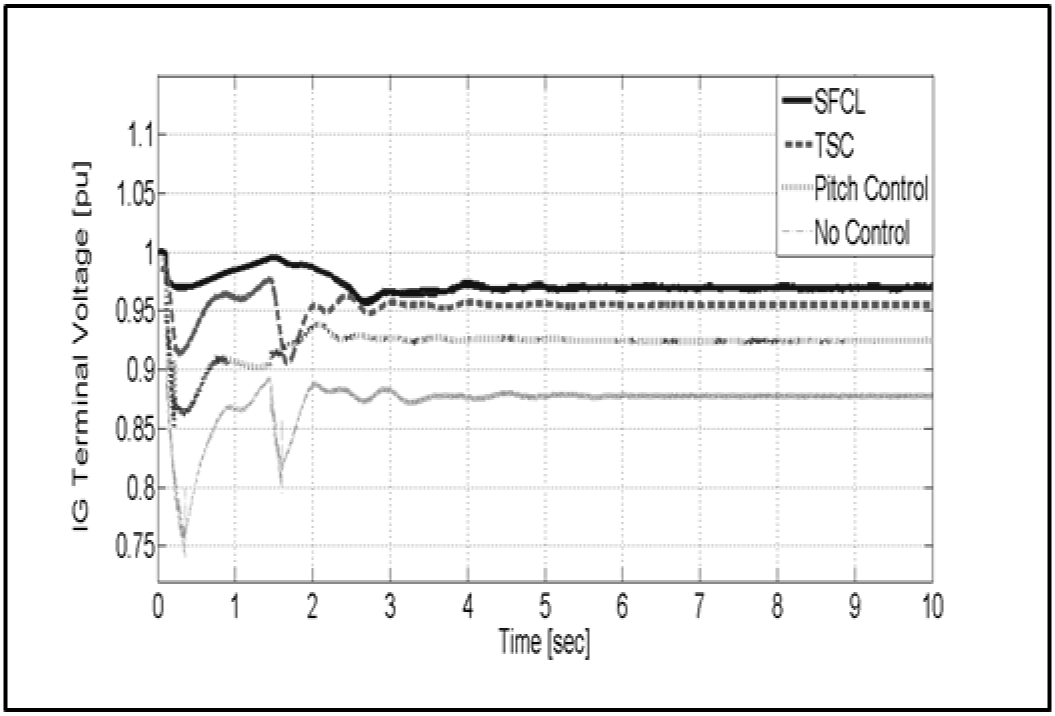

Figure 39: Responses for IG Terminal Voltage.

Figure 38 shows the response for the terminal speed response for 1LG fault in case of unsuccessful reclosing. From the graph it can be seen that there is not much difference when the speed is compared between different corrective measures.

Figure 39 shows the response for IG terminal voltage. It is clearly visible that the SFCL not only holds the system to the lowest voltage sag, but also helps regain its steady state quicker and its response is faster than the other two methods.

Figure 40 shows the response for fault current from the IG. The SFCL reduces the peak magnitude of the fault current much more and holds them around 1.1 pu as compared with the pitch method or TSC method.

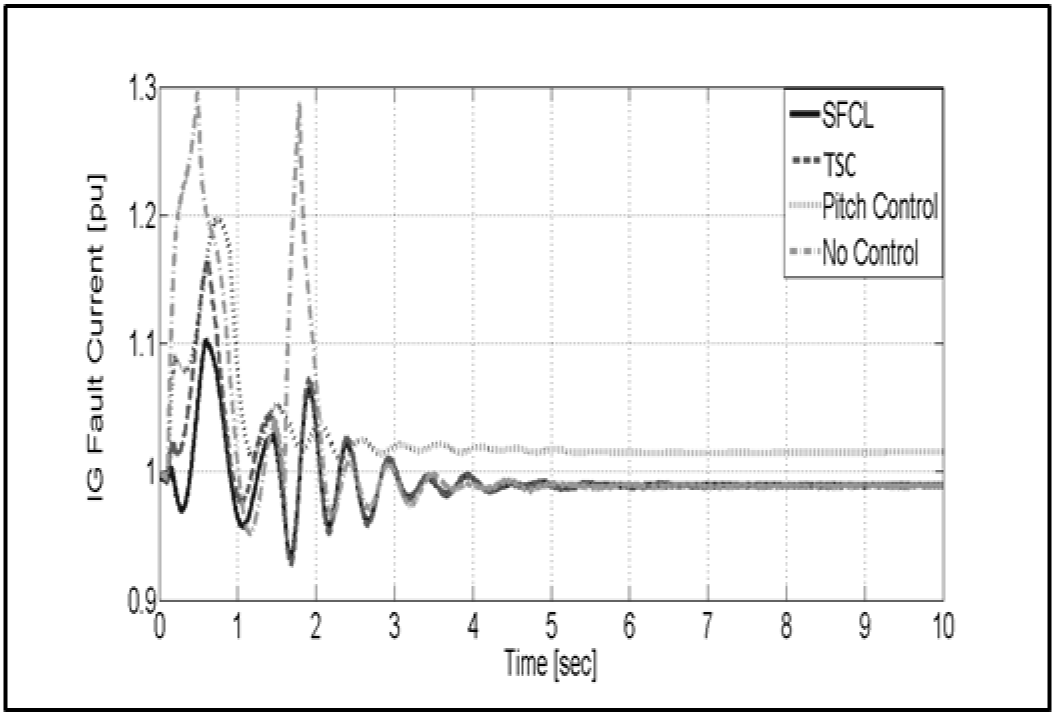

Figure 40: Responses for Fault Currents from IG.

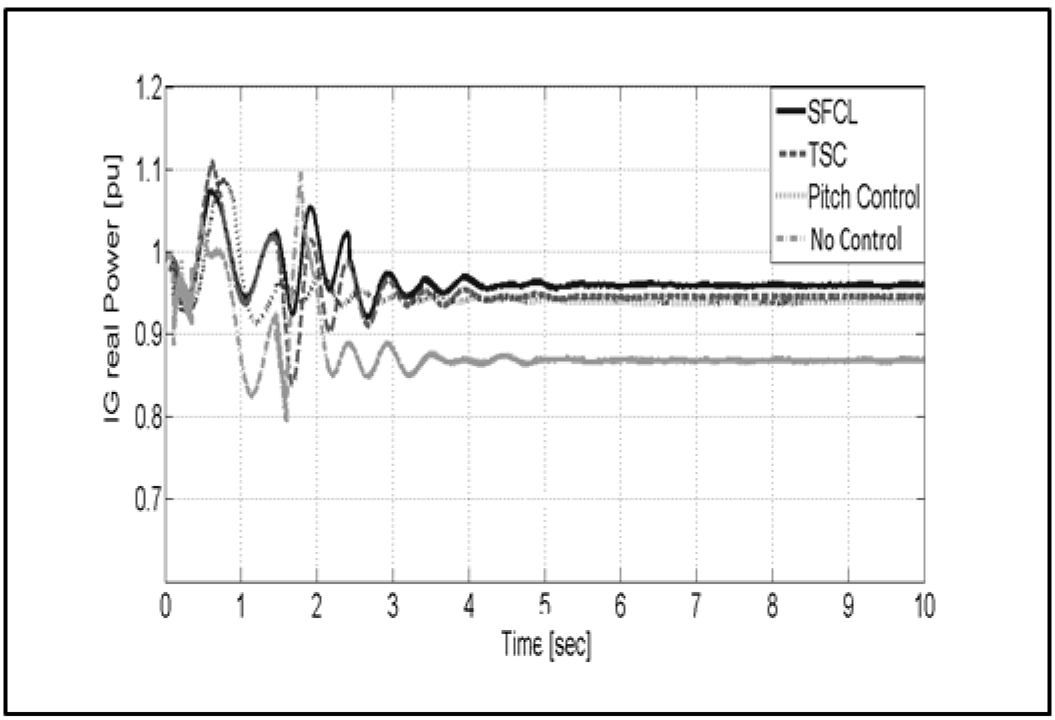

Figure 41: Responses for Real Power of IG.

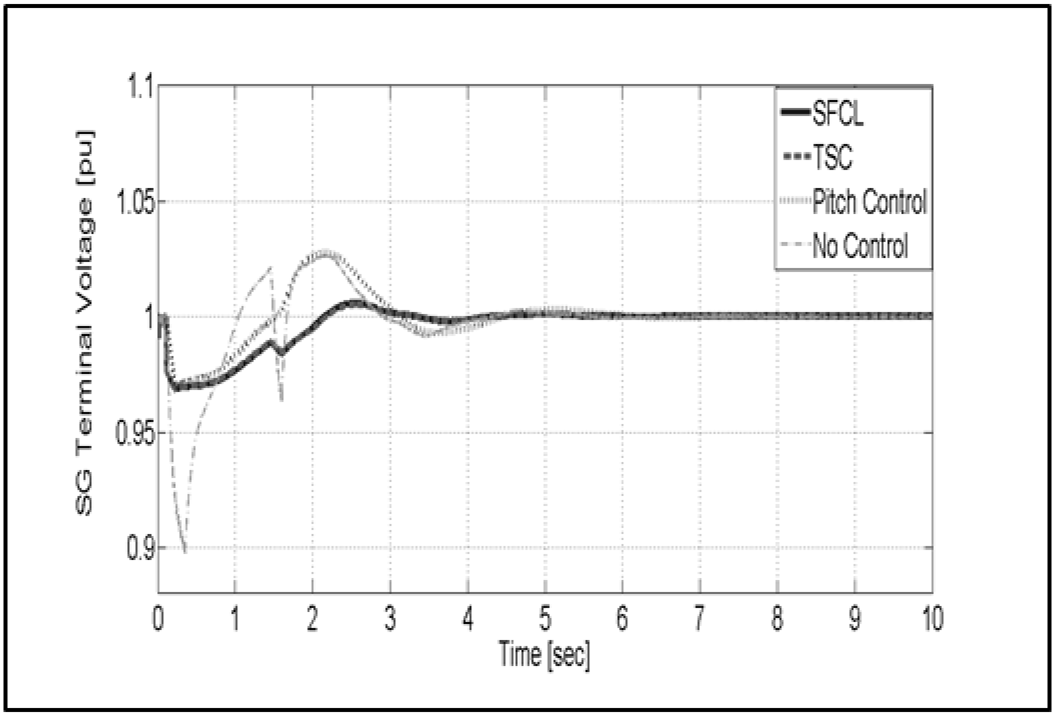

Figure 42: Responses for Terminal voltage of SG.

Figure 41 shows the responses for the IG real power. It is observed that the SFCL helps the system regain its original steady state. And the performance of the SFCL is better than that of the pitch method or TSC method.

Figure 42 shows the response for terminal voltage of SG. Both the SFCL and TSC have good responses for SG, but the pitch control is not good and its response is slower compared to other corrective measures adopted.

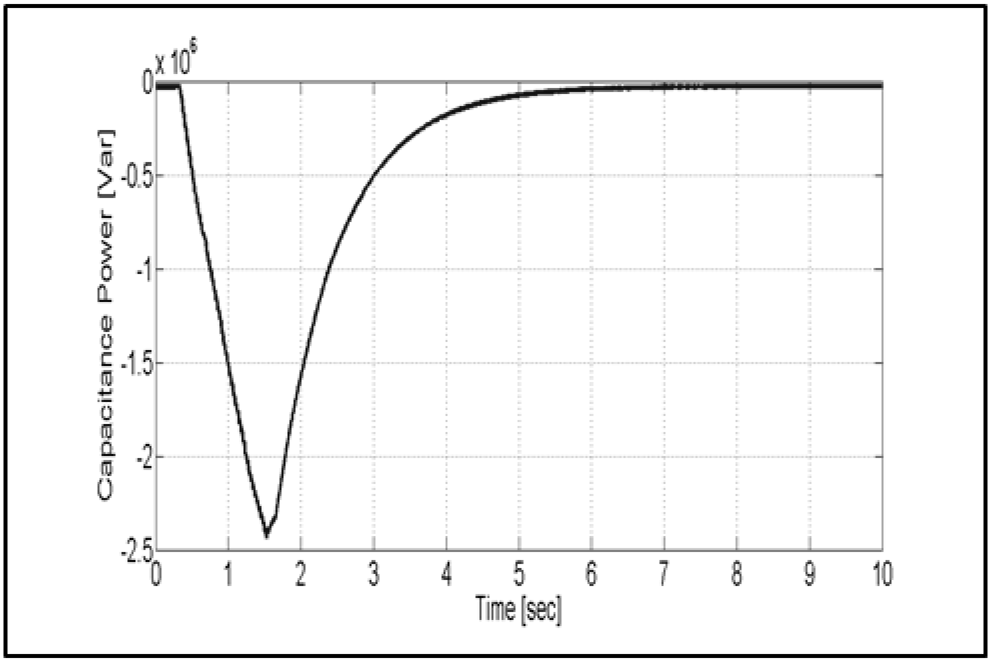

Figure 43: Responses for Capacitive Power.

Figure 43 shows the response for capacitive power and the reactive power it supplies to the system in case of fault.

B. Comparison between SFCL, TSC and Pitch Control

1) Comparison In Terms of Cost

The actual cost of SFCL is not known specifically, but the cost of using the SFCL for high voltage transmission systems is very high. The SFCL has to be maintained in a superconducting state to maintain its almost negligible impedance at steady state and the cost of it runs to millions of dollars. This makes using a highly economic centered technology. Before applying SFCL in any system it should be carefully analyzed whether the advantages it brings with itself are enough bargains with the cost. As far as the TSC is concerned because of its simple structure, it will arguably have a lower cost than the SFCL.

On the other hand, because of its simple structure, we can estimate that the pitch control should have a lower cost than the SFCL. But its performance is clearly inferior to SFCL.

2) Comparison In Terms of Controller Complexity

As far as the controller structure is concerned, the SFCL has a more complex control structure. It has a superconducting coil and it also needs liquid helium to maintain its superconductivity. For TSC, it has some costly devices in terms of the thyristor and the capacitor, but still it is simple in terms of the controller. In addition, the TSC doesn't need a superconducting state to operate and hence it reduces a lot of complexity.

On the other hand, the pitch control is very simple. So it is very obvious that design and complexity of the SFCL will be more complex when compared with the pitch control or TSC.

3) Comparison In Terms of Voltage Stability

As has been discussed so far, the SFCL provides a significant improvement in both successful and unsuccessful voltage reclosing. It has been seen throughout the discussion that both the TSC and SFCL are capable of maintaining stability of the given system. However, if the cost is not an issue, then the SFCL has a definite advantage over TSC when it comes to hindering the fault current or maintaining stability of the system.

The comparison when made with the pitch control method gives the reader a clear idea that the SFCL is more effective in maintaining the stability in case of faults and also in prompt improvement to bring back the system to stability after the fault has occurred.

VII. CONCLUSION AND FUTURE WORK

A. *Overall Conclusion*

In this work, a model of SFCL has been developed and its performance is measured and analyzed with the wind generator system. The SFCL has been used to limit the fault current level when the integration of wind energy system is done with the existing grid. The performance of the proposed SFCL is compared with that of the TSC method and pitch control method. In this work both balanced and unbalanced, permanent and temporary faults are considered. From the simulations results it can be concluded that the performance of the SFCL is better than that of the pitch control or TSC method.

B. *Contribution to the Thesis*

The following points can be noted from the discussion about the novel contributions to this thesis.

(i) The proposed SFCL method, TSC and pitch control system can enhance the voltage stability of the wind generator system.

(ii) The performance of the proposed SFCL is much better than that of the pitch method or TSC method, especially in case of permanent 3LG fault.

(iii) Although the cost of the SFCL is high and it is more complex to make, the sheer number of advantages it brings with it makes it a worthwhile investment, especially while integrating the fixed-speed wind generator systems with the main grid power system.

This study helps the reader understand the relative effectiveness of the SFCL, TSC and pitch control method for voltage stability enhancement of wind generator system.

C. Future Works

i) In the future work, the integration of SFCL with the permanent magnet based variable-speed wind generator systems will be considered.

ii) The performance of the wind generator with different wind turbine characteristic equations can be analyzed in the future to see how it behaves with different equations used, especially as far as cut off range of wind speed is concerned.

iii) A comparison can be made with SMES, a proven technology in the field of energy storage systems.

iv) A study on multi-mass shaft wind turbine system can be done.

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