Comparison among Series Compensators for Fault Ride through Capability Enhancement of Wind Generator Systems

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Abstract- A comparison among series connected auxiliary devices, such as Superconducting Fault Current Limiter (SFCL), Dynamic Voltage Restorer (DVR), Thyristor Switched Series Capacitor (TCSC), and Series Dynamic Braking Resistor (SDBR), is performed in terms of fault ride through capability improvement, harmonics suppression, controller complexity, and cost of a fixed speed wind generator system. The tested system consists of one synchronous generator and one squirrel cage induction machine based wind generator, which feed an infinite bus through a double circuit transmission line. Simulation results show that all the devices perform well during symmetrical faults, however, in spite of its controller complexity, the DVR has the best performance among all devices in terms of voltage and speed control of wind generators. The SFCL is the costliest among all devices, however, it is the most efficient in reducing the fluctuations of active power and stator current of the wind generators. The SDBR is the cheapest, and shows a better enhancement in damping active power and limiting fault current as compared to the DVR and TCSC. Despite the ability of TCSC to compensate the reactive power for power quality improvement, it is less desirable to achieve a better performance under transient conditions.

Keywords- Balanced Faults, Dynamic Voltage Restorer (DVR), superconducting fault current limiter (SFCL), Series Dynamic Braking Resistor (SDBR), Thyristor switched series capacitor (TCSC), Transient stability, Total Harmonic Distortion (THD), Wind Generators.

1. Introduction

Renewable energy resources integration in the electrical grid is increasing. The growth of wind turbines connection into the grid is the most significant. Although the new technology of the variable speed wind generators, such as doubly fed induction generators and synchronous generators can ride through faults in most cases because they are equipped with the sophisticated power electronic controllers [1], however, in the last two decades a significant amount of the fixed speed type wind generator systems were installed due to their rugged construction and low cost [2]. But these generators have stability issues that must be considered. One of the issues with the squirrel cage induction machine based wind generator is the high consumption of reactive power during faults and voltage sag, which will delay the grid voltage restoration and may lead the wind generator to be taken out of service [2]-[3].

Fig.1 shows a low voltage ride through curve as an example of grid code requirements for large scale wind generators. A detailed review of grid code technical requirements regarding the connection of wind farms to the electrical power system is given in [4]. There are many auxiliary devices that are reported to help wind generator maintain a ride through capability such as the static synchronous compensator (STATCOM), braking resistor (BR), and superconducting magnetic energy storage (SMES) [5]. These devices can be classified into shunt connected and series connected devices depending on the connection configuration.

The Dynamic voltage restorer (DVR), Series Dynamic Braking Resistor (SDBR), Thyristor switched series capacitor (TCSC), and the high temperature superconducting fault current limiter (SFCL) are the most common series connected means to ride wind generators through faults and voltage sags [6-9]. But, to the best of our knowledge, no comparative analysis among these series devices for the application to the wind generator system has been performed so far. With this background, this work aims to fill in the gap and provides a comparative study among them. And this is the originality of this work.

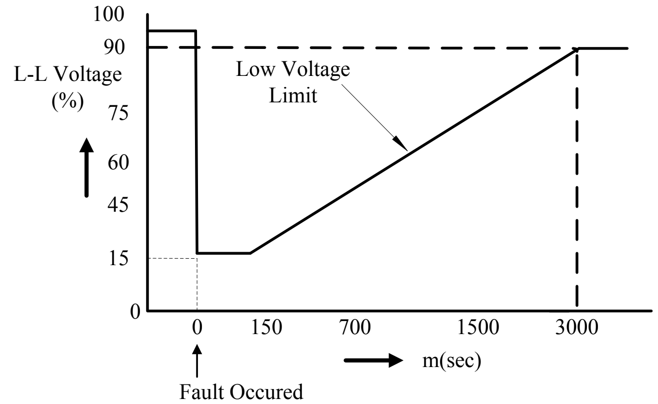

Fig. 1. Low voltage ride through (LVRT) capability.

The need of a device that can inject and compensate reactive power to the system is fulfilled by the use of Reactive Power Compensation (RPC) devices, such as DVR, STATCOM, and TCSC. The DVR is able to inject reactive power to both the grid and the wind generator; it injects less reactive current compared to STATCOM, and it has the ability to stabilize the fixed speed wind generator [5]. The benefits of TCSC are its ability to control the amount of reactive power compensation in the transmission lines by controlling the amount of series capacitance inserted, in addition to its ability to limit fault currents [8]. The resistive type of SFCL is used in this paper; considering its ability to recover the wind generator system in a time period less than 0.5 seconds and also the ability to control the losses within the operation period [10]. The SDBR is an efficient replacement for costly RPC devices which dissipate wind generator's active power and boost the terminal voltage up to help keep up with the grid code [9].

In this work, simulations are done using the Matlab/Simulink software. The effectiveness of the proposed methodology is tested considering temporary faults in a power system model consisting of a wind generator and a synchronous generator. Various indices in terms of speed deviation, terminal voltage deviation, active/reactive power deviation and stator current deviation of wind generator are used for evaluating the system performance. The comparison among these series devices is done in terms of fault ride through capability enhancement, harmonics suppression, controller complexity and cost.

The organization of the paper is as follows: Section II describes the modeling of the power system and the wind turbine. Sections III, IV, V and VI explain the DVR, SFCL, SDBR, and TCSC control systems, respectively. Section VII enlists the simulation results and overall comparison. Finally Section VIII concludes this work.

2. System Under Study And Modeling Of Wind Turbine

Fig. 2 shows the model system [5] that has been used in this work. The system consists of one synchronous generator (100 MVA, SG), and one wind turbine generator (50 MVA induction generator, IG), connected to an infinite bus through a transmission line with two circuits. The DVR, SFCL, SDBR and TCSC are connected in series at the terminal of the wind generator.

A fixed capacitor C is connected at the terminal of the wind generator to keep the power factor unity for the IG. The synchronous generator parameters as well as induction generator parameters used in this work are described in [5] and [7].

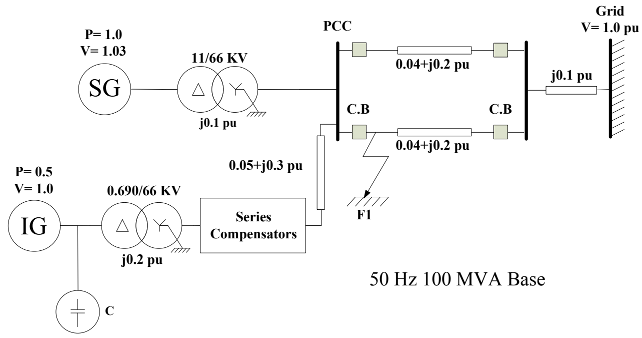

Fig. 2. Power system model.

For the modeling of wind turbine in this work, (1), (2) and (3) are used, and [5] can be consulted for further explanation.

$$P\omega=0.5*\rho*\pi*R2*Vw\ 3*Cp(\lambda, \beta) \quad (1)$$

$$\lambda = \frac{Wr*R}{Vw} \quad (2)$$

$$Cp=\frac{1}{2}(\lambda-0.022\beta^{2}-5.6)e^{-0.17\lambda} \quad (3)$$

Where Pω is the extracted power from the wind, ρ is the air density [kg/m3], R is the blade radius [m], Vw is the wind velocity [m/s], and Cp is the power coefficient which is a function of both tip speed ratio, λ, blade pitch angle, β [deg] and Wr is the rotational speed [rad/s]. In this work, the MOD-2 model [11]-[12] is considered for the Cp - λ characteristic.

3. Control scheme of dvr

3.1. Basics of DVR

The Dynamic voltage restorer (DVR) is a series connected device that injects the voltage into the system due to series connected transformers to maintain a constant root mean square (RMS) voltage at the terminal of the wind generator during disturbances such as voltage sags and faults. The fault ride-through capability of the DVR for a squirrel cage induction generator and doubly fed induction generator is reported in [6] and [13], respectively. The DVR has various control techniques and configurations. A comparison among various topologies of DVR with respect to power and voltage ratings is shown in [14]. A comparative study of compensation strategies is reported in [15]-[16]. The Power Flow of the DVR used in this work is demonstrated in Fig. 3. The energy storage in case of generator acts like a load and consumes the whole active power of wind generator under faults condition. While consuming active power, reactive power is delivered to the wind generator and the grid if voltage recovery is required.

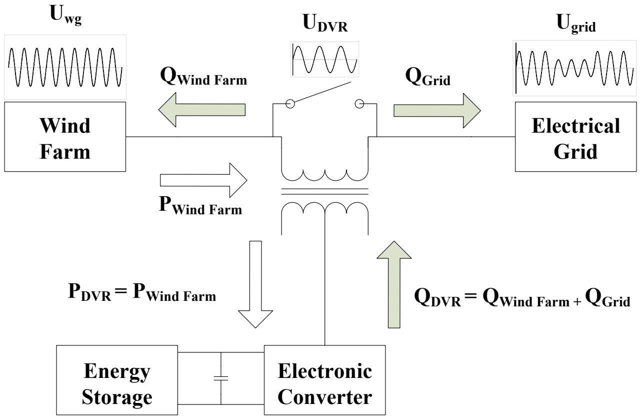

Fig. 3. DVR configuration.

3.2. Control of DVR

The Power rating of DVR was computed based on (4). For the present study system, the power rating of the DVR must be equal to the power rating of the wind generator, assuming that the fault voltage would drop to zero.

$$P_{DVR} = \frac{V1\text{-}V2}{V1} * Pwg \tag{4}$$

Where PDVR is the rated power of the DVR, V1 is the nominal voltage, V2 is the minimum voltage level during the sag/fault, assuming phase angle jump is negligible; otherwise it might lead to higher power ratings [17]. There are many control strategies applied in other works, however, in this work In-Phase Compensation strategy is utilized [15]-[16], giving that we are neglecting the phase angle jump. This leads to simpler control and lower DVR ratings as compared to other compensation techniques. With these small phase angle jumps, a large transient occurs at the beginning and at the end of the disturbance, and therefore this is the main drawback of this method.

The Phase-Locked Loop (PLL) as shown in Fig. 4 keeps the DVR Synchronized with Grid. The DVR reference voltage UDVR, d-q, ref is computed by taking the difference between the grid voltage, UGrid and the reference Voltage, Uref.

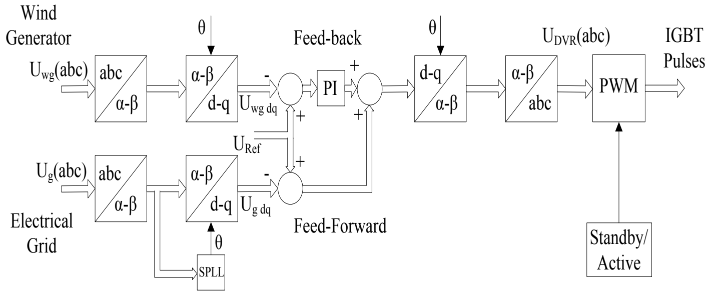

Fig. 4. Control scheme of DVR.

The DVR actual voltage UDVR, d-q is computed by taking the difference between the wind generator voltage UWG and the reference Voltage Uref. A closed loop control is used, with feed-forward Compensation and feedback proportional-integral (PI) regulator to compensate the difference between the DVR actual voltage, UDVR, d-q and the DVR reference Voltage UDVR, d-q, ref. Therefore, the response of the DVR is improved. Then this regulated voltage is transformed into the three phase reference voltage in order to generate the IGBT inverter pulses. The DVR System parameters are shown in Table I. The more details about this control system are described in [3], [15] and [18].

Table I. Parameters of DVR system

Parameters	Value
Rated Power	50 MVA
Transformers Ratio	1
Filter Inductance	0.14 mH
Filter Capacitance	20 mF
PI Controller	Kp=1 Ki=0.1

4. Control scheme of SFCL

4.1. Basics of SFCL

Stability of power system is vital in term of power, voltage and frequency stability, and the ability of the system to ride through faults is needed [19]-[20]. The SFCL is proved to be an efficient means to improve power system stability [4]. Although there are many types of SFCL, the resistive type is used in this work due to its faster response. Since the SFCL limits the fault current, it can save the cost spent on higher rating circuit breakers.

4.2.Control of Resistive Type SFCL

For simplicity, in this work we have used a simplified version of the resistive type SFCL as shown in Fig. 5. Initially the switch SW is closed, and an inductor L is in the circuit and its value is kept very low, like 0.001 pu. If the fault current is above a certain value, the quench occurs.

Then the SW is opened and the current is diverted through a high value resistance R, and thus limits the current.

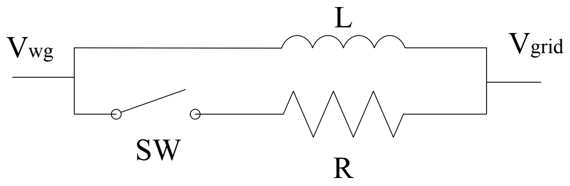

Fig. 5. Model of SFCL.

The effective value of SFCL resistance is selected based on the power system model as shown in Fig. 1. In this case the fault current level has been set at the value of 1.1 pu. This threshold value of fault current is determined by trial and error in order to obtain the best system performance. After careful study we find that the performance for IG fault current is the best with 0.5 pu resistance of the SFCL [7].

5. Control scheme of SDBR

5.1. Basics of SDBR

A series dynamic braking resistor contributes directly to the balance of active power during faults, with the potential to eliminate the need to use of complicated reactive power control (RPC) devices [9]. it does this dynamically by inserting a resistor at the terminal of the generator, therefore mitigating the power, voltage, and speed instability of the generator, simply by dissipating active power and boosting the terminal voltage up. There are various topologies of SDBR, the insertion of the resistor can be discrete at lower cost simply by just adding the resistance into the line, or it can be smoothly done by the use of power electronics. Moreover, it can be done in many stages or in single stage. Various types are discussed in [21]-[22]. In this work, the single stage discrete SDBR is used. The general configuration is shown in Fig. 6.

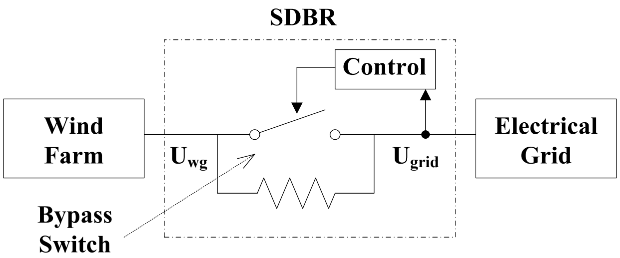

Fig 6. SDBR schematic arrangement.

As seen from Fig. 6 the SDBR is bypassed during normal operation of the grid, but when the fault occurs the current is diverted to flow through the resistor in the line which would help recover the post fault voltage and return back within acceptable limits. During faults high current would flow through the resistor, which increases the internal temperature of the SDBR. Therefore, when selecting the SDBR the breaking temperature must be considered in addition to the maximum dissipated energy.

Fig.7. illustrates the effect of SDBR on stator voltage, where Vwg is stator voltage, Vgrid is the grid voltage, Vwg is increased in magnitude by the voltage, across SDBR (I*RSDBR). Since the mechanical torque is proportional to the square of the stator voltage of an induction machine as shown in (5), where Vs is the stator voltage and T is the developed torque, it can be inferred that the presence of SDBR will increase the mechanical power extracted from the generator, and so the generator will decelerate during disturbances.

$$T = \frac{3{V_s}^2 R_2}{\omega s\,[(R_1+\frac{R_2}{s})^2+X_{eq}^2]} \qquad (5)$$

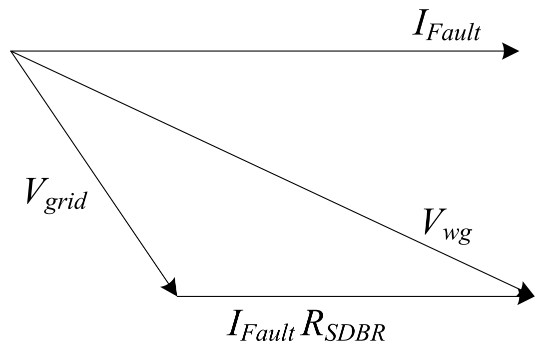

Fig. 7. Voltages phasor diagram.

5.2. Control of SDBR

The control of SDBR Fig.6 is simply implemented; as the generator's stator voltage goes below the reference point, it senses the fault and the bypass switch is opened to insert the resistor into the grid, and divert the fault current into the SDBR. The value of the resistance is chosen to be 0.5 pu similarly as it is for the SFCL in the previous section.

6. Control scheme of TCSC

6.1. Basics of TCSC

The main use of Thyristor Controlled Series Capacitors (TCSC) in power systems is to dynamically control the reactance of a transmission line in order to provide sufficient load compensation. The benefits of TCSC are in its ability to control the amount of compensation of a transmission line, its ability to operate in different modes, and the ability to limit fault currents. These traits are very desirable not only in normal load variation cases, but also in faults and low voltages [23]-[24]. The behavior of power system and the induction machine based wind generator during faults is highly inductive. The TCSC is designed to operate in the same way as the Fixed Series Compensation, (FSC), by providing variable control of the system reactance. The added capacitance compensates the reactive power absorbed by the generator, and boosts the voltage of the Induction generator's terminals, which helps the fault ride through. The basic structure of a TCSC is shown in Fig. 8. The ability of

TCSC to limit fault current and control voltage unbalance of wind farm systems is discussed in [8].

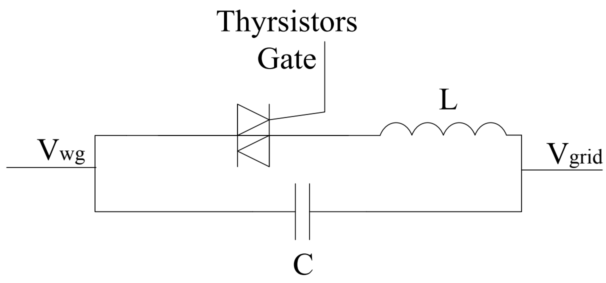

Fig. 8. TCSC structure

6.2.Control of TCSC

The TCSC can operate in two modes, such as the inductive mode as a Thyristor Controlled Reactor (TCR), and the capacitive mode as a Fixed Series capacitor (FSC), providing that the TCSC must not work in the region where XL(α) is equal to XC, to prevent the excessive voltage and current caused by resonance.

Fig. 9 shows the basic control scheme of TCSC, where the difference in voltage is the input signal when the fault is initiated. The signal is then processed through a PI controller. In this study, the TCSC will only work in the capacitive mode in case of fault. The limiter is used to keep the firing angle within the limits in order to avoid generating pulses when the firing angle (alpha) is within the resonance region [25]. The thyristors pulse duration should be as short as possible to ensure proper commutation after the current crosses zero. In this work, the values of the capacitance and inductance are chosen based on the trial and error to get the best performance of the TCSC. The TCSC controller parameters are shown in Table II.

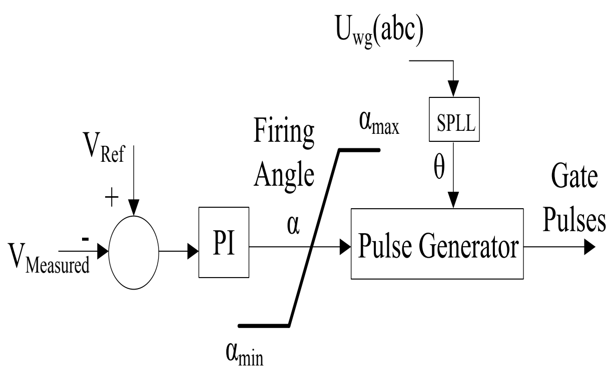

Fig. 9. Control of TCSC.

Table II. TCSC controller parameters

TCSC Parameters	Value
Series capacitance	700 μF
Series Inductance	10 μH
PI Controller	K_p=100 K_i=0.01
Series resistance	0 ohms
Thyristors Snubber capacitance	250 nF
Thyristors Snubber capacitance	500 ohms

7. Simulation results and discussions

In this work, simulations are performed through the Matlab/Simulink software considering temporary three lines to ground (3LG) faults at a point F1 as shown in power system model of Fig. 1. It is considered that the fault occurs at 0.1 sec, circuit breakers on the faulted lines are opened at 0.2 sec, and circuit breakers are closed again at 1.2 sec. It is assumed that the circuit breakers clear the line when the current through it crosses the zero level. The simulation time is 5 seconds and the mode is discrete with a step time of 50 μs.

Although the speed of wind is continuously varying, however, for transient stability analysis variation in wind speed can be neglected over a short period of time. So, we have assumed a constant wind speed of 11 m/s.

7.1. Fault Ride Through Capability Enhancement Under Symmetrical Faults (3LG)

The Figs. 10 (A-E) show the responses for the wind generator variables under 3LG fault. The active power, stator voltage, rotor speed, current, and reactive power, respectively. Figs. 10. (a-e) represent the close up view of the original figures (Figs. 10 (A-E)), respectively. The shaded area in the Figs. 10 (a-e) represents the period of operation of the series devices which is between the fault incident and the circuit breakers (C.B) opening.

It is obvious and clear in all figures that the wind generator will never gain its stability back under the fault condition if no compensation method were added, for example the active power drops down to zero at 0.1 sec (at fault) and tries to recover after the circuit breaker opens at 0.2 sec but fails without any compensation. However, all series devices can achieve the (Fault Ride Through) FRT capability of the wind generator but their performance varies with their behavior and capabilities.

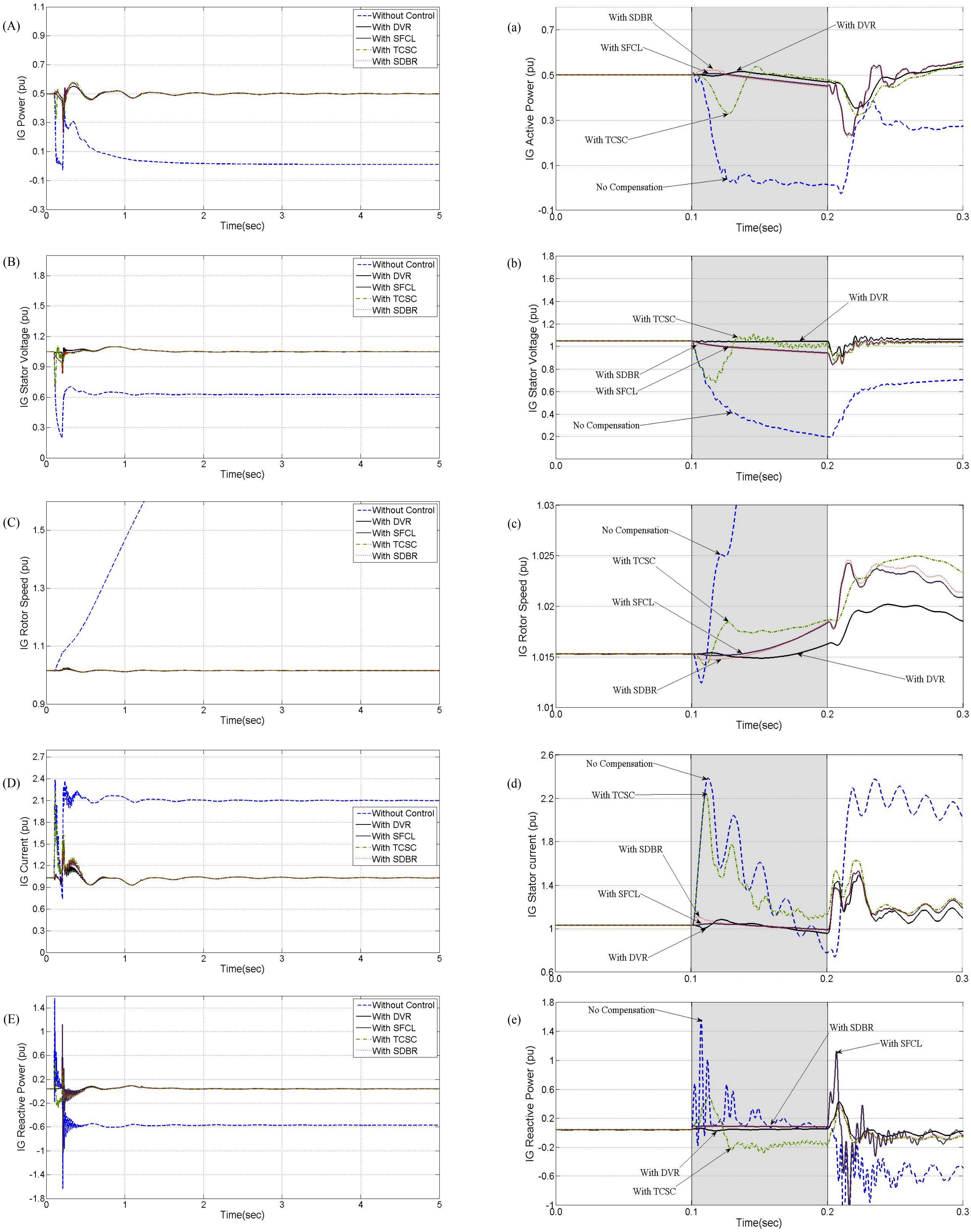

Fig. 10. A, a) IG Active Power. B**,** b) IG Stator Voltage. C, c) IG Rotor Speed. D, d) IG Stator Current. E, e) IG Reactive Power.

7.2. Quantaiztion of the Results

To clearly understand and compare the effectiveness of the mentioned control methods, we used some performance indices, such as vlt_ig(pu.sec), pow_ig(pu.sec), spd_ig(pu.sec), cur_ig(pu.sec), and rea_ig(pu.sec). They are calculated as follows:

$$\text{vlt\_ig(pu.sec)} = \int_0^T |\Delta V| dt \quad (6)$$

$$\text{pow\_ig(pu.sec)} = \int_0^T |\Delta P| dt \quad (7)$$

$$\text{spd\_ig(pu.sec)} = \int_0^T |\Delta Wr| dt \quad (8)$$

$$\text{cur\_ig(pu.sec)} = \int_0^T |\Delta I| dt \quad (9)$$

$$\text{rea\_ig(pu.sec)} = \int_0^T |\Delta Q| dt \quad (10)$$

In (6)–(10), $|\Delta V|$, $|\Delta P|$, $|\Delta Wr|$, $|\Delta I|$, and $|\Delta Q|$ denote the terminal voltage deviation, real power deviation, stator current deviation, and speed deviation of IG, respectively. Th is 5 sec, which is the simulation time of the system. The smaller the values of indices, the better the performance of the system is.

Table III tabulates the performance of DVR, SDBR, SFCL and TCSC control methods 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 when series compensators are employed compared with no control. Although the results are pretty close, it is obvious that the SFCL has the most effective performance in terms of active power stability with 8.0% improvement and fault current suppression 98.1%. The DVR is the most effective control in terms of voltage, speed, and reactive power stability enhancement 99.9%, 98.3%, and 92.17%, respectively. It must be noted that the DVR cannot limit fault currents in a way the SFCL and SDBR do. DVR can only store active power and inject reactive power.

Both the SFCL and SDBR have the same working principle with different dynamics, however, since the SFCL is controlled by the fault current level, so it has the best performance in terms of current limitation than the SDBR which is voltage controlled. The TCSC has least efficient performance during transients, yet it can enhance the FRT if compared to the "No Control" case.

Table III. Values of indexes during 3LG fault

Index parameters	value of indices				
	No Control	DVR	SDBR	SFCL	TCSC
pow_ig(pu.sec)	2.260	0.0436	0.0421	0.0359	0.0454
vlt_ig(pu.sec)	2.078	0.0406	0.0400	0.0362	0.0459
spd_ig(pu.sec)	4.770	0.004228	0.0041	0.0037	0.0045
cur_ig(pu.sec)	5.343	0.9668	0.9808	0.9634	0.9556
rea_ig(pu.sec)	2.760	0.2229	0.2300	0.2161	0.2346

7.3. Harmonics Study.

Harmonics Impact on the system can be harmful to most grid elements. Considering IEEE standards, for example, IEEE 519-1992, which limits the injection of harmonic current makes it essential to do harmonic analysis on new integrated devices, Table IV shows the Total Harmonic Distortion (THD) introduced by each element during their period of operation. The THD can be calculated as in (11)-(12). A maximum THD value less than 5% is expected under normal conditions.

$$THD_{Voltage} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + ... + V_n^2}}{V_1} \quad (11)$$

$$THD_{Current} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + ... + I_n^2}}{I_1} \quad (12)$$

Where V1, V2, ... Vn and I1, I2, ... In are the components of the voltage and current, respectively, measured at the PCC point in Fig. 1 when the fault is initiated.

According to table IV, all the devices can well reduce the injected harmonics generated by the fault, circuit breakers operation and the device itself, however, the TCSC cannot keep voltage and current harmonics within grid standards during fault period. The DVR and SDBR with the proper filtering seem to inject fewer harmonics than the TCSC, and prevent the high amount of harmonics flowing in case of no control and can actually keep up with grid standards. The SFCL is the best among all in terms of harmonics control.

Table IV. THD% introduced into the system

Signal	**Total Harmonic Distortion (THD%)**				
	No Control	**DVR Control**	**SFCL Control**	**SDBR Control**	**TCSC**
Voltage	284.2	3.908	2.237	2.264	11.98
Current	50.04	0.158	0.121	0.172	9.080

7.4. Comparison In Terms of Cost

A cost analysis has been reported for the SFCL system in [26], and the capital cost are estimated roughly to be in the range of hundreds of thousands USD. Also, in spite of its simple operation, it's known to have a very high running cost because of the continuous cooling process to maintain its superconductivity. On the other hand, a cost analysis is performed for the DVR reported in [27], where the calculation is based on the basic component capital cost of the system for a 13.8 kv voltage level which is in the range tens of thousands USD. Considering the aforementioned discussion, it can be concluded that the DVR is cheaper than the SFCL. Unfortunately, no study of the SDBR and the TCSC cost is reported, but based on the complexity of the controller and the configuration of both the TCSC and SDBR, the SDBR and TCSC are much simpler than the DVR, as they don't require series transformer, power electronic converters, or energy storage. So, we can say that the SFCL is the most expensive, and the SDBR is the cheapest. Between the DVR and the TCSC, the TCSC is cheaper.

7.5. Comparison In Terms of Controller Complexity

As far as the controller structure is considered, although the SFCL has a superconducting coil and it also needs liquid helium to maintain its superconductivity, the DVR has a more complex control structure. It has the VSC and filters and the series transformers in addition to the energy storage. Actually the DVR can control active and reactive powers, which increases the controller complexity.

For the TCSC, it has some sophisticated components such as thyristors, the inductor and the capacitor, but still it is simple in terms of the controller. The SDBR basically is a resistor, so it's considered the simplest among all. Finally we can say that the DVR is the most complex among all, and the SDBR is the simplest system

7.6. Overall Comparison

Finally, Table V summarizes the outcomes of section VII "Results & Discussions" of this paper.

Table V. Overall comparison

Criteria	**Stabilization Methods**			
	DVR	***SFCL***	***SDBR***	***TCSC***
Transient Active Power Control	***	***	***	**
Transient Voltage Control	***	**	**	*
Speed Variations Control	***	***	***	**
Fault Current control	**	***	**	*
Reactive Power support	***	**	**	*
Harmonics	**	***	***	*
Controller Complexity	Very Complex	Very Simple	Simple	Simple
Cost	Less than SFCL	More Costly	The Cheapest	Less than the DVR

*poor, ** Moderate, *** High

8. Conclusion

A comparison among series connected auxiliary devices, such as the DVR, SFCL, SDBR, and TCSC for fault ride through capability enhancement of wind generator systems was made. The following points can be noted based on the simulation results.

(i) All series devices discussed in this work can enhance the overall fault ride through capability. Although the results are pretty close, but some methods are better than others.

(ii) The performance of the reactive power compensators (DVR and TCSC) is better than that of active power compensators (SFCL and SDBR) in terms of voltage stability.

(iii) The performance of the active power compensators (SFCL and SDBR) is better than that of reactive power compensators (DVR and TCSC) in terms of current and active power stability.

(iv) The initial cost of the SFCL is the highest and the manufacturing is complex, however, the control of the SFCL is simple and it is very effective. The initial cost of the SDBR and TCSC is the lowest, and doesn't require running cost other than maintenance, but the controller is more complicated than the SFCL. The DVR is the most complex and its initial cost is higher than the TCSC and SDBR, and lower than the SFCL, but it requires extra running cost for the storage device maintenance.

(v) In terms of harmonics distortion, the SFCL introduces less harmonics than other devices, because it doesn't consists of power-electronics. On the other hand, all devices can significantly suppress the harmonics generated by the faults and circuit breakers operation.

This study helps the readers understand the relative effectiveness of the series stabilization methods and provides a guideline for selecting a suitable technique for the stabilization of wind turbine generator systems. As an extension to this work, a large power network consisting of many synchronous generators, wind generators, energy storage, and smart grid elements will be considered.

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