Comparison of SMES and SFCL for Transient Stability Enhancement of Wind Generator System

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Abstract -- **Superconducting magnetic energy storage (SMES) and superconducting fault current limiters (SFCL) can be used to stabilize the wind generator system. While both SMES and SFCL use superconducting coils for their operations, this paper makes a comparative study of these two devices in case of their applications in the wind generator system. The comparison is done on the basis of transient stability enhancement, controller complexity, and cost. In order to analyze the effect of the SMES and SFCL on wind generator stabilization in more detail, several performance indices are considered. Simulation results show that both the SMES and SFCL can stabilize the wind generator system during a severe fault. However, the performance of the SMES is better than that of the SFCL. Also, from the controller viewpoint, the SMES system is more complex than the SFCL system. Moreover, from the perspective of cost, the SMES might be costlier than the SFCL. As a whole, this study would help the readers understand the relative effectiveness of the SMES and SFCL methods, and then select a suitable method for wind generator stabilization.**

Index Terms--**Superconducting magnetic energy storage (SMES), superconducting fault current limiters (SFCL), transient stability, wind generator.**

I. INTRODUCTION

The depletion of conventional energy resources and the perpetual increase in demand for energy in today's industrialized world have necessitated the need to explore nonconventional energy sources and to find optimum methods of exploiting these alternative energy potentials. Among these, wind energy today ranks as one of the most promising renewable energy technologies for generating electric power due to its free, clean, and renewable character, besides having an extremely large potential. In recent years, extensive research and development activities have been in progress universally on the development, manufacturing, and erection of cost-competitive, energy-efficient, and reliable wind energy conversion systems (WECS). Modern wind turbine generation systems (WTGS) usually are variable speed WTGS. Nevertheless, over the former years, fixed-speed WTGS were installed in large proportions in power grids. As wind parks have a lifetime over 20 years, it is still a matter of interest to investigate the interaction of fixed-speed WTGS with power system [1]. Fixed-speed WTGS utilize squirrel cage induction generators directly connected to the power grid. However, induction generators have stability problems similar to the transient stability of synchronous machines [2-5]. Therefore, it is important to analyze the transient stability of power systems including wind power stations.

Superconducting magnetic energy storage (SMES) is a large superconducting coil capable of storing electric energy in the magnetic field generated by DC current flowing through it. An SMES unit based on a self-commutated inverter using insulated-gate-bipolar-transistor (IGBT) is capable of controlling both the active and reactive powers simultaneously and quickly. Thus the SMES has been shown as an effective tool to stabilize the fixed-speed wind generator [6-9] as well as variable speed wind generator system [10]. Again, superconducting fault current limiters (SFCL) can suppress short circuit currents using unique quench characteristics of superconductor [11-15]. In the event of a fault, the superconductor undergoes a transition into its normal state (i.e., quenching). After quenching, the current is commutated to a shunt resistance and is then limited rapidly. Using this excellent performance of superconductors, the SFCL has been demonstrated as a tool to stabilize the variable speed wind generator system [16-17].

While both SMES and SFCL use superconducting coils for their operations, this paper makes a comparative study on their performance of the transient stability enhancement of fixed-speed wind generator system, and this is the novel feature in this work. The comparison is also done on the basis of controller complexity and cost. Another originality of this paper stands on the fact that there is no report available in the literature regarding the application of the SFCL in the fixed-speed wind generator system. Furthermore, in order to

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analyze the effect of the SMES and SFCL on wind generator stabilization in more detail, several performance indices are considered.

The organization of this paper is as follows: Section II describes the modeling of the wind turbine. Section III describes the model system for the proposed study. Sections IV and V explain the control schemes of the SMES and SFCL, respectively. Section VI analyzes the simulation results. Finally, section VII provides conclusions regarding this work.

II. MODELING OF WIND TURBINE

The modeling of wind turbine rotor is complicated. According to the blade element theory [18], 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 [18]:

$$P_w=0.5*\rho*\pi*R^2*V_w^3*C_p(\lambda,\beta) \tag{1}$$

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

In this work, the MOD-2 model [19] is considered for C_p-λ characteristics, which is represented by the following equations, and shown in Fig. 1.

$$\begin{aligned}&\lambda=(\omega_R*R)/V_w\\&C_p=1/2(\lambda-0.022\beta^2-5.6)\,e^{-0.17}\end{aligned} \tag{2}$$

where ω_R is the rotational speed [rad/s].

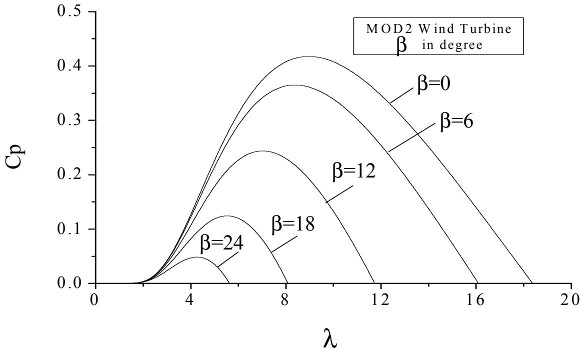

Fig. 1. C_P- λ curves for different pitch angles.

III. MODEL SYSTEM

The model system shown in Fig. 2 has been used for transient stability analysis in this work. The model system consists of one wind turbine generator (50MVA induction generator, IG) and one synchronous generator (100MVA, SG), 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. 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. 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). The automatic voltage regulator (AVR) and governor (GOV) control system models shown in Figs. 3 and 4, respectively, for the synchronous generator are considered in this work. Table I shows the synchronous generator parameters [20] as well as induction generator parameters [21] used in this work. The SFCL and SMES are connected in series and parallel, respectively, at the induction generator terminal bus circuit.

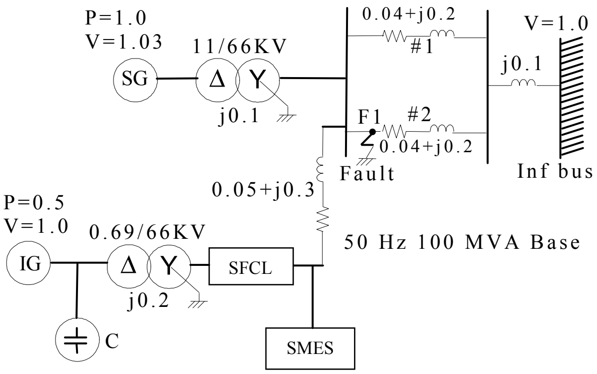

Fig. 2. Power system model.

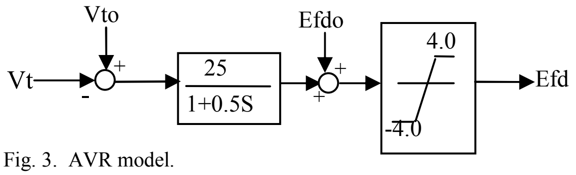

Fig. 3. AVR model.

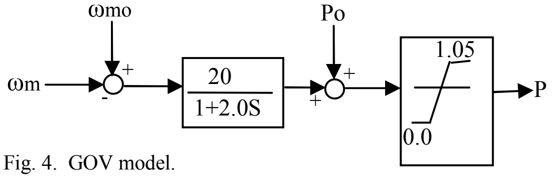

Fig. 4. GOV model.

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]	0.7	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		
$T'do$ [sec]	5.0		
$T''do$ [sec]	0.04		
$T''qo$ [sec]	0.05		
H [sec]	2.5		

IV. MODELING OF SMES

An SMES device is a DC current device that stores energy in the magnetic field. The DC current flowing through a superconducting wire in a large magnet creates the magnetic field. Fig. 5 shows the basic configuration [22] of the proposed SMES unit, which consists of a Wye-Delta 66KV/0.77KV transformer, a 6-pulse PWM rectifier/inverter (50 MVA) using insulated-gate-bipolar-transistor (IGBT), a two quadrant DC-DC chopper using IGBT, and a superconducting coil or inductor of 0.24H. The PWM converter and the DC-DC chopper are linked by a dc link capacitor of 60 mF. The detailed explanation of the voltage source converter (VSC) and two-quadrant DC-DC chopper are available in [9].

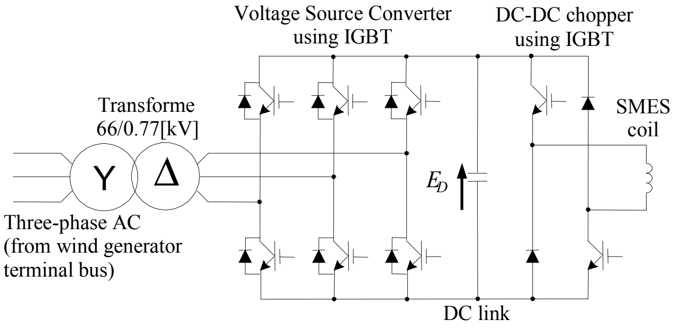

Fig. 5. Basic configuration of SMES system.

For an SMES system, the inductively stored energy (E in Joule) and the rated power (P in Watt) are commonly the given specifications for SMES devices, and can be expressed as follows:

$$E=\frac{1}{2}L_{sm}I_{sm}{}^{2}$$
$$P=\frac{dE}{dt}=L_{sm}I_{sm}\frac{dI_{sm}}{dt}=V_{sm}I_{sm} \tag{3}$$

where L_{sm} is the inductance of the coil, I_{sm} is the DC current flowing through the coil, and V_{sm} is the voltage across the coil. The SMES unit is located at the wind generator terminal bus. The proposed SMES has the rating of 50MW, 0.05MWh.

A. PWM Voltage Source Converter

The pulse width modulation (PWM) voltage source converter (VSC) provides a power electronic interface between AC power system and superconducting coil. In the PWM generator, the sinusoidal reference signal is phase modulated by means of the phase angle, α, of the VSC output ac voltage. The procedure to determine α is described in detail in [9]. In this work, the amplitude modulation index of the sinusoidal reference signal is chosen 1.0. The modulated sinusoidal reference signal is compared with the triangular carrier signal in order to generate the gate signals for the IGBT's. The frequency of the triangular carrier signal is chosen 450 Hz. The DC voltage across the capacitor is 1000 Volt, which is kept constant throughout by the 6-pulse PWM converter.

B. Two-Quadrant DC-DC Chopper

The superconducting coil is charged or discharged by adjusting the average (i.e., DC) voltage across the coil to be positive or negative values by means of the DC-DC chopper duty cycle, D, controlled by a conventional PI controller as shown in Fig. 6, where ΔP indicates the real power deviation of induction generator. When the duty cycle is larger than 0.5 or less than 0.5, the coil is either charging or discharging respectively. When the unit is on standby, the coil current is kept constant, independent of the storage level, by adjusting the chopper duty cycle to 50%, resulting in the net voltage across the superconducting winding to be zero. In order to generate the gate signals for the IGBT's of the chopper, the PWM reference signal is compared with the saw tooth carrier signal. The frequency of the saw tooth carrier signal for the chopper is chosen 100 Hz.

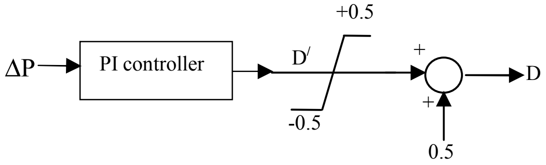

Fig. 6. Control of chopper duty cycle.

V. MODELING OF SFCL

A variety of SFCLs with various approaches to limiting current have been developed and tested. The FCL conceived of in this paper consists of a detector, a controller, and a limiting resistance, all common hardware found in an FCL of any type [23].

SFCL is employed as an S/N (Superconducting to Normal) transforming device which uses a shunt resistance as shown in Fig. 7. In the event of a fault, the superconductor undergoes a transition into its normal state (i.e., quenching). As the superconducting coil needs a short time in order to recover normal operating condition after a quench, two SFCL devices connected in parallel are employed. Thus the SFCL shown in Fig. 1 actually consists of two SFCLs, namely SFCL1 and SFCL2, as shown in Fig. 7. Following a fault at first SFCL1 works, and when the circuit breaker is opened, SW2 is closed just at the same time and hence current flows in the superconducting coil of SFCL2. In this work, 0.5 pu value of the limiting resistance is considered in order to obtain the best system performance.

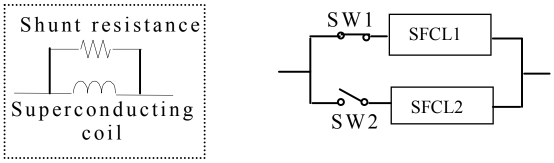

Fig. 7. SFCL model.

VI. SIMULATION RESULTS AND DISCUSSIONS

In this work, simulations are performed by using Alternative Transients Program (ATP) [24]. Simulations are carried out considering that a balanced (3LG: Three-phase-to-ground) fault occurs at point F1 near the synchronous generator at line #2 as shown in the system model at 0.1 sec, the circuit breaker is opened at 0.2 sec, and the circuit bearer is closed again at 1.0 sec. The time step and simulation time have been chosen as 50.0μsec and 10.0sec, respectively.

A. *Transient Stability Enhancement Analysis*

In order to clearly understand the effect of the SMES and SFCL on wind generator stabilization, several performance indices, namely, *vlt(pu.sec)*, *spd(pu.sec)*, *pow(pu.sec)*, and *ang(deg.sec)*, as shown below in (4), (5), (6), and (7), respectively, are considered.

$$vlt(pu.\sec) = \int_0^T |\Delta V| dt \tag{4}$$

$$spd(pu.\sec) = \int_0^T |\Delta \omega_r| dt \tag{5}$$

$$pow(pu.\sec) = \int_0^T |\Delta P| dt \tag{6}$$

$$ang(\deg.\sec) = \int_0^T |\Delta \delta| dt \tag{7}$$

In (4) to (7), ΔV, $\Delta\omega_r$, ΔP, *and* $\Delta\delta$ denote the terminal voltage deviation of wind generator, the speed deviation of wind generator, the real power deviation of wind generator, and the load angle deviation of synchronous generator, respectively, and T is the simulation time of 10.0 sec. The lower the values of the indices, the better the system's performance.

Table II shows the values of the performance indices during 3LG fault. It is seen that both the SMES and SFCL are effective in transient stability enhancement of the wind generator, however, from the viewpoints of the indices *vlt (pu.sec)*, *spd (pu.sec)*, and *pow (pu.sec)*, the SMES is much better than the SFCL, while with respect to the index *ang (deg.sec)*, the SFCL is somewhat better than the SMES.

TABLE II
VALUES OF INDICES FOR STABILIZATION METHODS DURING 3LG FAULT

Index parameters	SMES method	SFCL method	Without controller
vlt (pu.sec)	0.22	0.35	4.46
spd (pu.sec)	0.02	0.06	7.81
pow (pu.sec)	0.16	0.31	4.63
ang (deg.sec)	46.00	42.12	103.05

Fig. 8 shows the responses of the IG terminal voltage. It is seen that the IG terminal voltage returns back to its steady state value due to the use of any of the devices of the SMES and SFCL. Fig. 9 shows the responses of the IG rotor speed. It is seen that because of the use of any of the devices of the SMES and SFCL, IG becomes stable. Fig. 10 shows the responses of the IG real power. In this case it is seen that any of the devices of the SMES and SFCL can maintain the IG real power at the rated level. Fig. 11 shows the responses of the SG load angle. It is clearly seen that the synchronous generator is transiently stable when any of the devices of the SMES and SFCL is used. This fact also indicates that the SMES and SFCL can make the entire power system stable during a severe fault.

However, although both the SMES and SFCL can make the wind generator stable, it is evident from the simulation results that the performance of the SMES is better than that of the SFCL.

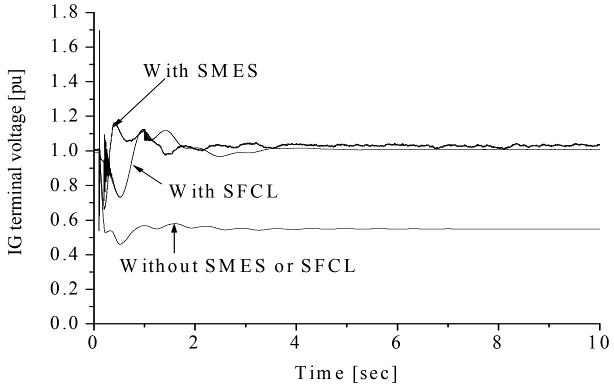

Fig. 8. Responses of IG terminal voltage.

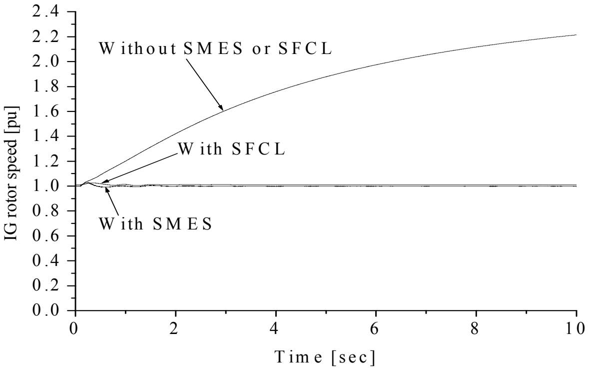

Fig.9. Responses of IG rotor speed.

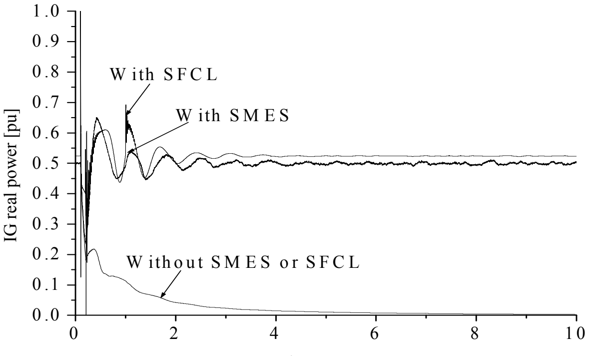

Fig.10. Responses of IG real power.

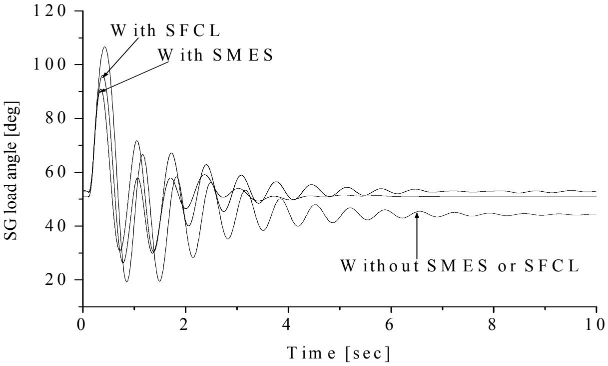

Fig.11. Responses of SG load angle.

B. *Controller Structure Analysis*

From the viewpoint of controller structure, the SMES is more complex than the SFCL, because the SMES has two control aspects, namely the VSC control and the DC-DC chopper control, while the SFCL has a simple control structure.

C. *Cost Analysis*

Although the actual costs of the SMES and SFCL are not known, it may be conjectured that the total installation and maintenance cost of the SMES is higher than that of the SFCL, because the major components of the SMES system are a transformer, a voltage source converter using IGBT, a DC link capacitor, a DC-DC chopper using IGBT, a large superconducting coil cooled by liquid helium, and a refrigerator that maintains the temperature of the helium coolant. On the other hand, the major components of the SFCL are superconductors, cryogenic systems and high voltage insulation devices. Thus the number of necessary components of the SMES system is bigger than that of SFCL.

According to S. Nomura, et al. [25], the unit capital cost per KW of SMES output power is 2000 USD/kW. Also, the following cost equation can be applied to the SMES made of solenoid type of magnets:

$$\text{Cost (M\$)} = 0.95\times[\text{Energy (MJ)}]^{0.67} \qquad (8)$$

In case of SFCL, cryogenic system is the most expensive compared to others. And cryogenic system could require more budgets according to the total volume and length of superconductors. Thus SFCLs are too expensive device for initial installation and maintenance during operation [11].

D. *Practical Implementation Challenges*

The main challenge to implement the SMES and SFCL in real system is their high cost. If the total implementation cost could be reduced, then both technologies could be made attractive. Thus much more research is needed on how the total installation and operation cost of the SMES and SFCL could be reduced.

One question might arise here regarding why the costly SMES and SFCL devices are considered for wind generator stabilization, while the less costly methods, like static synchronous compensator (STATCOM) [26], static vary compensator (SVC) [27], and pitch control [4] methods are available. The STATCOM and SVC methods can control only reactive powers, and the pitch control method can control only active power. Thus none of these three methods (STATCOM, SVC, and pitch control) can control simultaneously the real and reactive powers. The SMES has the ability to control both the real and reactive powers simultaneously and quickly. Again, SFCL can provide a very good solution to reduce the higher level of short-circuit current during a fault, which is increased by the rapid development of the WTGS. Therefore, in spite of their higher costs, the SMES and SFCL have been considered for wind generator stabilization.

VII. CONCLUSION

This paper makes a comparative study of SMES and SFCL on the basis of the transient stability enhancement of wind generator system, controller complexity, and cost. From the simulation results, the following conclusions can be drawn.

a) Both the SMES and SFCL can stabilize the wind generator system during a severe fault. However, the performance of the SMES is better than that of the SFCL.

b) From the controller viewpoint, the SMES system is more complex than the SFCL method.

c) From the perspective of cost, the SMES might be costlier than the SFCL.

As a whole, this study would help the readers understand the relative effectiveness of the SMES and SFCL methods, and then select a suitable method for wind generator stabilization.

In our future work, a variable speed wind generator instead of a fixed-speed wind generator would be considered. Also, multi-shaft wind turbine model system with different inertias would be taken into account. Furthermore, an analysis would be made on how the ratings of the SMES and SFCL could be reduced so that their total costs could be decreased, while maintaining the stability of the wind generator system.

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