Application of Optimized SFCL and STATCOM for the Transient Stability and LVRT Capability Enhancement of Wind Farms

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Abstract: In this paper, the combined superconducting fault current limiter (SFCL) and STATCOM are used to improve transient stability and low-voltage ride-through (LVRT) capability of wind turbine generation system (WTGS). The SFCL absorbs the accelerating energy of the generator, and therefore, improves the WTGS transient stability. Also, STATCOM helps the restore connecting point voltage to improve LVRT capability by reactive power compensation (RPC) after fault clearing. The optimization problem of SFCL resistance and STATCOM capacity is formulated based on the transient stability and LVRT capability of WTGS. The Simulation study shows the superior improving LVRT capability of combined SFCL and STATCOM over individual SFCL or STATCOM. Also, the requirement capacity of STATCOM for RPC is significantly reduced. PSCAD/EMTDC software (V4.2) is used for simulation.

Keywords: SFCL, STATCOM, Transient Stability, Wind Turbine, Reactive Power Compensation (RPC).

I. INTRODUCTION

The growing number distributed energy generators requires new strategies for the planning and operation of the power systems in order to maintain or even to improve the power supply reliability and quality [1, 2]. Optimal placement of the dispersed generation in electrical distribution systems was carried out considering the voltage profile improvement indexes and decreased losses in this study. Also, minimizing the power system costs, specially the costs associated with network load growth is the final aim of a distribution system plan [3-6]. Safety of the power system equipment and quality of the delivered power to the costumers are highly related to work close to nominal frequency of the power system and satisfying the voltage level constraints [7, 8]. To keep power system frequency around its nominal value, active power mismatches between supply and demand have been regulated by fast ramping reserve such as natural gas, whose services are costly for decades [9-12]. However, shifting toward integrating higher level of wind power into the power system, increases generations variability and raises need for updated operational process such as demand respond or installing grid scale storage to improve flexibility and maintain reliability of the power system [13, 14]. Other issue of increasing integration of wind power is voltage sag in WTGS connecting point. The downstream faults in the power system could result in large fault current flow that not only might damage the series equipment but also can cause voltage sag at WTGS connecting point. This voltage sag might disconnect WTGS from power system. This is adverse to the reliability and stability of power system when the wind power penetration level is high [4, 5, 15]. In order to avoid this problem, the transmission system operators (TSOs) impose some technical requirements for the integration of WTGS, as grid codes. In the grid code requirements, the low-voltage ride-through (LVRT) is one of the important and pertinent issues [9, 16]. The ability of WTGS to stay connected to the power system during faults and voltage sag is stated as LVRT capability. As shown in Fig. 1(a), The WTGS must stay connected when the connecting point voltage remains inside the shadow area up to limit line 1. A short disconnection is allowed, when the connecting point voltage is between line 1 and line 2. In addition, WTGS have to provide the reactive current compensation to support the connecting point voltage during fault as shown in Fig. 1(b) [10, 17].

Fig.1: (a) Limit curve for LVRT requirements of E.ON grid code, (b) Reactive current to be delivered to grid

Authors in [18] has shown that installation of STATCOM can effectively reduce the loss and harmonics while the system voltage is controlled at desired level with the minimum ripple. Therefore, the installation of additional shunt FACTS device such as STATCOM and SVC at WTGS connecting point to provide the reactive current to comply LVRT requirements is necessary [18-21].

Another interface for integration WTGSs and power system is superconducting fault current limiter (SFCL), which is mainly implemented for fault current limiting applications. The applications of SFCLs, in the connecting point, not only reduce the large fault current but also can improve the transient stability of the WTGS [22-24]. In [25-27], resistive-type SFCL has been proposed for improving LVRT capability of squirrel cage induction generator (SCIG) and double-fed induction generator (DFIG), respectively. The resistance value of SFCL in these papers is selected based on trial-and-error approach which cannot guarantee the optimal value. The study
results show that the higher value of SFCL resistance, the better enhancement of transient stability can be resulted. The high resistance value of SFCL results in the big size, the high cost and the high energy loss during fault.

In this paper, the combined SFCL and STATCOM are proposed for enhancement transient stability and LVRT capability of WTGS. Also, this study proposed a mathematical approach to evaluate optimal SFCL resistance and STATCOM capacity based on LVRT requirements and transient stability of WTGS. The WTGS is considered as a fixed-speed system, equipped with a SCIG. The drive-train is represented by two-mass model. SFCL has been modelled as a variable resistor by PSCAD/EMTDC software based on the electric field and current density (E–J) characteristic of the superconductor.

II. PRINCIPLE OPERATION OF COMBINED SFCL AND STATCOM

A. Resistive-Type SFCL

There are various types of SFCLs, which generally can be classified into resistive and inductive types [28, 29]. Each type of SFCL has its merits and demerits. The resistive type SFCL is used more due to its compact size and simple principle of operation than inductive type SFCL [30–32]. The physical property of the resistive type SFCL is based on the E–J characteristic of the high temperature superconductor (HTS) and its dependence on temperature (T). The E–J characteristic of the HTS can be expressed by the following equation:

$$E = \begin{cases} 
0 & T < T_c, J < J_c \\
E_c \left( \frac{J}{J_c} \right)^n & T < T_c, J > J_c \\
\rho(T_c) \left( \frac{T}{T_c} \right) J & T > T_c 
\end{cases}$$

(1)

The E–J characteristic of SFCL can be divided into three sub-regions as follows [33]:

- Superconducting state,
- Flux flow state and
- Normal conducting state

Where, $E_c, J_c$ and $T_c$ are the critical field, current density and temperature, $\rho$ is the specific resistivity in a normal state and $n$ is the exponent of E–J power law at flux flow state [34]. In a normal operation mode, the current density and temperature are below their critical values $J_c$ and $T_c$. Therefore, the HTS is in superconducting state and is represented by zero resistance. During the fault condition, the current density exceeds $J$ and the HTS enters flux flow state. Therefore, the electric field increased with the current density by $E \propto (J/J_c)^n$. Due to the resistive power dissipation in this state, the HTS is heated up to critical temperature $T_c$ [35]. Then, the resistance value of SFCL is increased and enters the normal conducting state. During this state, the electric field is proportional to current density and the resistance of the HTS varies approximately in a linear relationship with temperature. In this study, the resistive type SFCL has been modeled as a variable resistor by PSCAD/EMTDC software based on E–J characteristic. Fig. 2 and 3 show the V–I curve and the variation of resistance of resistive type SFCL during fault, respectively.

![Fig. 2: The V–I curve of resistive type SFCL](image)

![Fig. 3: The resistance of resistive type SFCL](image)

B. STATCOM MODEL

The configuration of a typical STATCOM is shown in Fig. 4(a). It consists of a two-level voltage source converter (VSC), common DC link capacitor and a coupling transformer connected in shunt with the AC power grid. Several techniques to control the STATCOM have been reported and proposed [36–39]. In this paper, two separate proportional-integral (PI) controllers are used to control the DC link and the STATCOM reactive power as shown in Fig. 4(b).

![Fig. 4: (a) Configuration of a typical STATCOM, and (b) Control scheme](image)

C. Evaluation Minimum Value of SFCL Resistance and STATCOM Capacity
The power system shown in Fig. 5(a) has been used to evaluate the optimal value of the SFCL resistance and STATCOM capacity for improving transient stability and LVRT capability of the WTs under short circuit fault condition. Fig. 5(b) shows the IG steady-state equivalent circuit.

Fig. 5: (a) Power system with SFCL and STATCOM for the study, and (b) Steady-state equivalent circuit of induction generator.

In a normal operation mode, the SFCL is in superconducting state and has zero resistance. As a result, the voltage drops and power losses of the SFCL are approximately equal to zero. Also, STATCOM is controlled to keep the voltage at the connecting point constant at determined value. The operation of SFCL and STATCOM under short circuit fault condition can be classified in the two following modes:

1) During fault period: During this period, the SFCL resistance is increased to reduce the fault current, improve the transient stability and increase the output efficiency [40]. Fig. 6 (a) shows the equivalent circuit of the system during fault period, where \( V_g \) and \( V_I \) are grid voltage and terminal voltage of IG. \( R_g \) and \( X_g \) are resistance and reactance of grid. \( X_r \) and \( X_t \) are reactance of transformer and line. \( R_{SFCL} \) is the resistance of SFCL. Fig. 6 (b) shows the thevenin equivalent circuit of the system seen from WTGS terminals during fault period. The thevenin voltage \( (V_{TH}) \) and impedance \( (Z_{TH}) \) seen from WTGS terminals can be written as follows:

\[
V_{TH} = \frac{V_g}{R_{SFCL}} + jX_{TH} = \frac{V_g}{R_{SFCL}} + j(R_g + R_{SFCL})(X_g + X_t + X_r)
\]  

\[
Z_{TH} = R_{SFCL} + jX_{TH} = R_{SFCL} + j(R_g + R_{SFCL})(X_g + X_t + X_r)
\]  

The minimum value of \( R_{SFCL} \) to improve transient stability of WTGS is assumed to be \( R_{SFCL}^{min} \) and it is determined as follows. When \( T_f = T_{th} \) during fault period, \( R_{SFCL} = R_{SFCL}^{min} \) and the slip of IG reaches its maximum value and it is assumed to equal to \( S_{TH}^{max} \). This corresponds to \( R_f/S \) at the smallest value and the converted electrical torque being at its largest value. The electrical torque \( T_e \) can be calculated as follows:

\[
T_e = \frac{R_f}{s_{TH}(s)} \frac{V_g^2}{s_{TH}(s)X_{TH}^2 + (X_f + X_{TH} + X_t)^2}
\]  

The electrical torque reaches its maximum value when \( R_f/S \) is the smallest value as follows:

\[
R_f = \frac{V_g^2}{s_{TH}(s)X_{TH}^2 + (X_f + X_{TH} + X_t)^2}
\]  

And the maximum electrical torque can be calculated as follows:

\[
T_e^{max} = \frac{R_f}{s_{TH}(s)} \frac{V_g^2}{s_{TH}(s)X_{TH}^2 + (X_f + X_{TH} + X_t)^2}
\]

Where, \( R_f^{min} \) and \( X_f^{min} \) correspond to \( R_{SFCL}^{min} \). As shown in Fig. 1(a), WTGS must stay connected when the connecting point voltage remains above 0.45 pu during fault period. In this study, to keep the thevenin voltage \( (V_{TH}) \) in shadow area of LVRT curve, the \( V_{TH}^{min} \) is assumed to be 0.5 pu during fault period. By substituting the value of \( R_f/ S_{TH}^{max} \) from (4) in (6), the result is (7) as follows:

\[
T_e = \frac{R_f}{s_{TH}(s)} \frac{V_g^2}{s_{TH}(s)X_{TH}^2 + (X_f + X_{TH} + X_t)^2} + (X_f + X_{TH} + X_t)
\]

Solving (7) gives the minimum SFCL resistance to ensure transient stability of WTGS and keep the connecting point voltage in shadow area of LVRT curve during the fault period.

Fig. 6: Equivalent circuit of system with SFCL and STATCOM, (a) during fault period, and (b) thevenin model.

2) During voltage recovery period: During this period, the resistance value of SFCL is decreased to zero and STATCOM helps to restore connecting point voltage to meet LVRT curve by RPC. Fig. 7 shows the equivalent circuit of the system in order to evaluate the required STATCOM capacity for IG during voltage recovery period. The current of STATCOM is represented by \( I_q \). The impedance of IG is represented by \( I_I(\omega) \) as follows:

\[
I_I(\omega) = s_{TH}(s) = \frac{R_f}{s_{TH}(s)X_{TH}^2 + (X_f + X_{TH} + X_t)^2} + (X_f + X_{TH} + X_t)
\]

By applying KVL at connecting point node, the connecting point voltage \( (V_{PCC}) \) can be written as:

\[
V_{PCC} = V_g - [(R_f + jX_f)(I_f + I_t)]
\]

Where,

\[
I_f = \frac{V_{PCC}}{R_f + j(X_f + X_t)}
\]

The STATCOM current is purely reactive and has +90 phase difference to \( V_{PCC} \). Therefore, the STATCOM current can be represented as a function of connecting point voltage as follows:

\[
I_q = \frac{I_{PCC}}{|I_{PCC}|} |I_q|
\]

By substituting (9) and (10) in (11), the result is (12) as follows:

\[
|I_q|^2 + A|x| + B = 0
\]

The required STATCOM current can be found by a second order equation as given in (12). Solving this equation gives the required capacitive STATCOM current rating for RPC to restore the connecting point voltage, during voltage recovery period.
D. Modeling WTGS

Fixed-speed wind turbine utilizes squirrel cage IG directly connected to the power grid. The wind turbine rotor speed is fixed and determined by the frequency of the supply grid, the gear ratio and the IG design. IGs always need to absorb a particular amount of reactive power. Thus, they generally have fixed reactive power support devices. The fixed-speed wind turbine has the advantage of being simple, robust, reliable and well-proven [4].

E. Wind Speed Model

The wind speed is modeled as the sum of $V_{\text{wind}}(t)$, $V_{\text{gust}}(t)$, $V_{\text{ramp}}(t)$ and $V_{\text{noise}}(t)$, and expressed by the following equation [16]:

$$V(t) = V_{\text{wind}}(t) + V_{\text{gust}}(t) + V_{\text{ramp}}(t) + V_{\text{noise}}(t)$$  \hspace{1cm} (13)

F. Wind Turbine Model

The mechanical power extracted from the WTs can be described as follow [15]:

$$P_{\text{wind}} = 0.5 \rho A_{\text{wt}} C_P(\lambda, \beta) v_w^3$$  \hspace{1cm} (14)

where, $P_{\text{wind}}$ is the power extracted from the wind, $\rho$ is the air density, $v_w$ is the wind speed, $C_P$ is the performance coefficient or power coefficient, $\lambda$ is the tip speed ration, $A_{\text{wt}}$ is the area covered by the wind turbine rotor.

G. shaft model / drive train system

The shaft model of the wind turbine is described by the two-mass model as shown in Fig. 8 and defined by the following equation [17-18]:

$$\frac{\partial \theta_s}{\partial t} = \omega_t - \omega_g$$  \hspace{1cm} (15)

$$\frac{\partial \omega_t}{\partial t} = \frac{1}{2H_t}(T_t - K_t \theta_t + D(\omega_t - \omega_g))$$  \hspace{1cm} (16)

$$\frac{\partial \omega_g}{\partial t} = \frac{1}{2H_g}(-T_e + K_g \theta_g - D(\omega_t - \omega_g))$$  \hspace{1cm} (17)

Where,
- $T_t$ the mechanical torque referred to the generator side,
- $T_e$ the electromagnetic torque,
- $H_t$ the equivalent turbine-blade inertia,
- $H_g$ the generator inertia,
- $\omega_t$ the turbine rotational speed,
- $\omega_g$ the generator rotational speed,
- $K$ the shaft stiffness
- $D$ the damping constant
- $\theta_s$ the angular displacement the ends of the shaft

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III. SIMULATION RESULTS

After optimization in the case of SFCL and STATCOM from (12) and (7) based on the parameter of simulated system in Fig. 9, the optimized parameters are $R_{\text{SFCL}}=1.47$ pu, $S_{\text{max}}=1.3$ pu and $I_q=1$ pu.

From (12), the optimized result in the case of only STATCOM, is $I_q=3$ pu.

Three-phase short circuit fault is simulated on the grid side, which starts at $t=10s$, as shown in Fig. 9. After 0.3s, the circuit breaker isolated the faulted line.

III. SIMULATION RESULTS

The simulations have been carried out by PSCAD/EMTDC for three cases, as follows:

Case A: Without using any STATCOM and SFCL,
Case B: With using STATCOM only and
Case C: With using combined STATCOM and SFCL.

A. Fault Current Limiting

Fig. 10 (a) shows the fault current of the line2 for three cases, respectively. In the cases of A and B, the fault current increases to the rms value of 0.5pu, approximately. By using the resistive-type SFCL, the fault current is limited to the peak value of 1.9 pu.

B. LVTRT Capability

Fig. 10 (b) shows the connecting point voltage of SCIG for three cases. It can be observed that the connecting point voltage of WTGS decreases to zero in cases A and B during fault, approximately.
Fig. 10: (a) Fault current for three cases, (b) PCC voltage, (c) Rotor speed and (d) Active power for three cases in fault

After fault clearance in case A, the connecting point voltage cannot be restored to pre-fault level. The combined SFCL and STATCOM not only decrease the voltage sag to 0.9pu, but also the voltage at connecting point can be restored quickly after the fault clearance compared to case B.

C. Rotor Speed

Fig. 10 (c) shows the rotor speed of the SCIG for three cases, respectively. As shown in Fig. 12, the rotor speed gradually reduces to the pre-fault level and the system is stable in both cases of B and C, but the SCIG is unstable in case A. Also, the combined RSFCL and STATCOM can provide a better damping to post-fault oscillations.

D. Active and Reactive Power

Fig. 10 (d) and Fig. 11 (a) show the active and reactive power exchanged between the WTGS and the grid for three cases, respectively. After the fault, the active power is restored in cases B and C. As shown in Fig. 11 (a), the absorbing reactive power from the grid is significantly reduced by using the combined SFCL and STATCOM, which help to restore the connecting point voltage quickly after the fault clearance.

E. Torque characteristics

Fig. 11(b) shows the electrical torque of the IG for three cases, respectively. As shown in Fig. 11 (b), the variation of the electrical torque is reduced in both cases of B and C, and restored in pre-fault value. But, the combined SFCL and STATCOM are very effective in suppressing the variations of the electrical torque and swings after fault clearing. Fig. 11 (c) shows the enlargement of Fig. 11 (b).

IV. CONCLUSION

In this paper, the application of the combined SFCL and STATCOM has been proposed for improving the LVRT and limiting fault current of fixed-speed WTGSs. Based on the simulation results of a system with WTGS and the combined SFCL and STATCOM, the following points can be drawn. 1) During the fault condition, the resistive type SFCLs not only limit the Fault current but also consume electrical energy and improve the transient stability of WTGS during fault. 2) In normal operation mode, STATCOM is controlled to keep the voltage at the connecting point constant at 1 pu and helps to restore connecting point voltage to meet LVRT curve by reactive power compensation after fault. 3) By using the combined SFCL and STATCOM, the requirement capacity of VSC for the STATCOM is reduced effectively, as shown in Fig. 14. 4) The comparison with STATCOM shows that the combined SFCL and STATCOM are more effective for the enhancement of LVRT and transient stability than STATCOM only. For future work, the controller tuning problems of FACTS can be searched and an alternative solution can be find.

DECLARATION
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