Simulation of implementing the function of SSSC converted from grid paralleling device based on power transmission

Jiajun Liu, Song Yang* and Kun Wang

Institute of Water Resources and Hydro-Electric Engineering, Xi’an University of Technology, Xi’an, Shaanxi, 710048, China

*Song Yang’s e-mail:11568954330@qq.com

Abstract. Grid paralleling device based on power transmission can be converted into a static synchronous series compensator after grid connecting successfully. At present, the power grid becomes more and more complicated, and short-circuit faults occur frequently. In order to regulate the system power flow and limit the short-circuit current of the system, it is worthwhile to develop the function taking advantage of the characteristics of the existing equipment. In this paper, the control strategy of adjusting power is obtained by establishing SSSC model. Meanwhile, according to the nature of SSSC which can be equivalent to series impedance, the current limiting function of SSSC in the event of short circuit fault is further analyzed. Finally, building the equivalent model of SSSC in PSCAD / EMTDC, the simulation results show that changing the equivalent impedance of SSSC can regulate the flow of line transmission effectively, and prove that SSSC has a certain current limiting function in case of short-circuit.

1. Introduction
With the rapid development of China’s economy, the demand for electricity in all walks of life is increasing and the requirements for power supply services and power quality are becoming more and more strict, which the interconnection of large-area power grids is an inevitable trend to satisfy the needs of power grid operation and management in the power market environment [1-2]. The interconnection structure is more and more complex, the power distribution problem is becoming more and more prominent, and the short-circuit current value is inevitably larger and larger. Therefore, if the measures are not taken to adjust and limit the current, not only will the investment in new substations and power plants be increased, but also will the original equipment of the system have a huge impact, which will seriously threaten the safety and stability of the power system [3]. How to compensate power and limit short-circuit fault current in power systems has become an urgent research topic.

At present, the academic community has proposed the concept of using flexible AC transmission systems (FACTS) to enhance the capability of power transmission [4]. The technology of controllable series compensation in FACTS can control line current, improve system stability and limit fault current. Compared to traditional capacitors or inductors fixed in series and other series compensation devices based on FACTS (such as TSSC, TCSC), SSSC is more flexible [5]. In recent years, SSSC has received more attention from researchers. The grid-connected device can be converted into SSSC by adding a transformer and some corresponding switches, setting the appropriate control strategy at the same time [6]. The feasibility of converting the grid-connected device to SSSC is verified by simulation in [7]. An improved PI control strategy to regulate the flow in the system to stabilize the system has been introduced in [8]. With the development of the power grid, the system short circuit
level is continuously improved. At present, in addition to increasing current limiting equipment in the system, another idea is to develop the current limiting function of the existing equipment in the system. The line reactance is required to increases rapidly to limit the fault current when the system fails. SSSC can be equivalent to the impedance in series, which can change rapidly by using appropriate control strategy. Therefore, it is worth to study the function of SSSC to adjust the power flow of transmission line and limit current.

Based on the research that the grid-connected device can be converted into SSSC, the impedance compensation control strategy is adopted to realize the purpose of SSSC to adjust the power. Meanwhile, SSSC can be used to limit the fault current with different inductive impedance characteristics, and it is established in PSCAD/EMTDC. The simulation results show that the adopted control strategy has a good power regulation and a certain limiting effect on the short-circuit fault current.

2. SSSC based on paralleling grid synchronization

After the interconnection of the power grid, the capacity of the power grid is expanded, the total load peak of the system is reduced, the total installed capacity and the standby capacity of the system are reduced, the reliability and stability of the power grid are improved, and the power quality is improved [9]. Therefore, when an interconnected system is accidentally disassembled, higher requirements are imposed on the rapid recovery of the power grid. The traditional simultaneous parallel device is mainly used to make the power plant and the system parallel by adjusting the speed and excitation of the generator to make the frequency difference and the voltage difference reach the range of parallel requirements. In [10], it proposes a new grid-connected method, which uses back-to-back voltage source converter (VSC) to transfer active power and reactive power to reduce the frequency difference and voltage difference between the two paralleling systems. When the condition of grid connection is satisfied, the two systems can be connected.

The grid-connected device will be out of operation after the success of the grid connection. In order to improve the comprehensive utilization of the device and the automation of the power system, it has introduced the process in detail in [6-7] that the synchronous paralleling device converts from the grid connected mode to SSSC mode by adding one coupling transformer, some corresponding breakers and switches, selecting some kind of control strategy, and operating breakers and switches. However, the power regulation function of SSSC and the limiting effect of SSSC on short-circuit fault current are not elaborated.

3. Working principle and mathematical model of SSSC

3.1. Model analysis of SSSC

SSSC can generate a three-phase sinusoidal synchronous voltage with adjustable value and perpendicular to the line current, and can mainly adjust the longitudinal component of the line voltage. By changing the equivalent impedance of SSSC, the line current and transmission power can be adjusted [11].The power system with SSSC and its equivalent circuit are shown in figure 1.

In figure 1, S1 and S2 are the power grids on both sides, $LX$ is the equivalent impedance of the transmission line, $T$ is the series coupled transformer, and $C_{dc}$ is the DC capacitor.

![Power system with SSSC](image1)

(a) Power system with SSSC.

![Equivalent circuit diagram with SSSC](image2)

(b) Equivalent circuit diagram with SSSC.

Figure 1 Power system with SSSC and its equivalent circuit.
\( \dot{U}_{ss} \) is the voltage of the SSSC injection system, and \( \dot{U}_{l} \) is the voltage drop on the equivalent reactance of the line, which is \( \dot{U}_{l} = jX_{l}I_{l}, \dot{U}_{1} = \dot{U}_{l} + \dot{U}_{ss} \). Let \( \dot{U}_{1} = U \angle \delta, \dot{U}_{2} = U \angle 0 \), assume that \( \dot{U}_{ss} \) is positive when it is consistent with the positive direction, and it is inductive compensation; when it is opposite to the positive direction, it is negative, and it is capacitive compensation. The magnitude relationship of the system voltage under the condition of capacitive compensation is as follows:

\[
U_{l} = U_{ss} + 2U \sin \frac{\delta}{2}
\]

Then the active power delivered by the line can be obtained as follows:

\[
P = \frac{U_{1}^{2} \sin \delta}{X_{l} + \frac{U_{m}}{T}} = \frac{U_{1}^{2}}{X_{l}} \sin \delta \pm \frac{U_{m}}{X_{l}} \cos \frac{\delta}{2}
\]

\[
Q = \frac{U_{1}^{2} (1 - \cos \delta)}{X_{l} + \frac{U_{m}}{T}} = \frac{U_{1}^{2} (1 - \cos \delta)}{X_{l}} \pm \frac{U_{m}}{X_{l}} \sin \frac{\delta}{2}
\]

It can be concluded from equations (2) and (3) that SSSC can improve the power transmission capability through impedance compensation without changing the network structure, meanwhile the transmission power can be reduced by changing \( U_{ss} \), and even the power flow reversal can be realized.

3.2. Function of Adjusting Line Transmission Power for SSSC

Assume that the amplitude and phase angle of the voltage across the transmission line remain unchanged after the SSSC is put into operation, then the power at both ends of the line is as follows:

\[
S_{1} = U_{1} I_{1}^{*} = \left( \frac{U_{1}^{*} \sin \delta}{X_{l}} + j \frac{U_{1}^{*} \cos \delta}{X_{l}} \right) \left( \frac{1 \pm \frac{U_{m}}{\sqrt{U_{1}^{2} - 2U_{m} U_{m}}} \cos \delta}{U_{1}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta} \right)
\]

\[
S_{2} = U_{1} I_{1}^{*} = \left( \frac{U_{1}^{*} \sin \delta}{X_{l}} + j \frac{U_{1}^{*} \cos \delta - U_{1}^{*}}{X_{l}} \right) \left( \frac{1 \pm \frac{U_{m}}{\sqrt{U_{1}^{2} - 2U_{m} U_{m}}} \cos \delta}{U_{1}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta} \right)
\]

Ignoring the line resistance, the change of active power is completely caused by the SSSC’s boosting effect; the changes of reactive power include reactive losses on the line and coupling transformers and reactive power injected by SSSC. The change of reactive power is as follows:

\[
\Delta Q_{s} = \frac{U_{1}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta}{X_{l}} \left( \frac{1 \pm \frac{U_{m}}{\sqrt{U_{1}^{2} - 2U_{m} U_{m}}} \cos \delta}{U_{1}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta} \right)
\]

The reactive power which is consumed by the line reactance and the coupling transformer leakage reactance is as follows:

\[
Q = \frac{X_{l} \psi}{\sqrt{U_{1}^{2} - 2U_{m} U_{m} \cos \delta}}
\]

\[
= \frac{U_{1}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta}{X_{l}} \left( \frac{1 \pm \frac{U_{m}}{\sqrt{U_{1}^{2} - 2U_{m} U_{m}}} \cos \delta}{U_{1}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta} \right)
\]

\[
= \frac{U_{1}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta + U_{m}^{2}}{X_{l}} \left( \frac{1 \pm \frac{2U_{m}}{\sqrt{U_{1}^{2} + U_{m}^{2}}} \cos \delta}{U_{m}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta} \right)
\]

\[
Q_{s} = \Delta Q_{s} - Q = \frac{U_{m}}{X_{l}} \left( U_{m} \pm \sqrt{U_{1}^{2} + U_{m}^{2} - 2U_{m} U_{m} \cos \delta} \right)
\]

In conclusion, changing the voltage of the SSSC injected into the transmission line can change the power flow on the line.
3.3 SSSC’s Current Limiting Function
When the system works normally, the smaller the line impedance is, the better the power transmits. However, in the event of a short-circuit fault in the system, the impedance of the system should be increased to limit the rapid rising of the short-circuit current [12-13]. In the condition of ignoring the line resistance, the change of current amplitude on the transmission line before and after putting SSSC into operation is changed as follows:

Before putting SSSC into operation:

\[ I = \frac{\sqrt{U_1^2 + U_2^2 - 2U_1U_2 \cos \delta}}{X_L} \]  

(9)

After putting SSSC into operation:

\[ I = \frac{\sqrt{U_1^2 + U_2^2 - 2U_1U_2 \cos \delta}}{X_L} \pm \frac{U_m}{X_L} \]  

(10)

It can be concluded from equations (9) and (10) that after the SSSC is put into operation, the current of the transmission line changes with \( \pm \frac{U_m}{X_L} \), and the current value can be adjusted by controlling the command value. After detecting a short-circuit fault in the system, the impedance of the transmission line can be quickly adjusted by changing the equivalent impedance of the SSSC, thereby protecting the system and the SSSC from high voltage and high current.

4. SSSC’s Control Strategy
The control is based on the double closed loop control of the SSSC output voltage and inductor current. In the control scheme, the PI regulator used in the current loop which has better robustness and can also reduce the steady-state error. In the two-phase rotating \( d \)-axis, \( q \)-axis, by introducing the \( d \)-axis and \( q \)-axis components of voltage and current, the decoupling control between the \( d \)-axis and \( q \)-axis is realized by the cross-feedback decoupling matrix, thereby directly controlling the voltage of \( d \)-axis and \( q \)-axis to realize the control of SSSC [14], as shown in figure 2.

The decoupling control can ensure that the SSSC obtains good dynamic performance. The phase-locked signal comes from the current on the transmission line, and the obtained angle is used for the coordinate transformation of the converter’s output voltage. In the ideal station, the \( d \)-axis component
of the output voltage is in phase with the line current, and the \( q \)-axis component is perpendicular to the line current. The DC side of the inverter uses external DC power supply to keep the DC voltage stable. Therefore, \( V_{\text{dref}} \) is set to 0 in the control, that is, the SSSC does not absorb the active power from the system. At the moment, the output voltage of SSSC is perpendicular to the line current. When the compensation voltage leads the line current by 90°, SSSC will be equivalent to an inductor; when the compensation voltage lags the line current by 90°, SSSC will be equivalent to a capacitor. From the goal to stabilizing the DC capacitor voltage and compensating for the line impedance, the voltage of the SSSC injection system can be obtained. Since the output voltage of the inverter has higher harmonics, which can be changed into \( \hat{U} \) by RLC filter and transformed into \( d \) and \( q \) components, and the reference voltage signals \( V_{\text{dref}} \) and \( V_{\text{qref}} \) of the voltage outer loop can be obtained.

5. Simulation Verification

According to Figure 1, the equivalent circuit diagram can be built in PSCAD after the grid-connected device converting into SSSC, in which the two turbines are replaced by two equivalent power sources and the phase angle difference between the two sides of the equivalent power supply is 30°. The simulation duration is 4s, which is shown in figure 3.

![Figure 3 Circuit simulation with SSSC.](image)

5.1 Simulation of SSSC Regulating Transmission Line Power

In the simulation, the SSSC can be started when K2 and K3 are closed at 0.79s and K1 is disconnected at 0.8s. The DC side of the converter uses 500V DC power supply to stabilize the DC voltage. Therefore, regardless of the influence of the DC side voltage, setting \( V_{\text{dref}} \) to 0, the control strategy does not adjust the active power. According to the compensation property and compensation amount to set the step signal, when the value is positive, which indicates that the reactive power of compensation is perceptual; when the value is negative, which indicates that the compensated reactive power is capacitive. The line voltage of the converter output is shown in figure 4(a). In order to verify the power adjustment function of the control strategy, the command of \( V_{\text{qref}} \) is 0 between 1.5 and 2.0s, that is, the line is not compensated; 40V between 2.0 and 2.8s, and 80V between 2.8 and 3.5s. So in these two periods, SSSC operates in different inductive compensation states. Between 3.5 and 4.0s, making \( V_{\text{qref}} \) be - 80V, SSSC runs in the capacitive compensation state.
Concluded from figure 4(b) and (c), the active power at the first and end of the transmission line is equal, which indicates that the control strategy is effective. The reactive power of the SSSC compensation is the reactive power shortage of the transmission line. Meanwhile, the SSSC is equivalent to a static synchronous reactive voltage source to regulate the reactive power. However, when the reactive power is adjusted, the active power returns to stability after a slight oscillation, that is, the interaction between active and reactive power is caused by the inaccuracy of the decoupling coefficient in the inner loop current control. Compensating for the appropriate impedance, the SSSC also has the ability to reverse the flow.

Concluded from figure 4(d), when the SSSC compensates the system for inductive compensation, the equivalent reactance of the system will increase, and the current on the transmission line will decrease. While for capacitive compensation, the equivalent reactance of the system will decrease, and the current will increase.

Figure 4 Simulation diagram of SSSC regulating transmission line power.

5.2 Current Limiting Function of SSSC
A three-phase short-circuit fault occurs on the transmission line at the 2.5s, which lasts for 0.5s. When the system doesn’t install SSSC, the normal working current on the transmission line does not exceed 40A. Considering the short-circuit fault in the most serious case, that is, the system occurs a three-phase short-circuit fault, the current increases rapidly, but the peak value exceeds 150A, which can be seen in figure 5(a).

Under the normal circumstances, in order to increase the reactive power delivered by the system, the equivalent reactance of the SSSC should be capacitive to reduce the total impedance of the system. When the system fails, in order to reduce the fault short-circuit current, the impedance of the system should be increased rapidly. At this point, SSSC is in the inductive compensation state to reduce the fault short-circuit current by increasing the positive value of $V_{qref}$. When the given value of $U_d$ is 40V,
the SSSC device can limit the magnitude of the system fault current to 140A; when the given value of \( U_2 \) is 140V, the SSSC device can limit the magnitude of the system fault current to 100A, which can be seen in figure 5(b).

6. Conclusion

The equivalent simulation model is built in PSCAD and the results show that SSSC has better power regulation and current limiting function. Since the system will generate a large short-circuit current when a short-circuit fault occurs, the SSSC will be subjected to a large current surge. Therefore, it is important to set the necessary protection configuration for SSSC, and it is one of the research directions that need to be followed. Since the current limiting capability of SSSC is currently limited, further research is needed. When a short circuit fault occurs, the system should quickly switch to the large reactance mode after the detection of a large current, or install an auxiliary current limiting circuit.

![Figure 5 Variation of transmission line current with fault.](image)

(a) SSSC not connected to system.  
(b) SSSC connected to system.

References

[1] Zhang, J., Li, B., Dai C.B. (2017) Study on Standard System for Global Energy Interconnection. Power System Technology, 41(7): 2055-2063.

[2] Liu, K.J., Li J., Luo J.S., et al. (2017) Synchronous Power Grid Development Trend and China's Energy Interconnection Development. Electric Power Construction, 37(6):1-9.

[3] Zheng, C., Ma, S.Y., Sheng, C.H., et al. (2014) Study on the Oscillation Coupling Mechanism Between Interconnected Power System and Provincial Power Grid. Proceedings of the CSEE, 34(10) : 1556-1565.

[4] Albatsh, F.M., Mekhilef, S., Ahmad, S., et al. (2015) Enhancing power transfer capability through flexible AC transmission system devices: a review. Frontiers of Information Technology & Electronic Engineering, 16(8): 658-679.

[5] Xie, X.R., Jiang, Q.R.. (2014) Flexible AC Transmission System: Principle and Applications (2 edition). Bei Jing: Tsinghua University Pres.

[6] Liu J.J., Liu, C.B., Xu, Y.F., et al. (2015) Control Strategies for Compound System of Power Grid Synchronization. Power System Technology, 39(7): 1932-1939.

[7] Liu, J.J., Wang, X.K. (2014)Simulation of Grid Paralleling Devices Converted into SSSC Based on VSC-HVDC. Proceedings of the CSU-EPSA, 2(11): 17-22.

[8] Jain, A., Yadav, L.K., Omer, A., et al. (2017)Analysis of Effectiveness of SSSC in Transmission Network using PI Controlled Technique. 1st International Conference on Power Engineering Computing and Control, PECON, 699-707.

[9] Zhou, Q.Y. (2017) Discussion on Interconnection Mode of Asian Power Grids. Power System Technology, 41(05):1491-1497.
[10] Liu, J.J., Tang, Y., Yao, L.X., et al. (2010) Research on the Principle and Simulation of Synchronization Parallel Between Grids by VSC. Proceedings of the CSEE, 30: 12-17.

[11] Liu, L.M. (2006) Analysis of Operation Characteristic and Experiments on Power Electronics Devices in Flexible Alternating Current Transmission System. Huazhong University of Science & Technology.

[12] Xu, S., Du, Q.J., Zhang, X.F., et al. (2017) Current Limiting Analysis and Parameter Design of A Novel UPFC With Fault Current Limiter. Power System Technology, 41(2):558-565.

[13] Lv, W.T.(2014) Research on Several Issue in Unified Power Flow Controller with Solid-state Fault Current Limiter for Power System Application. Zhe Jiang University.

[14] Kamel, S., Jurado, F. (2014) Fast decoupled load flow analysis with SSSC power injection model. IEEJ Transactions on Electrical and Electronic Engineering, 9(4).