TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 13, No. 3, March 2015, pp. 431 ~ 440
DOI: 10.11591/telkomnika.v13i3.7175

Coordinated Control of SFCL and SVC for Power System Transient Stability Improvement

Abdelkrim Zebar*, Khaled Zehar
Department of Electrotechnics, College of Engineering, Université of Setif1, Setif, 19100, Algeria
*Corresponding author, e-mail: zebarkarim@yahoo.fr

Abstract

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. To improve stability, inductive type superconducting fault current limiter (SFCL) and shunt FACTS Controller (SVC) can be effectively used. This paper proposes the use of combined model based SFCL and SVC for enhancing the transient stability of a multi-machine power system considering the automatic voltage regulator. The main role of the proposed combined model is to attain at the same time a flexible control of reactive power using SVC Controller and to reduce fault current using superconducting technology based SFCL. In the present work, modification of the admittance matrix method is used for modeling of SFCL; Critical Clearing Time (CCT) has been used as an index for evaluated transient stability. The transient stability is assessed by the criterion of relative rotor angles, using numerical integration method. The effectiveness of the proposed combined model is tested on the IEEE benchmarked four-machine two-area test system applied to the case of three-phase short circuit fault in one transmission line. A simulation results are presented in this document.

Keywords: *superconducting fault current limiter, static var compensator, transient stability, critical clearing time*

1. Introduction

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the power system stability becomes a power transfer-limiting factor [1]. In power system stability studies the term transient stability usually refers to the ability of the synchronous machines to remain in synchronism during the brief period following large disturbances, such as severe lightning strikes, loss of heavily loaded transmission lines, loss of generation stations, or short circuits on buses [2]. To cope with the increasing demand for electric power, more and more FACTS devices are employed to improve the transmission capability of existing transmission facilities. As a result, the stability margin of power systems has decreased while the complexity of power systems has increased considerably. Thus, new techniques in power system control which can improve the dynamic performance and transient stability of power systems present an even more formidable challenge [3].

A static var compensator is a member of FACTS family primarily used to regulate bus voltage by injecting controllable reactive power into the system. It is also capable of improving transient stability and damping of a power system by using some auxiliary signals superimposed over its voltage control signals [4-5].

The use of Fault Current Limiters (FCLs) is being evaluated as one element necessary to limit the fault current and enhance the power system transient stability [6]. A superconducting fault current limiter (SFCL) is a device with negligible impedance in normal operating conditions that reliably switches to a high impedance state in case of extra-current. Such a device is able to increase the short circuit power of an electric network and to contemporarily eliminate the hazard during the fault. It can be regarded as a key component for future electric power systems [7].

One of the requirements of transient stability analysis is to compute a transient stability index (TSI) for the contingencies, which is used to assess the stability of single contingency and

Received September 22, 2014; Revised December 10, 2014; Accepted January 7, 2015

furthermore rank the severity of different contingencies [8]. The Critical Clearance Time (CCT) of a fault is generally considered as the best measurement of severity of a contingency and thus widely used for ranking contingencies in accordance with their severity [9]. In this paper Critical Clearing Time (CCT) is employed as a transient stability index to evaluate test system. The Critical Clearing Time is defined as "the maximum time between the fault initiation and its clearing such that the power system is transiently stable".

Many methods for transient stability analysis and assessment have been proposed and improved over the years, such as equal area criteria, numerical integration and Lyapunove method, in this study the numerical integration method is required in order to get the exact CCTs. The numerical integration method is the most reliable and accurate method for transient stability assessment [10].

The aim of this proposed work is to investigate the potential impact of the combined application of superconducting fault current limiter (SFCL) and shunt FACTS Controller (SVC) for improving both transient stability and voltage regulation of the power system. Moreover, the optimal location of the proposed coordinated controller (SFCL–SVC) is also analyzed. The effectiveness of the proposed combined model is tested on the IEEE benchmarked four-machine two-area test system applied to the case of three-phase short circuit fault in one transmission line. Computer simulation results for system under study are presented and discussed.

2. Mathematical Model

This section gives a mathematical model for the power system network which includes modelling of synchronous generator, SFCLs and SVCs.

2.1. Synchronous Generator

With some typical assumptions, the synchronous generator can be modelled by the following set of differential equations [11]:

$$\dot{\delta}_i = \omega_s(\omega_{ri} - 1) \tag{1}$$

$$\dot{\omega}_{ri} = \frac{1}{2H_i}\left(P_{mi} - P_{ei} - D_i(\omega_{ri} - 1)\right). \tag{2}$$

$$\dot{E}'_q = \frac{1}{T'_{d0}}\left(E_{fd} - E'_q + \left(X_d - X'_d\right)I_d\right). \tag{3}$$

$$\dot{E}'_{fdi} = \frac{K_A}{T_E + K_A K_F}\left(V_{ref} + V_S - V_{ti}\right) - \frac{K_E}{T_E + K_A K_F} E_{fdi}. \tag{4}$$

Where δ is the power angle of the generator, ω is the rotor speed with respect to synchronous reference, H is the inertia constant of the generator, T_m is the mechanical input torque to the generator which is assumed to be constant, T_e is the Electromagnetic torque to the generator, D is the damping constant of the generator, E'_q is the quadrature-axis transient voltage, E_{fd} is the output of terminal voltage transducer, K_A is the gain of the exciter amplifier, K_E is the gain of the exciter, K_F is the gain of the stabilizer, V_{ref} is the reference voltage, V_S is the additional signal, T'_{d0} is the direct-axis open-circuit transient time constant of the generator, T_E is the time constant of the automatic voltage regulator, X_d is the direct-axis synchronous reactance, X'_d is the direct axis transient reactance, $V_{ti} = \sqrt{\left(\dot{E}'_q - X'_d I_d\right)^2 + \left(X_q I_q\right)^2}$ is the terminal voltage of the generator, I_d and I_q are direct and quadrature axis currents of the generator, respectively.

2.2. SFCL

Depending on the different superconducting materials and the operation principle the superconducting fault current limiters can be classified into different types [12]. In the resistive type the superconductor is directly connected in series to the line to be protected since in the inductive concept the superconductor is magnetically coupled into the line [13-14].

In order to illustrate the contribution of the SFCL on transient power system stability, the proposed model should be integrated into a control algorithm of power system. In this way, several analytical methods have been developed by researchers to integrate and adapt FACTS Controllers and different kind of SFCL to solving the static and dynamic behavior of power system. These are the methods of equivalent power injection, the method of modification of the admittance matrix and the method of fictitious node [15]. In the present work, the modification of the elements of the admittance matrix is adapted.

SFCL is a device that limits the fault current by generating an impedance when a fault occurs. In addition, the limiting impedance generated to limit fault currents proves helpful in increasing generator output degraded by a fault, thus providing stabilization. as FCLs installed in series with transmission lines can be just operated during the period from the fault occurrence to the fault clearing [6].

The equivalent circuit in π of the transmission line with SFCL is illustrated in Figure 1. The admittance matrix method is based on changing the standard elements (Yij) in coordination with the new model to be integrated.

When the resistive SFCL is injected in a branch (jk), the element of the new admittance associated to this branch is given by:

$$Y_{jk}^{new} = \frac{1}{(r_{jk}+R_{SFCL})+jx_{jk}}. \tag{5}$$

When the the inductive SFCL is injected in a branch (jk), the element of the new admittance associated to this branch is modified as:

$$Y_{jk}^{new} = \frac{1}{r_{jk}+j(x_{jk}+X_{SFCL})}. \tag{6}$$

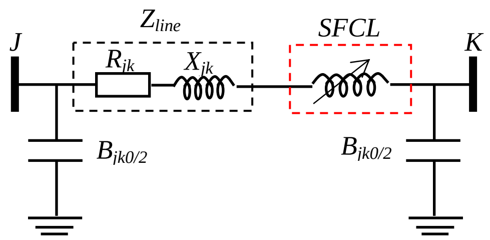

Figure 1. Modified transmission line with SFCL

In this study only inductive SFCL type is considered and we decided to take values of SFCL 20 Ω. It is not necessary to take a large value of SFCL because the design of the SFCL to obtain a value higher can be difficult (important length of the superconducting conductor). Although 20 Ω is the most effective value on the transient stability enhancement, which is determined based on the results of simulation using various limiting reactance values.

2.3. SVC

In the literature various SVC models have been developed and included within the load flow program, the optimal power flow and the transient stability analysis [16-8].

The Static Var Compensator (SVC) model is a variable shunt capacitor that is varied to maintain a constant voltage at the bus to which it is connected. A common approximation consists in assuming that the controlled variable is the equivalent susceptance of the SVC (b_{svc}). The simplified control scheme is depicted in Figure 2 and undergoes the following differential equation [19]:

$$\dot{b}_{svc} = (K_r(\omega_s - \omega_{ri}) - b_{svc})/T_r. \tag{7}$$

Where K_r is the regulator gain and T_r is the Regulator time constant.

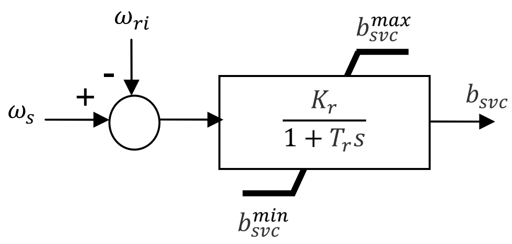

Figure 2. SVC simplified control scheme

The model is completed by the algebraic equation expressing the reactive power injected at the SVC node:

$$q = b_{svc}V^2. \quad (8)$$

3. Transient Stability Evaluation

Transient stability entails the evaluation of a power system's ability to withstand large disturbances, and to survive transition to a normal operating condition [10]. The transient stability analysis is performed by combining a solution of the algebraic equations describing the network with numerical solution of the differential equations. However, due to the non-linearity of the differential equations, the solving process is tedious and complicated. Thus, numerical integration methods have been applied to examine a system's stability.

The algorithm for the transient stability studies involves the following steps:

a) Reads the line and bus data. It includes the data for lines, transformers and shunt capacitors.
b) Form admittance matrix, Ybus.
c) Solve the initial load flow.
d) Reads generator data.
e) Modify Ybus by adding the generator and load admittances.
f) Compute the pre-fault admittance matrix Ypre-fault by eliminating all nodes except the internal generator nodes.
g) Solve the generator swing equation for the pre-fault period.
h) Set t = 1s a three-phase fault occurs at any line in the system, and fault bus voltage equal to zero.
i) Compute the new faulted admittance matrix Yfault.
j) Solve the swing equation for the fault period.
k) Isolate the line witch fault occurred.
l) Compute the post-fault system admittance matrix Ypost-fault.
m) Solve the swing equation for the post fault period.
n) Plots the swing curves for all generators.

In this paper, we define the CCT as the small lest from all CCTs values for different generators.

4. Simulation Results

To study the efficiency and the robustness of the proposed coordinated controller based SFCL and SVC on the transient and voltage stability; the model is integrated in the IEEE benchmark four-machine two-area eleven bus test system in the case of three phase short circuit fault in the transmission line. The one line configuration is shown in Figure 3. Technical data such as machine, voltage regulator, governor turbine, buses and branches information are taken from. [20] The transient stability is assessed by the criterion of relative rotor angles, using the Time domain simulation method. The toolbox SimPowerSystems of MATLAB/SIMULINK software is used to carry out simulations studies.

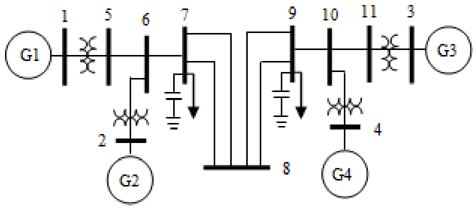

Figure 3. On-line diagram of the Electrical Power System used for simulations

4.1. Optimal Location of Combined SFCL–SVC Controller

Optimal location and control of multi FACTS devices and multi SFCL is a vital and complex research area. In the literature many modern techniques and indices proposed for optimal location and control of multi FACTS devices. For secure operation of power systems, it is required to maintain an adequate voltage stability margin, not only under normal conditions, but, also, in contingency cases. In this study the voltage stability index using continuation power flow proposed for optimal location of SVC and SFCL. First, buses are classified based on two procedures:

Procedure 1: all buses are classified based on voltage stability index, the weak buses are identified based on voltage stability index, in this study, the bus 8 is considered as a candidate bus, the main role of the SVC is to control voltage at this bus by exchanging reactive (capacitive or inductive) power with the network.

Procedure 2: Buses are classified based on the value of fault currents (three phase fault).

From the continuation power flow results which are shown in the Figure 4, the buses 5, 6, 7, 8, 9, 10 and 11 are the critical buses. Among these buses, bus 8 has the weakest voltage profile. Figure 5 shows PV curves for IEEE four-machine two-area test system without considering SFCL and SVC.

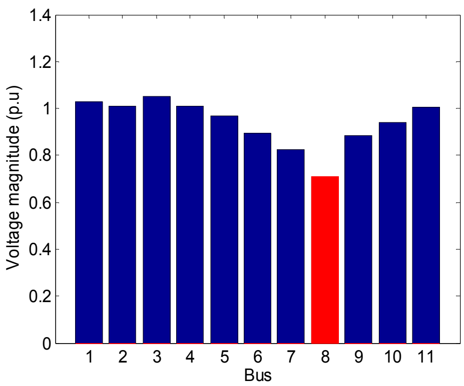

Figure 4. PV curves for the IEEE four-machine two-area test system

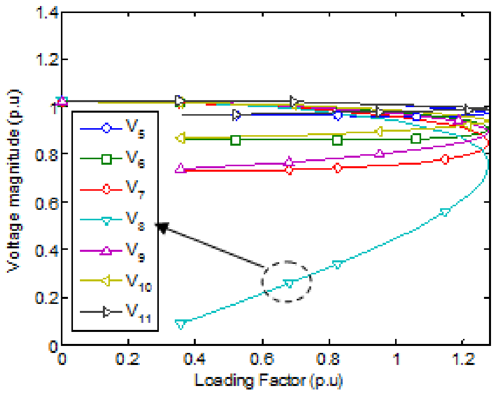

Figure 5. Critical buses based on continuation power flow

4.2. Impacts of Combined SFCL–SVC Controller on Power System Transient Stability Enhancement

Four cases are studied. Base case, which indicates the original system where there is no SFCL and SVC, in the system. Second case, with only SVC at the weak bus (low voltage stability index). Third case, with only SFCL located at the bus which has high fault current. Finley With both SVC and SFCL at the same bus, which weak bus and has high fault current. Figure. 6 shows the location of the SFCL and the SVC controller.

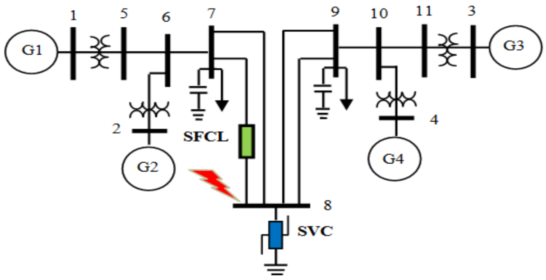

Figure 6. Modified electrical test system considering combined controller: SFCL and SVC

4.2.1. Case 1

A 3-phase fault occurs at t = 1 second on line 7–8 near the bus 8 and it is cleared by opening the line at both ends. Generator 2 is the nearest generator to the fault location and therefore it has the most rotor speed deviation for this fault. The fault clearing time (FCT = 0.266 s) at first then (FCT = 0.300 s).

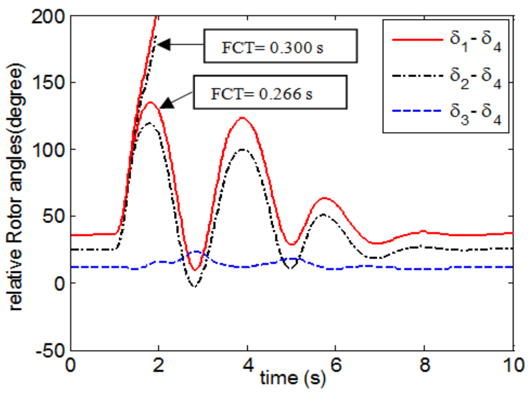

Figure 7. Relative rotor angles without SFCL–SVC

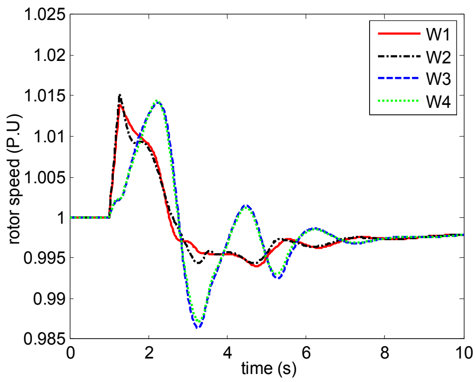

Figure 8. Rotor speed deviation without SFCL–SVC

Simulation results on the rotor angle differences and rotor speed deviation of four generators without considering SFCL and SVC Controller are shown in Figures 7–8 respectively. It can be seen that the relative rotor angles are damped and consequently the system maintains its stability, but when the fault clearing time increased to 0.300 s, the relative angles (δ14, δ24 and δ34) increase indefinitely, so at this critical situation the system loses its stability. Figure 9 shows the distribution of voltage magnitudes at all buses.

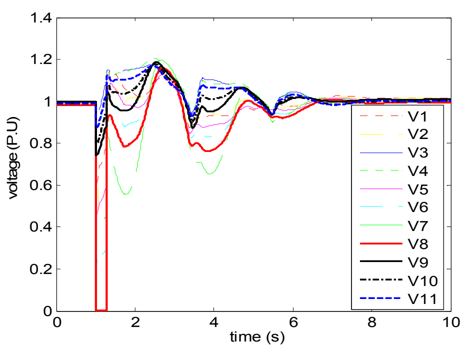

Figure 9. Voltage magnitudes without SFCL–SVC

4.2.2. Case 2

In order to maximize voltage stability index and to improve power system transient stability, SVC of B_{SVC}^{max}=2.0 pu located at the weak bus (low voltage stability index).The SVC will try to support the voltage by injecting reactive power on the line when the voltage is lower than the reference voltage. The mentioned fault in the previous sub-section is applied again.

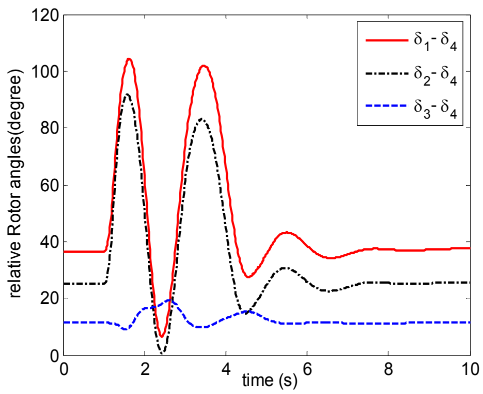

Figure 10. Relative rotor angles with only SVC

Time domain simulation performed at the cleared time 0.333 s, we can see from Figure. 10 the maximum relative rotor angles are (δ14 = 97°, δ24 = 91° and δ34 = 10°), the relative rotor angles (δ14, δ24 and δ34) are damped and therefore the system becomes stable compared to the first case (system unstable). The critical clearing time is enhanced to a new value (0.366 s). Figure 11 shows the improvement of magnitude voltages at critical bus compared to the case 1without considering SVC.

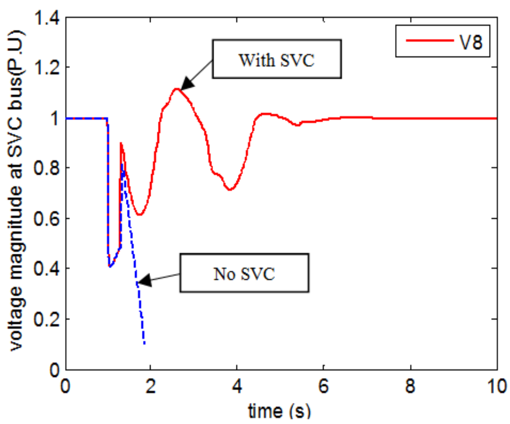

Figure 11. Voltage of bus 8 with only SVC

4.2.3. Case 3

The use of the SFCL to enhance the margin security is evaluated in this subsection; the SFCL is placed in line 7–8. The first mentioned fault in the sub-section (case 1) is applied again. The fault is cleared after 0.433 s.

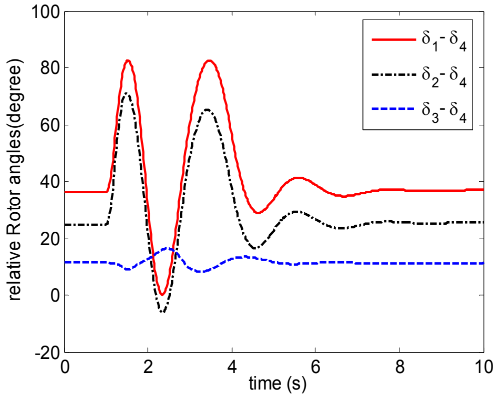

Figure 12. Relative rotor angles with only SFCL

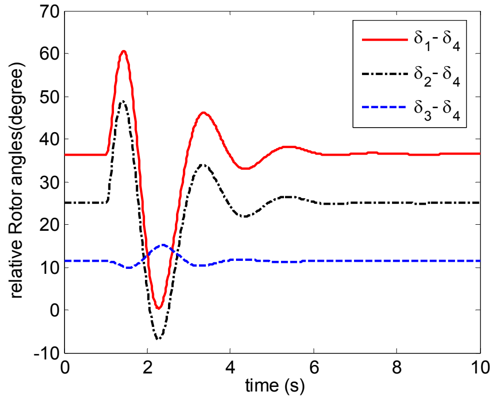

Figure 13. Relative rotor angles considering SFCL–SVC

In Figure 12 It can be seen that the maximum relative rotor angles are (δ14 = 82°, δ24 = 77° and δ34 = 8°), the relative rotor angles (δ14, δ24 and δ34) are damped and therefore the system becomes stable compared to the first and second cases (system unstable). It can be also seen that the system response with the SFCL is better than that with the SVC in the sense of the settling time is reduced. The critical clearing time is enhanced to a new value (0.483 s). Figure 13 shows the improvement of magnitude voltages at critical buse compared to the case 1 and case 2 without considering SFCL.

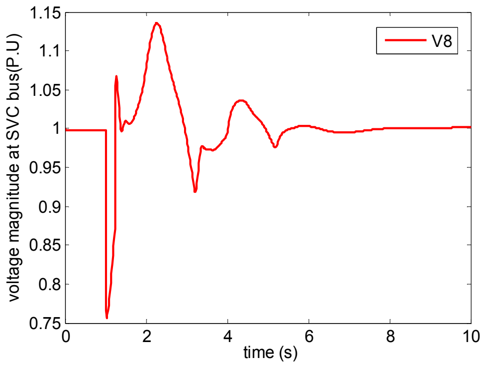

Figure 14. Voltage of bus 8 considering SFCL–SVC

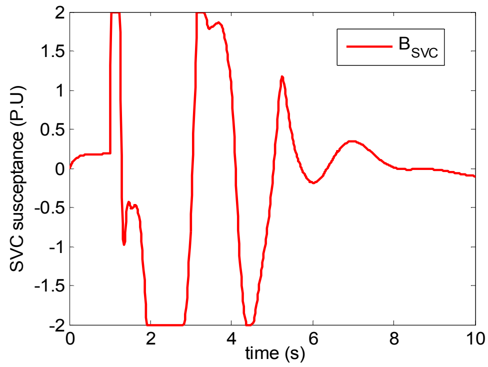

Figure 15. SVC Susceptance

4.2.4. Case 4

In case 2 and 3 the SVC and SFCL are applied independently however in this case through coordination to support the excessive reactive power during fault. Time domain simulation performed, as well exposed in Figure 13, 14 and 15, the maximum relative rotor angles (δ14 = 60°, δ24 = 55° and δ34 = 5°) are reduced compared to case 1(without SFCL and SVC), case 2 (with only SVC) and case 3 (with only SFCL), the clearing time enhanced at a new value (CCT = 0.55 s), this allows the system to be more stable. As we can see in Figure 14, the magnitude of voltages at critical bus is enhanced, it is important to note that improvement of voltages during and after fault contribute to the coordination of the protection system. Figure 15 shows the Susceptance of SVC exchanged with the network during fault and after opening the affected line. It is important to conclude that integration of shunt FACTS compensator (SVC) in coordination with SFCL in suitable location may help the system to improve the transient stability. Table 1 shows the values of margin stability (CCT) obtained corresponding to different cases.

Table 1. Margin stability (CCT) for different cases

	Controller	Margin stability (CCT) 's'
Case 1	Without SFCL and SVC	0.283
Case 2	With only SVC at the weak bus	0.366
Case 3	With only SFCL at the bus which has high fault current	0.483
Case 4	With both SVC and SFCL at the weak bus	0.550

5. Conclusion

In this study, the multi-machine power system transient stability improvement via superconducting fault current limiter (SFCL) and shunt FACTS Controller (SVC) when applied independently and also through coordinated application was discussed and investigated. Simulation results performed on the IEEE benchmarked four-machine two-area test system considering three phase short circuit clearly indicate that proposed combined controller placed at suitable locations can be used as an effective mean capable to enhance the margin stability and extend the critical clearing time in a multi-machine power system. Future research will focus on investigation the effect of combined application of superconducting fault current limiter and other transient stability improvement FACTS devices in the presence of the distributed generation by considering the optimal value of SFCL and location of this hybrid Controller.

References

[1] KK Sen, ML Sen. Introduction to FACTS Controllers: Theory, Modeling and Applications. published by John Wiley & Sons, Inc., and IEEE, New Jersey, USA, 2009.
[2] A Karami, SZ Esmaili. Transient stability assessment of power systems described with detailed models using neural networks. *International Journal of Electrical Power and Energy Systems.* 2013; 45: 279–292
[3] L Cong, Y Wang, DJ Hill. Transient stability and voltage regulation enhancement via coordinated control of generator excitation and SVC. *Journal of Electrical Power and Energy Systems*. 2005; 27: 121–130
[4] AE Hammad. Analysis of power system stability enhancement by static var compensators. *IEEE Trans. PS 1.*1986; (4): 222–227.
[5] NG Hingorani, L Gyugyi. *Understanding FACTS; Concept & Technology of Flex-ible AC Transmission Systems*. IEEE Press Book, 2000.
[6] AL Bettiol, A Souza, JL Todesco, JR Tesch. *Estimation of critical clearing times using neural network.* In: IEEE bologna powertech conference. Bologna, Italy; 2003.
[7] M Sjostrom, R Cherkaoui, B Dutoit. Enhancement of power system transient stability using superconducting fault current limiters*. IEEE Trans. Applied Superconductivity.* 1999; 9(2):1328-1330.
[8] K Phorang, M Leelajindakraireak, Y Mizutani. *Damping improvement of oscillation in power system by fuzzy logic based SVC stabilizer. Asia Pacific.* IEEE/PES Transmission and Distribution Conference and Exhibition. 2002; 3: 1542–1547
[9] R Ebrahimpour, EK Abharian, S Moussavi Z, AA Motie Birjandi. Transient stability assessment of a power system by mixture of experts. *International Journal of Engineering* (IJE). 4(1): 93–104
[10] P Kundur. Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions. *IEEE Transactions on Power Systems.* 2004; 19(2): 1387-1401.
[11] N ABU-TABAK. Stabilité dynamique des systèmes électriques multi-machines: modélisation, commande, observation et simulation. Doctoral Thesis, University of Lyon, 2008.
[12] M Noe, M Steurer. High-temperature superconductor fault current limiters: concepts, applications, and development status. *SUST*. 2007; 20.
[13] S Nemdili, S Belkhiat. Electrothermal modeling of coated conductor for a resistive superconducting fault-current limiter. *J. Supercond. Nov. Magn*. 2012. doi:10.1007/s10948-012-1895-4
[14] Ali A, Mehdi H, Mahmoud S. Enhancement Fault Ride-Through Capability of DFIG by using Resistive and Inductive SFCLs. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2014; 12: 5946 ~ 5953

[15] S Messalti, S Belkhiat. Comparative Study of Resistive and Inductive Superconducting Fault Current Limiters SFCL for Power System Transient Stability Improvement. *J Supercond Nov Magn.* 2013; 26: 3009–3015.DOI 10.1007/s10948-013-2114-7.

[16] M Basu. Multi-objective optimal power flow with FACTS devices. *Energy Conversion and Management (Elsevier).* 2011; 52: 904–910.

[17] Selvarasu R, Surya Kalavathi M. SVC Placement for Voltage Profile Enhancement Using Self-Adaptive Firefly Algorithm. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2014; 12: 5976 ~ 5984

[18] Lin Xu. Coordinated Control of SVC and PSS for Transient Stability Enhancement of Multi-Machine Power System. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2013; 11: 1054~1062.

[19] CW Taylor. Power System Voltage Stability, New York: McGraw-Hill, 1994.

[20] M Klein, G Rogers, Moorty, P Kundur. Analytical investigation of factors influencing PSS performance. *IEEE Trans. on Energy Conversio*n. 1992; 7(3): 382-390.