# STABILITY ENHANCEMENT OF HA TIEN - PHU QUOC POWER SYSTEM USING A SERIES STATIC SYNCHRONOUS COMPENSATOR (SSSC)

# NÂNG CAO ỔN ĐỊNH CỦA LƯỚI ĐIỆN HÀ TIÊN – PHÚ QUỐC SỬ DỤNG THIẾT BỊ BÙ ĐỒNG BỘ TĨNH NỐI TIẾP (SSSC)

**Nguyen Thi Mi Sa[1], Truong Dinh Nhon[1], Le Chi Kien[1], Ho Van Luan[2]**

[1]*Hochiminh City University of Technology and Education, Vietnam; misa@hcmute.edu.vn*

[2]*Southern Power, EVN SPC; holuanspc@gmail.com*

**Abstract -** This paper presents comparative simulation results of Ha Tien - Phu Quoc power system using a Series Static Synchronous Compensator (SSSC). For improving the stability of the studied system, an Adaptive Neural Fuzzy Inference System (ANFIS) controller is designed. For simplicity, the power grid in Phu Quoc Island can be modeled as an equivalent Synchronous Generator (SG) with a local load connected to Ha Tien Town bus that can be considered as an infinite bus. Time-domain approach based on nonlinear model simulations is systematically performed. It can be concluded from the simulation results that the proposed SSSC joined with the designed ANFIS damping controller can offer better damping characteristics of the studied system under severe operating conditions.

**Key words -** Synchronous Generator (SG); Adaptive Neural Fuzzy Inference System (ANFIS); Series Static Synchronous Compensator (SSSC); Stability Enhancement; Power grid.

**Tóm tắt -** Bài báo trình bày so sánh kết quả mô phỏng của lưới điện Hà Tiên – Phú Quốc sử dụng thiết bị bù đồng bộ tĩnh nối tiếp (SSSC). Để nâng cao tính ổn định của hệ thống, một bộ điều khiển mờ thích nghi (ANFIS) được thiết kế. Để đơn giản, lưới điện trên đảo Phú Quốc có thể mô hình bằng một máy phát điện đồng bộ (SG) kết nối với tải nội bộ và nối với lưới điện ở Thị trấn Hà Tiên được xem như một bus vô hạn. Kết quả mô phỏng trong miền thời gian dựa vào mô hình phi tuyến sẽ được trình bày. Có thể kết luận từ các kết quả mô phỏng rằng thiết bị bù đề xuất SSSC kết hợp với bộ điều khiển thiết kế có thể cung cấp hệ số giảm chấn tốt hơn cho hệ thống khi các điều kiện vận hành nghiêm trọng xảy ra.

**Từ khóa -** Máy phát điện đồng bộ (SG); Bộ điều khiển mờ thích nghi (ANFIS); Thiết bị bù đồng bộ tĩnh nối tiếp (SSSC); Nâng cao ổn định; Hệ thống điện.

## 1. Introduction

Ha Tien - Phu Quoc power system is the first power grid in Vietnam that uses 110 kV undersea cable. With the cable length of about 57 km, compensation of the system must be considered to maintain normal operating conditions. One of the traditional method is using reactor to keep the open circuit voltage at the end bus under 1.1. pu. This paper suggests using one of the second generation of Flexible AC Transmission System (FACTS) devices based on voltage-sourced converter (VSC) i.e. Series Static Synchronous Compensator (SSSC) instead of reactor. SSSC is a series FACTS device and can be effectively used for controlling the power flow [1]. On the other hand, it can be used for improving power transfer limits, for congestion management in the network as well as for damping oscillatory modes [2]. In addition, an auxiliary stabilizing signal can also be superimposed on its power flow control function to improve the damping of oscillations that occur in power systems [3].

The simulations of a 24-step inverter-based SSSC using Electromagnetic Transients Program (EMTP) are performed in [4]. In [5], the application of SSSC for improving the damping characteristic of the studied offshore wind farm integrated into power grid is presented. For improving the controllability of SSSC a novel Adaptive Neural Fuzzy Inference System (ANFIS) controller is proposed since it combines both fuzzy logic and artificial neural network advantages to produce a powerful processing [6].

This paper is organized as follows. Section 2 introduces the configuration and models of the studied system including SG-based power plan model and the proposed SSSC model. Section 3 demonstrates the design procedure and design results of the damping controllers of the SSSC using ANFIS technique. Section 4 depicts the comparative transient responses of the studied system with the proposed SSSC joind with the designed damping controller under a severe disturbance. Finally, specific important conclusions of this paper are drawn in Section 5.

## 2. Configuration Of The Studied System

Figure 1 shows the configuration of the equivalent Ha Tien - Phu Quoc power system which includes two 40 MVA SG in Phu Quoc Island connected to Ha Tien bus through 57 km undersea cable. The proposed SSSC is connected in series with transmission line near the Point of Common Coupling (PCC) to control the power flow and compensate for the oscillation of the system. The detail model of each element is presented as follows.

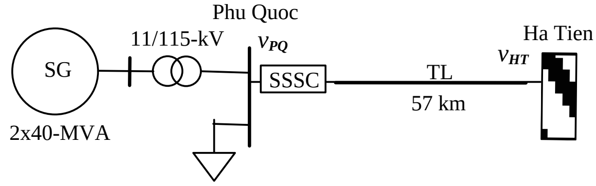



***Figure 1.*** *One line diagram of the studied system*

### *2.1. Synchronous Generator Model*

The SG model used in this paper is the same as the one developed in [7]. This model takes into account the sub-transient effects and is established based on the following assumptions.

(a) The model is established on the *dq*-axis reference frame that is fixed on the rotor of the SG and is rotating with the rotor speed.

(b) The rotor has two windings on each axis, i.e., one field winding and one damper winding on the *d*-axis and two damper windings on the *q*-axis;

(c) The transients of stator windings and the effects of speed deviation in the stator-winding voltage equations are properly neglected;

(d) All quantities are in per unit (p.u.) except that time is in seconds, rotor angle is in electrical radians, and base angular frequency is in electrical radians per second.

The complete *d*- and *q*-axis equivalent circuits and the corresponding equations of a SG can be referred to [7]. The IEEE type ST1A excitation system model (fast static exciter) is employed in this paper [8].

The excitation system [7] with the automatic voltage regulator (AVR) and the employed power system stabilizer (PSS) are shown in Figure 2.

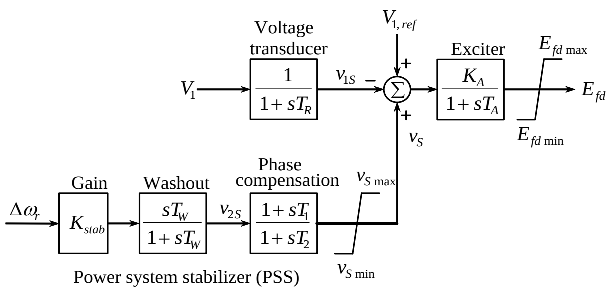



***Figure 2.*** *Fast static exciter and PSS model*

### *2.2. SSSC Model*

Figure 3 shows the basic structure of the proposed SSSC. The SSSC consists of a voltage-source inverter (VSI) that converts a DC voltage into a three-phase AC voltage. Hence, the equivalent SSSC consists of a three-phase voltage source with fundamental frequency, a series coupling transformer, a DC capacitor, and a controller.

Using the synchronous reference frame, the *d*- and *q*-axis components of the series injected voltage ($v_{se}$) can be expressed by [4-5] respectively

$$v_{dse} = n_c K_{inv} V_{dc-sssc} \cos(\alpha_{se}) \qquad (1)$$

$$v_{qse} = n_c K_{inv} V_{dc-sssc} \sin(\alpha_{se}) \qquad (2)$$

where $n_c$ is the turns ratio of the coupling transformer, $V_{dc\text{-}sssc}$ is the DC capacitor voltage, $\alpha_{se}$ is the phase angle of the injected voltage, and $K_{inv}$ is the inverter constant that relates the DC-side voltage to the AC-side line-to-neutral voltage. From the DC-side equivalent circuit and by balancing the power exchanged between the AC side and the DC side, the dynamic equation of the DC capacitor $C_{dc}$ can be described by

$$\left(C_{dc}\right) p(V_{dc-sssc}) = n_c K_{inv} \left[ i_d \cos\left(\alpha_{se}\right) + i_q \sin\left(\alpha_{se}\right) \right] - \frac{V_{dc-sssc}}{R_{dc}} \qquad (3)$$

The SSSC may be operated under capacitive or inductive mode to increase or decrease the power flow through transmission line, respectively. Only the capacitive mode of the SSSC is used in this paper. The control block diagram of the reactance scheme-based controller [9-10] for a SSSC in capacitive mode is shown in Figure 3.

A phase-locked loop (PLL) is used to determine the reference angle θ, which is phase-locked to phase a of the voltage v1. The magnitude of the line current i and its relative angle θir with respect to the PLL angle are then calculated. The phase angle of the line current θi is calculated by adding the relative angle θir to the PLL angle θ. The angle βse in Figure 4 can be added to the phase angle θv to acquire the final angle αse, where θv of the required voltage is either (θi + π/2) in an inductive mode or (θi – π/2) in a capacitive mode. Figure 4 also shows an auxiliary signal (or damping signal) Xax that comes from a damping controller that will be designed for the SSSC in the next section to achieve stability improvement. Whenever the damping controller is used, the subtraction of Xref and Xax, instead of only Xref, is multiplied by the current magnitude |ITL| to obtain required voltage magnitude $V_{se,ref}$.

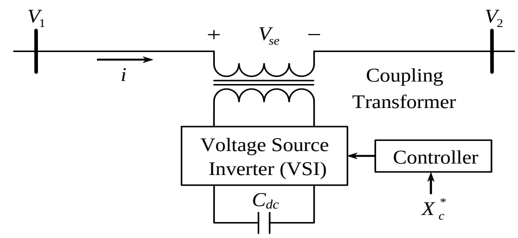



***Figure 3.*** *Basic configuration of a SSSC*

## 3. Design ANFIS Controller For SSSC

For the design of the ANFIS controller, the rotor speed deviation at PCC bus ($\Delta\omega_r$) and its derivative ($d(\Delta\omega_r)/dt$) are fed to the ANFIS to generate the additional signal to the control scheme of the SSSC as shown in Figure 4 with the structure of ANFIS depicted in Figure 5 and the rules are given as follows:

If ($x = A_i$) and ($y = B_i$) then ($f_i = p_i x + q_i y + r_i$) (4)

where *x* and *y* are the inputs, and $A_i$, $B_i$ are the fuzzy sets, $f_i$ are the outputs within the fuzzy region specified by the fuzzy rule, and $p_i$, $q_i$ and $r_i$ are the designed parameters that are determined during the training process, and *i* is the number of membership functions of each input [11].

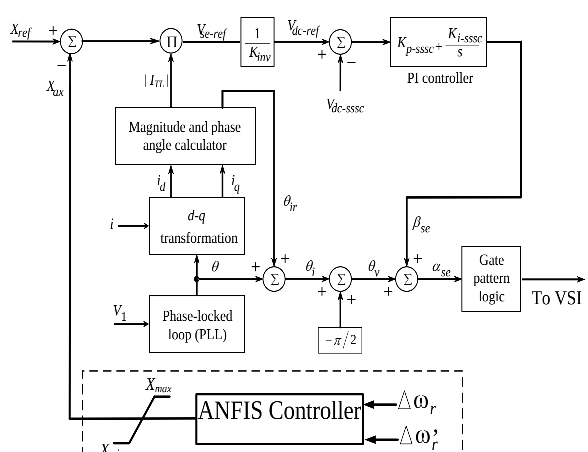



***Figure 4.*** *Control block diagram of a SSSC including the ANFIS controller*

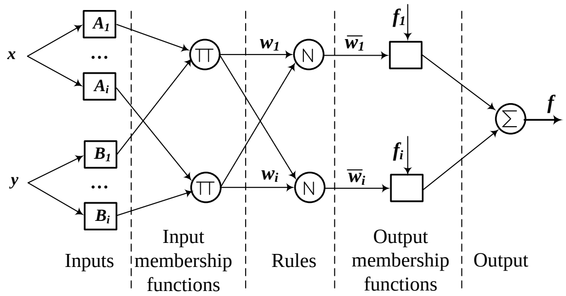



***Figure 5.** Structure of an ANFIS model*

In this paper, five linguistic variables for each input variable and seven linguistic variables for output variable are defined.

By using the ANFIS toolbox in MATLAB with the type of membership function, the number of epochs, and the learning algorithm are chosen as Gauss, 30, and Hybrid learning, respectively.

## 4. Time Domain Simulation

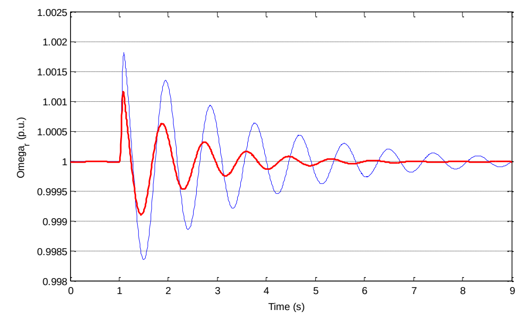
This section utilizes the nonlinear system model to compare the damping characteristics contributed by the proposed SSSC joined with the designed damping controller under a disturbance condition. It is assumed that the studied system is operated under the same selected nominal operating conditions used in Table 1. The simulation results in this section are performed by applying MATLAB/SIMULINK toolbox.

***Table 1.** Employed system parameters*

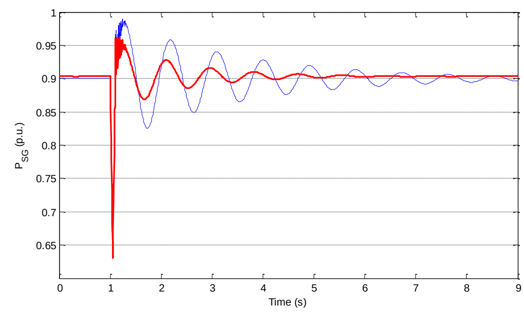
| System bases |
|---|
| $V_{base}$ = 15/115 kV, $S_{base}$ = 40 MVA, $\omega_{base} = 2\pi f_{base}$, $f_{base}$ = 50 Hz |
| Single SG with thyristor excitation system |
| $S$ = 40 MVA, $V$ = 11 kV, $PF$ = 0.975 lagging<br>$X_d$'' = 0.23 pu, $X_d$' = 0.2995 pu, $X_d$ = 0.8979 pu, $X_q$'' = 0.2847 pu<br>$X_q$' = 0.646 pu, $X_q$ = 0.646 pu, $X_l$ = 0.2396 pu, $\tau_{do}$' = 7.4 s, $D$ = 2 pu<br>$K_A$ = 200, $T_R$ = 0.01 s, $K_{stab}$ = 20, $T_W$ = 10.0 s, $T_A$ = 0.02 s<br>$T_1$ = 0.05 s, $T_2$ = 0.02 s, $T_3$ = 3.0 s, $T_4$ = 5.4 s, $T_B$ = 10.0 s<br>$R_{SG}$ = 0 pu, $X_{SG}$ = 0.0012 pu |
| SSSC with its control system |
| $S$ = 25 MVA, $V$ = 110 kV, $f$ = 50 Hz<br>$R$ = 0.01 pu, $L$ = 0.2 pu, $V_{dc}$ = 40 kV, $C_{dc}$ = 175 μF<br>$K_{p\text{-}sssc}$ = 0.0015 , $K_{i\text{-}sssc}$ = 0.15 |

The following transient responses of the studied system with the proposed SSSC without and with the designed ANFIS controller are plotted in the blue lines and red lines respectively when a severe three-phase short-circuit fault happen at Ha Tien bus. In this case, the fault suddenly happens at $t$ = 1 s and is cleared after five cycles.

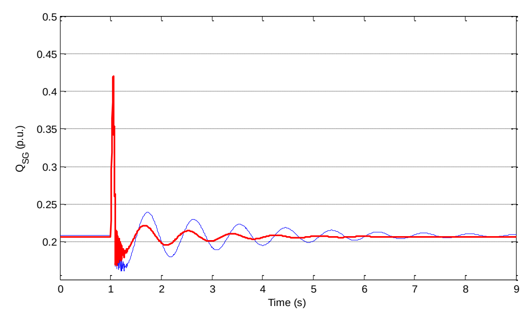
As shown in Figure 6, rotor speed, active and reactive power of the SG are respectively presented in Figures 6(a), 6(b) and 6(c). It is clearly observed from these comparative transient simulation results that the proposed SCCC with the designed ANFIS controller can offer better damping to the SG. Furthermore, the voltage profile of PCC (Figure 6(d)) and SSSC (Figure 6(e)) also show the improvement of the oscillation when the ANFIS controller is proposed.



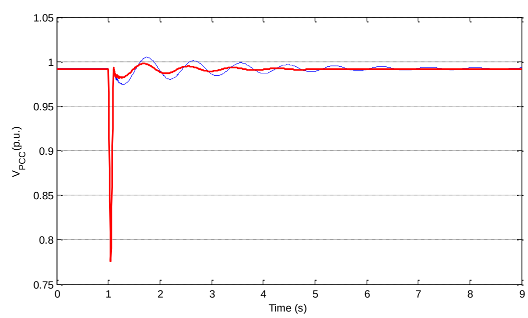

*(a) Rotor speed of SG*



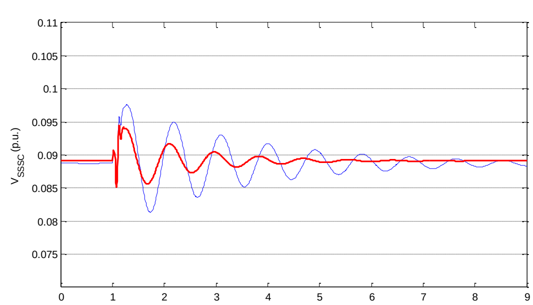

*(b) Active power of SG*




*(c) Reactive power of SG*




*(d) Voltage at PCC*




*(e) Active power of SG*

***Figure 6.** Comparative responses of the studied system*

## 5. Conclusions

This paper has presented the stability improvement of an Ha Tien - Phu Quoc power system. The proposed SSSC is connected in series with the transmission line. An ANFIS controller is designed. Time-domain simulations of the studied system subject to a severe fault at the connected bus have been systematically performed to demonstrate the effectiveness of the studied system. It can be concluded from the simulation results that the proposed SSSC joined with the designed controller has better damping characteristics to improve the performance of the system.

## REFERENCES


[1] L. Gyugyi, C. D. Schauder, and K. K. Sen, "Static synchronous series compensator: A solid-state approach to series compensation of transmission lines", *IEEE Trans. Power Delivery*, vol. 12, no. 1, pp. 406-417, Jan. 1997.

[2] S. Jiang, A. M. Gole, U. D. Annakkage, and D. A. Jacobson, "Damping performance analysis of IPFC and UPFC controllers using validated small-signal models", *IEEE Trans. Power Delivery*, vol. 26, no. 1, pp. 446-454, Jan. 2011.

[3] H. F. Wang, "Design of SSSC damping controller to improve power system oscillation stability", in *Proc. IEEE AFRICON*, 28 Sep.-01 Nov. 1999, Capetown, South Africa, vol. 1, pp. 495-500.

[4] K. K. Sen, "SSSC-Static synchronous series compensator: Theory, modeling, and applications", *IEEE Trans. Power Delivery*, vol. 13, no. 1, pp. 241-245, Jan. 1998.

[5] D.-N. Truong and L. Wang, "Application of a static synchronous series compensator to improve stability of a SG-based power system with an offshore wind farm", in *Proc. 2012 IEEE PES General Meeting*, 22-26 Jul. 2012, San Diego, CA, USA.

[6] J.-S. R. Jang, "ANFIS: adaptive-network-based fuzzy inference system", IEEE Transactions on Systems Man and Cybernetics, vol. 23, no. 3, pp. 665-685, May/June 1993.

[7] P. Kundur, *Power System Stability and Control*, New York: McGraw-Hill, 1994.

[8] IEEE, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE Standard 421.5-2005, Dec. 2005.

[9] G. N. Pillai, A. Ghosh, and A. Joshi, "Torsional oscillation studies in an SSSC compensated power system", *Electric Power System Research*, vol. 55, no. 1, pp. 57-64, Jul. 2000.

[10] A. C. Pradhan and P. W. Lehn, "Frequency-domain analysis of the static synchronous series compensator", *IEEE Trans. Power Delivery*, vol. 21, no. 1, pp. 440-449, Jan. 2006.

[11] L. Wang and D. N. Truong, "Stability Enhancement of a Power System With a PMSG-Based and a DFIG-Based Offshore Wind Farm Using a SVC With an Adaptive-Network-Based Fuzzy Inference System," in IEEE Transactions on Industrial Electronics, vol. 60, no. 7, pp. 2799-2807, July 2013.


*(The Board of Editors received the paper on 13/09/2017, its review was completed on 18/10/2017)*