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Neuro Fuzzy based SSSC for Active and Reactive Power Control in AC Lines with Reduced Oscillation

***Abstract**. The FACTS (Flexible AC Transmission System) devices have been considered as excellent controllers in a power system for better reliability and transmission capacity on a long-term and cost-effective basis. The static synchronous series compensator (SSSC) is one of robust FACTS devices that can control the flow of power in AC lines. In this paper, modelling and simulation of active and reactive power flow control in transmission lines and voltage control using SSSC with adaptive neuro-fuzzy logic is proposed. The mathematical model of SSSC in power flow is also proposed. The results show the ability of SSSC to control the flow of power in the AC lines of power system within line voltage limitations.*

*Streszczenie. Przedstawiono modelowanie i symulację sterowania przepływem mocy czynnej I biernej przy wykorzystaniu SSSC (synchroniczne kompensatory szeregowe) oraz zastosowaniu adaptacyjnej logiki neuro-fuzzy. Przedstawiono model matematyczny systemu SSSC. (**System SSSC do sterowania przepływem mocy czynnej I biernej z wykorzystaniem logiki neuro-fuzzy**)*

Keywords: Power control, FACTS, SSSC, ANFIS.
Słowa kluczowe: FACTS, SSSC, sterowanie mocą bierną
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Introduction

A vast growth of demand for modern industrial technology and load voltage instability of power system has become a serious menace to the stability of the system. In such cases, it is very important to enhance the power system stability but that become very complex [1]. In general, FACTS devices are faster and more effective oversite, to increase the carrying capacity of the AC transmission system and mitigate the abnormal operating conditions that may occur in the system using a set of advanced power-electronics based controllers and systems [2]. Power electronic converter circuit with switched inductors or capacitors can be controlled directly, without producing a reactive power [3]. The SSSC has been developed as a new FACTS generation of improved performance compared with the conventional capacitor based on the series compensators [4]. SSSC is a voltage source inverter, which produces a controllable AC voltage source connected in series to AC lines in a power system. The injected voltage is in quadrature with the line current and effects as an inductive or a capacitive reactance so as to influence the power flow in the transmission lines [5]. The SSSC injects a controllable voltage over an identical and inductive range, independent of the magnitude of the line current to maintain the transmission power of the interconnected systems. The SSSC connected in series with the transmission line through boosting transformer as shown in Figure 1. When the injected voltage is kept in quadrature with the line current, it effects as inductive or capacitive reactance so as to regulate the power flow through the transmission line, and when the injected voltage is kept in quadrature with the voltage (phase voltage), it effects as phase angle regulator. VSC generates six-pulse voltage waveform it connected to the DC capacitor in order to maintain the desired DC level. SSSC is capable of control the flow of reactive power [6]. In recent years, new artificial intelligence approaches have been proposed to design the FACTS based power flow [7]. M.T. Alkhayyat, et al [8] compared three methods for injected voltage with unbalanced current compensation in addition to the harmonic's minimization and reactive power compensation using UPQC. Amidaddin Shahriar et al [9] proposed a steady state model for interline power flow controller in order to controlling active and reactive power separately. A. Ajami and S.H. Hosseini [10] uses unified power flow controller UPFC for current balancing and power control for one line. Using power source with FACTS devices rather than shunt capacitor reduces the rating of the inverter [11]. The contribution of this study is to use a SSSC controller for active and reactive power flow control in transmission lines with adaptive neuro-fuzzy logic. In this paper, SSSC acts as a reactive compensator. This done by injection the voltage in quadrature with respect to the line current. The results show the ability of SSSC to control the flow of active and reactive power in the controlled line and thus the overall power coordinate between the AC lines.

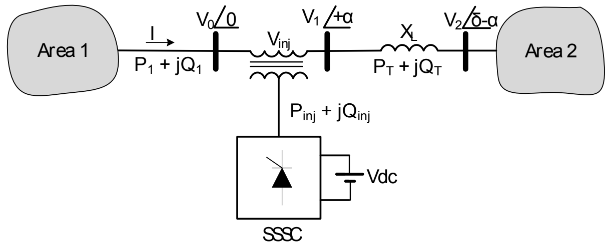

Fig. 1. SSSC with transmission line system

Modelling and control of SSSC

SSSC converter can be considered as a controllable voltage source. Figure 2 represents the principle of the quadrature injected voltage with respect to the line current. The ideal series voltages source equations of the SSSC is:

$$V_{inj} = |V_{inj}| < \beta \quad (1)$$

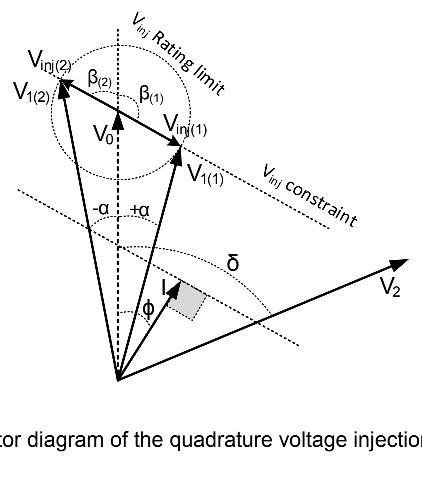

Fig. 2. Vector diagram of the quadrature voltage injection

The phase angle of the injected voltage (β) is varied so that the injected voltage kept in quadrature to the line current.

SSSC operating modes

SSSC operates by adding a controlled voltage of variable magnitude and phase angle at the power system frequency (V_{inj}) in two modes reactive compensation mode and load angle. The control mode depending on reference signal line current or phase voltage [12]. SSSC is controlling the phase angle "load angle" between sending end and receiving ends of the AC line [13]. The "active and reactive power flow" can be regulated between the two ends of the transmission system by controlling the magnitude of the injected voltage and its phase angle. The active and reactive power flow in controlled AC line after inject the controllable voltage (V_{inj}) are:

(2) $$P_{inj} = \frac{V_1 V_{inj}}{X} sin(\delta \pm \alpha)$$

(3) $$Q_{inj} = \frac{{V_1}^2}{X} - \frac{V_1 V_{inj}}{X} cos(\delta \pm \alpha)$$

where: V_1 – controlled bus voltage, β – phase angle of the injected voltage, V_{inj} – injected voltage, X – reactance of the boosting transformer.

According to equations 2 and 3 four quadrants control regions can be achieved as shown in Figure 3.

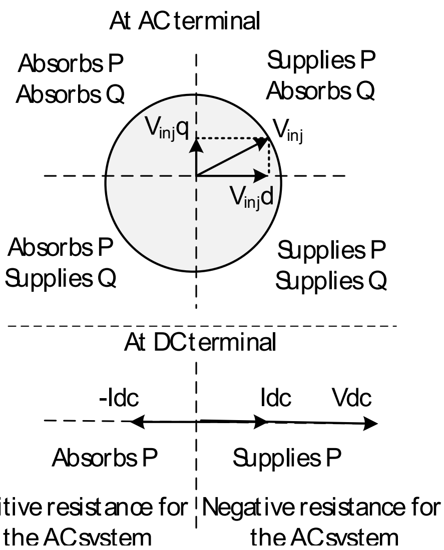

Fig. 3. SSSC operating modes

The SSSC injects a controllable voltage so that the active and reactive power add or subtract with the power flow in the control transmission line. The regulated powers can be obtained with any desired quantity within a rating limit.

The injected voltage consists of quasi sinusoidal controllable voltage (depending on the frequency of switching devices and configuration of the inverter) with variable amplitude [14]. SSSC can operate as a phase shift regulator and can provide either capacitive or inductive voltage compensation [15]. The main part of SSSC is the voltage source inverter VSI with the DC link energized by DC source. The injected voltage Vs has two parameters the amplitude ($0<V_S<V_{Smax}$) and phase angle ($0< \beta <360^{\circ}$).
The total "active and reactive power" in transmission line 2 are:

(4) $$P_T = P_1 \pm P_{inj}$$

(5) $$Q_T = Q_1 \pm Q_{inj}$$

where: P_{inj} – injected active power, Q_{inj} – injected reactive power.

Depending on Eq. 4 and 5, the active and reactive power can be regulated by adding or subtracting the injection powers.

Injected voltage measurement

The d-q theory was applied to measure the power components (active & reactive). It is based on time-domain also valid for the operating system in both steady-state and transient and can apply for generic waveforms of current and voltage in power system [16]. The simplicity of calculations is another advantage of this theory, which includes algebraic calculation except the required for separating the alternated and mean values of power components calculation [17]. The d-q theory implements "park transformation" to transform the abc coordinates (stationary reference) to rotating coordinates or dq coordinates [18]. The transformation is applied for voltages and currents in the time domain as follows:

(6)
$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

(7)
$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos\left(\emptyset + \frac{2\pi}{3}\right) \\ -\sin(\emptyset) & -\sin\left(\emptyset - \frac{2\pi}{3}\right) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

(8) $$\emptyset = (\omega t + \varphi)$$

where: $\emptyset$ – phase shift between the rotating and fixed coordinates with respect to time, φ– phase shift between the voltage and line current. Two compensated power components can be calculated by:

(9) $$p = V_d I_d + V_q I_q$$

The injected voltage:

(10) $$V_{inj} = \sqrt{{V_{injd}}^2 + {V_{injq}}^2}$$

Control scheme of compensator

Figure 4 shows the control scheme of the compensator.

The voltages (three phase) are measured with low pass filter for eliminating the noise "high-frequency components" then the injected voltage calculated using the equations (9) and (10). From the system, this measured signal works as input to the closed-loop control (as feedback). The desired reference values of voltage V_{ref} is compared with the calculated values of measured values for generating error signals $Error_V$. This signal is processed in the controller where:

(11) $$Erorr_V = V_{ref} - V_{inj}$$

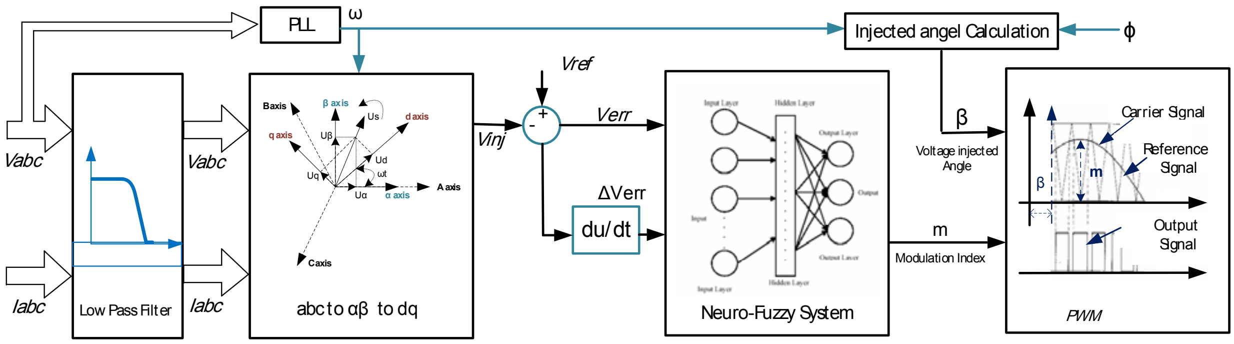

Fig. 4. ANFIS based SSSC Control scheme

A combination of the fuzzy logic with adaptive learning can be trained easily and don't need high experience for knowledge as required in the conventional Mamdani-fuzzy logic [19]. With ANN learning algorithm, the rule-base can be reduced. The parameters of input and output "membership functions" MF are to be specified through the period of training. A designed ANFIS controller consists of five-layers. Each layer has constant nodes (no need to tune) or variable node (need to tune) through training period.

Figure 5 shows the validation test. The vector's inputs are error of V and Δ error of V, the output m "modulation index". Figures 6 shows the validation surface of the Fuzzy logic system.

The ANN algorithm function is to adjusting the parameters of the membership functions of output and input so that the output of Neuro-Fuzzy best matching the data of training [20].

In this work. The inputs are split into five trapezoidal membership functions" with overlapping of 50%, so, the two vector inputs a "25-control rule resultant linear functions

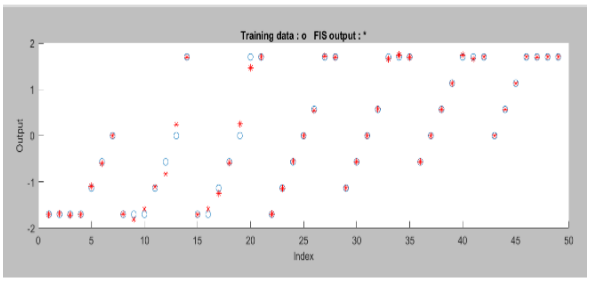

Fig. 5. Neuro-fuzzy logic validation test

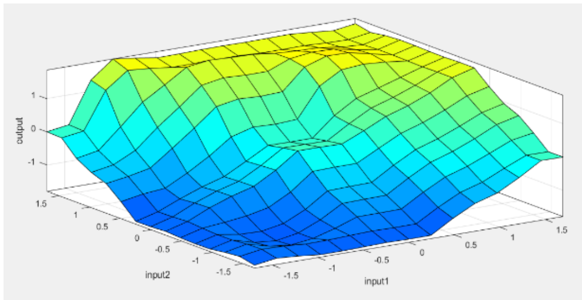

Fig. 6. Neuro-fuzzy logic validation surface

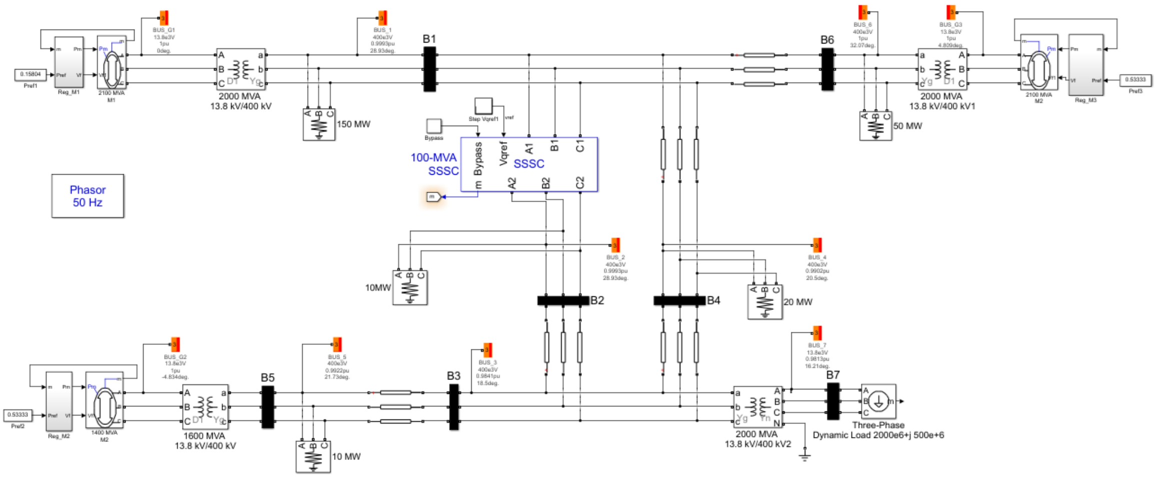

Fig. 7. Ten-bus system with SSSC

Simulation results

The Ten-bus power system consisting of three generators as shown in Figure 7. SSSC installed in transmission line at bus 2 for controlling the flow of active and reactive powers. The compensator is provided with a DC voltage source which helps in absorbing or feeding the reactive or active power.

As shown in Figure 8, the test start by step changing the injected voltage of SSSC at time equal 2 sec. The compensation process done by inject a voltage (V_{inj}) which was make in quadrature to the line current.

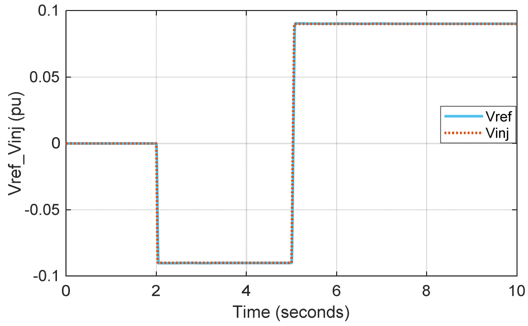

Fig. 8. SSSC injected voltage

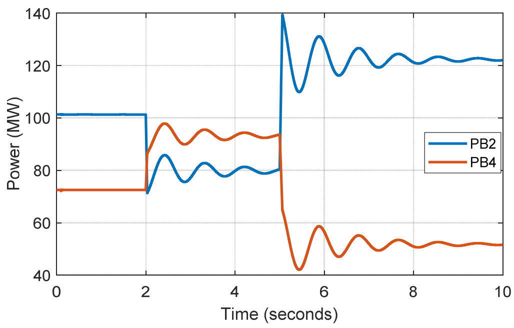

Fig. 9. Active power variation with SSSC

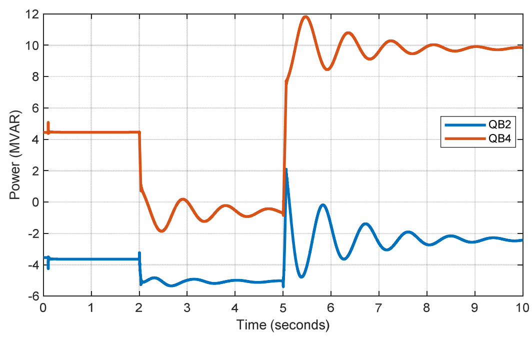

Fig.10. Reactive power variation with SSSC

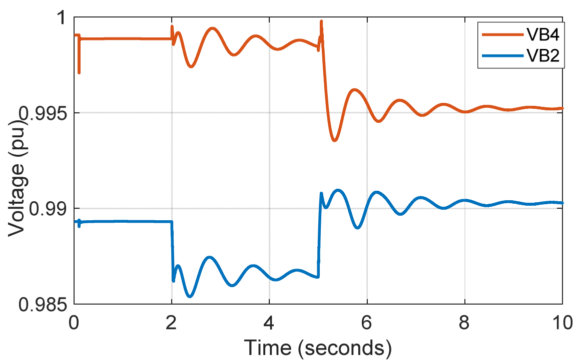

Fig. 11. Change in voltage with SSSC

As shown in Figure 9, at time equal 2 sec, active power is changed from 100MW to 80 MW at bus2. At time equal 4 sec the injected voltage is rotated 180 degree (refer to the vector diagram shown in Figure2) so that the load angle increased. Based on equation 2, active power changed from 80MW to 120 MW at bus2. In the same times, active power in bus 4 changed from 75MW to 90 MW then reduced to 50 MW respectively (two parallel lines). Reactive power variations in bus 2 and 4 are depicted in Figure 10. Figures 11 and 12 show the change in bus voltages and line currents after the instance of voltage injection respectively

Figure 13 shows the step change response of the system to the active power. From this figure, it is clear that the new controller design (Neuro-Fuzzy controller) has a smoother response and also faster than the conventional PI controller to reaches the steady state.

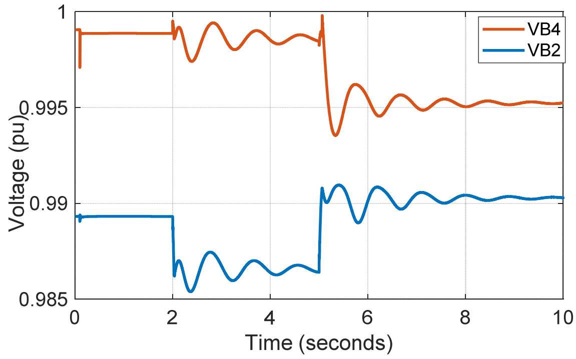

Fig. 12. Change in current with SSSC

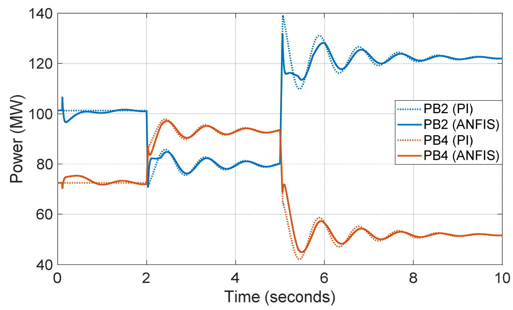

Fig.13. Power oscillation enhancement with ANFIS

Conclusion

In this study, Neuro-Fuzzy logic controller based SSSC for power flow control has been modelled and simulated. The amplitude and the phase angle of the injected voltage can be adjusted by SSSC so that they can inject the controllable voltage that can regulate the active and reactive power and then controlling the powers through the parallel transmission lines. A Neuro-fuzzy logic controller was designed to enhance the performance response of the SSSC. Simulation results show that the significant management of the powers "active and reactive" in parallel lines is obtained by dividing the whole power between the parallel transmission lines.

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