Active and reactive power flow management in parallel transmission lines using static series compensation (SSC) with energy storage

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ABSTRACT

The power flow controlled in the electric power network is one of the main factors that affected the modern power systems development. The Static Series Compensatior with storage energy, is a FACTS powerful device that can control the active power flow control of multiple transmission lines branches. In this paper, a simulation model of power control using static series compensator with parallel transmission lines is presented. The control system using adaptive neuro-fuzzy logic is proposed. The results show the ability of static series compensator with storage energy to control the flow of powers components "active and reactive power" in the controlled line and thus the overall power regulated between lines.

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1. INTRODUCTION

The power flow control importance has become more evident with deregulation and competitive environment in the power networks. Deregulation is the opening up of a service or product to competition. This permits the end customers to select their service of energy provider [1]. The flow of active and reactive power in an interconnected system, that transfer through the transmission lines are governed by the magnitude of the sending and receiving end voltages and phase angle between these two end voltages and inductance of the line [2]. The limits of power transfer in the transmission lines can be specified by three main aspects [3]:

a. Uncontrolled the level of power flow.
b. The level of Stability and this is due to the limitation imposed by the regulations for a secure and the dynamical stable of power transfer.
c. Thermal limit due to transmission line physical limitation.

At a particular time, there are a certain power flow amount and direction that needed to be increased or decreased to the desired level and desired paths depending on the consumer demand. At this instance, the ability for controlling the flow of power is important. Usually, this is implemented by mechanically controlled devices, like tap changer, phase shifting transformers, capacitors and inductors banks. However, the disadvantage of these devices are slow response reaction that needed during disturbances. The development in power electronics switching devices have providing a faster response compared to the conventional the mechanical types, and also needs less maintenance [4]. The FACTS (Flexible AC

Transmission System) devices development has started with the growing capabilities of power electronic devices for high power ratings been made available in converters with low switching losses.

FACTS devices can be divided into 2-groups which are converter and Non- converter based FACTS controller. Non-Converter type is contain Thyristor-controlled series capacitor (TCSC) and Static Var compensator (SVC) which have of absorbing or generating reactive power with use the ac reactors and capacitors. While Converter FACTS group contain SSC, STATCOM, IPFC and UPFC these devices capability of independently controls the reactive and also active power flow in the line [5]. The transmitted power through the line is a function of the, the sending and receiving end voltages magnitude, phase angle (load angle) and transmission line impedance. The distributed power in transmission lines system depends on the impedance of the lines in the system. The Static Series Compensator (SSC) is a member of 2nd generation of FACTS which use the concept of synchronous voltage source converter (VSC) for giving a uniquely comprehensive ability for transmission line control [6]. The SSC with energy storage (ES) is able for controlling selectively or simultaneously all the effecting parameters to the power flow in the transmission system. Alternatively, SSC able to control independently flow of both active power and reactive power in controlled transmission line [7]. SSC is series connected with a transmission line and construct of a three phase bridge inverter which is controlled by the SSC controller to inject a three-phase synchronous voltage [8]. SSC operates by adding a controlled voltage of variable magnitude and phase angle at the power system frequency (V_{pq}) as shown in Figure 1. SSC can operate in two modes *reactive compensation* and *load angle control* depending on the reference signal line current or phase voltage [9]. In this paper SSC operate as a load angle control by taking the phase voltage as a reference for injection, this done by kept the injected voltage phase angle (γ) in quadrature phase shift with the system phase voltage instead of the current. Consequently, SSC is control the phase angle "load angle" between sending end and receiving ends of transmission system. The active and reactive power flow can be regulated between the two ends of transmission system by controlling SSC injected voltage magnitude and phase angle:

$$V_{pq}=|V_{pq}|<\pm\gamma \quad (1)$$

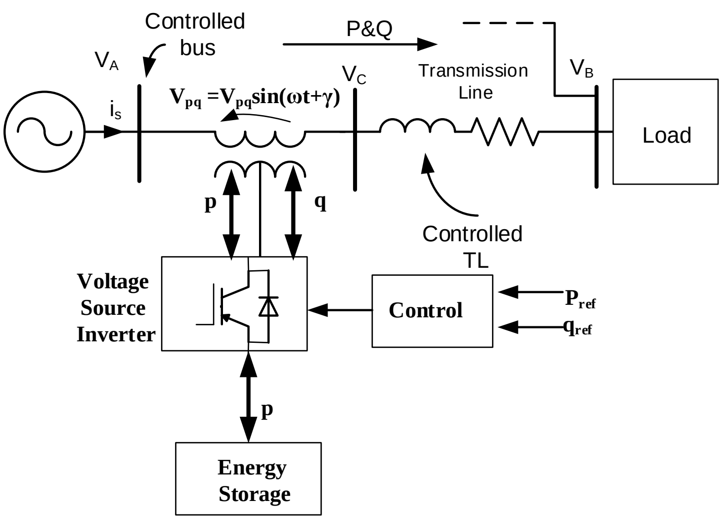


Figure 1. Schematic diagram of SSC and the phasor diagram of injected voltage

From Figure 1, the active and reactive power flow in controlled transmission system after inject the controllable voltage (V_{pq}):

$$p = \frac{V_C V_B}{X}\sin(\delta \pm \gamma) \quad (2)$$

And:

$$q = \frac{{V_C}^2}{X} - \frac{V_C V_B}{X}\cos(\delta \pm \gamma) \quad (3)$$

Where V_C is the controlled bus voltage and γ the phase angle of the injected voltage, V_B is the receiving end voltage and X is the reactance of transmission line. Figure 2 shows, connect of SSC in series with the one of parallel transmission. The SSC in inject a controllable voltage so that the active and reactive power add or subtract with the power flow in the control transmission line and. The regulated line powers can be achieved with any proportions wanted.

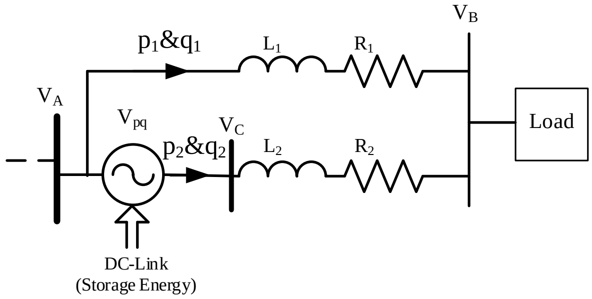


Figure 2. Inserting SSC with SE in transmission line

2. MODELLING AND CONTROL

SSC SSC injects a sinusoidal controllable voltage (depending on frequency of switching devices and configuration of the inverter) with variable amplitude [10]. SSC able to operate in phase shift regulator and emulate as a controller of power flow [11]. VSI (Voltage Source Inverter) is SSC heart that is feeded from an energy storage "external DC link", the SSC voltage V_{pq} has 2-parameters the amplitude ($0<V_{pq}<V_{pqmax}$ and phase angle ($0<\gamma<360^0$) as shown in Figure 3. Addition active and reactive power.

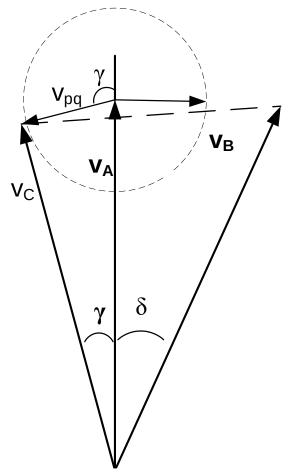


Figure 3. Vector diagram

$$p_{pq}=\frac{v_{pq}v_A}{X}\sin(\gamma) \quad (4)$$

$$q_{pq}=\frac{v_A}{X}-\frac{v_{pq}}{X}cos(\gamma) \quad (5)$$

The total active and reactive power in transmission line 2 are:

$$p_T = p_2 \pm p_{pq} \quad (6)$$

$$q_T = q_2 \pm q_{pq} \quad (7)$$

Depending on (6) and (7) the active and reactive power can be regulated by adding or subtracting the injection powers.

3. ACTIVE AND REACTIVE POWER MEASURIMENT

D-q theory was applied for measuring power components (active power & reactive power). It is based on "time-domain" also valid for operating system in "steady-state"' and in "transient state", and can applied for generic waveforms of current and voltage in power system [12]. The simplicity calculations is another advantage of this theory, which include algebraic calculation in except the required for separating the alternated and mean values of power components calculation [13]. The d-q theory implements “park transformation” to transform the *abc* coordinates (stationary coordinate) to (the rotating coordinates) or *dq* coordinates [14]. These transformation is utilized for currents and voltages in time domain as a standard frame this mean (va, vb and vc) is as follows:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos\left(\emptyset + \frac{2\pi}{3}\right) \\ -\sin(\emptyset) & -\sin\left(\emptyset - \frac{2\pi}{3}\right) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{9}$$

$$\emptyset = (\omega t + \theta) \tag{10}$$

Where ($\emptyset$) is the phase shift between the rotating and fixed coordinates in time domain, also (θ) is phase shift between the voltage and load current [15]. Two power components compensated can be calculated by:

$$p = V_d I_d + V_q I_q \tag{11}$$

$$q = V_d I_q - V_q I_d \tag{12}$$

4. CONTROL SCHEME OF COMPENSATOR

Figure 4 shows the control scheme of compensator. The voltages and currents (three phase) are measured and for eliminating the noise "high frequency components" the inputs are filtered then the active and reactive power calculated using park transformation (8) to (12). From the system. These measured signals in (1) and (2) work as inputs to the closed loop control (as a feedback). The desired references values of active and reactive power "p_{ref} and q_{ref}" are compared with the calculated values of measured values for generating error signals "$Error_p$ and $Error_q$". These signals are processed in the controller where:

$$Erorr_P = p_{ref} - p \tag{13}$$

$$Erorr_q = q_{ref} - q \tag{14}$$

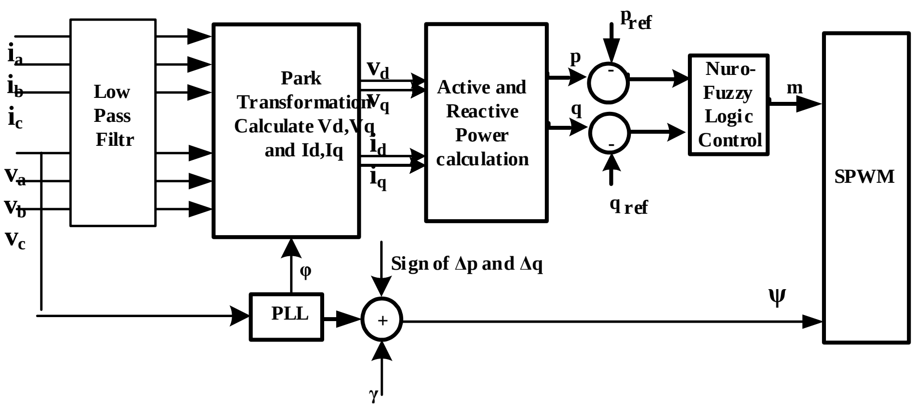


Figure 4. Block diagram for SC control system

5. NEURO-FUZZY CONTROL DESIGN

Neuro-fuzzy controller are adequate to ununcertain system, especially to the system with mathematical model difficult to derive. Neuro-fuzzy logic play an important function in many applications especially the practical [16]. Takagi-Sugeno "TS" choose in this study as inference mechanisms [17]. ANN "The Artificial Neural Network" is applied for tuning the TS-controller membership functions. TS type have variable gain "non-linear gain". TS type provide a wide gain variations [18]. The using of ANN for adapting the fuzzy system parameters which can achieved a better respons. Combine the fuzzy specific approach with adaptive learning, this type of control can be trained easily and don't need for a big expert for knowledge as required in the conventional Mamdani-fuzzy logic [19]. By using ANN learning algorithm the rule-base can be reduced. The parameters of input and output MF "membership functions" are to be specified through the period of training. ANFIS controller designed consists of 5-layers, which in each layer has constant nodes (no need to tune) or variable node (need to tune) through training period. The 5-layers outputs emulate ANFIS design procedure referring to [20]. The advantage of using ANN algorithm is for adjusting the parameters of the membership functions of output and input so that the output of Neuro-fuzzy best matching the data of training. A hybrid learning "Lease Squares Estimate-LSE and Gradient Descent-GD" is used to identify the parameters network. In this study the inputs are split to 9 trapezoidal MF "membership function with 50% overlapping", so, the two vector inputs an "81-control rule" resultant linear functions required to be determined. Validation test shown in Figure 5. To tunne the rules of TS using ANN. The vectors inputs are "E_q and E_{p}", the output m "modulation index". Figure 6 and 7 show the validation surface of Fuzzy logic system and the Fuzzy logic rules.

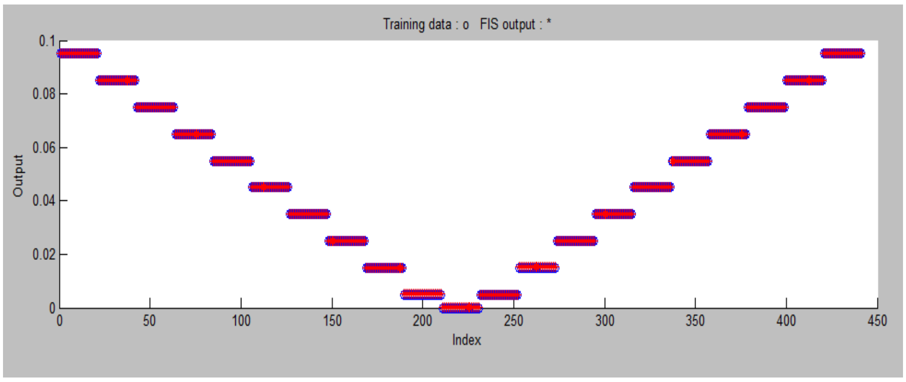


Figure 5. Fuzzy logic validation test

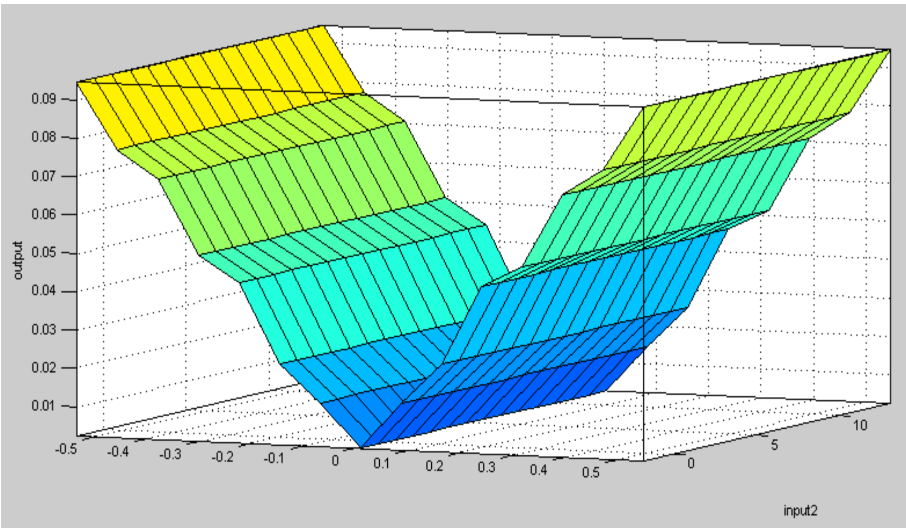


Figure 6. Neuro-fuzzy logic validation surface

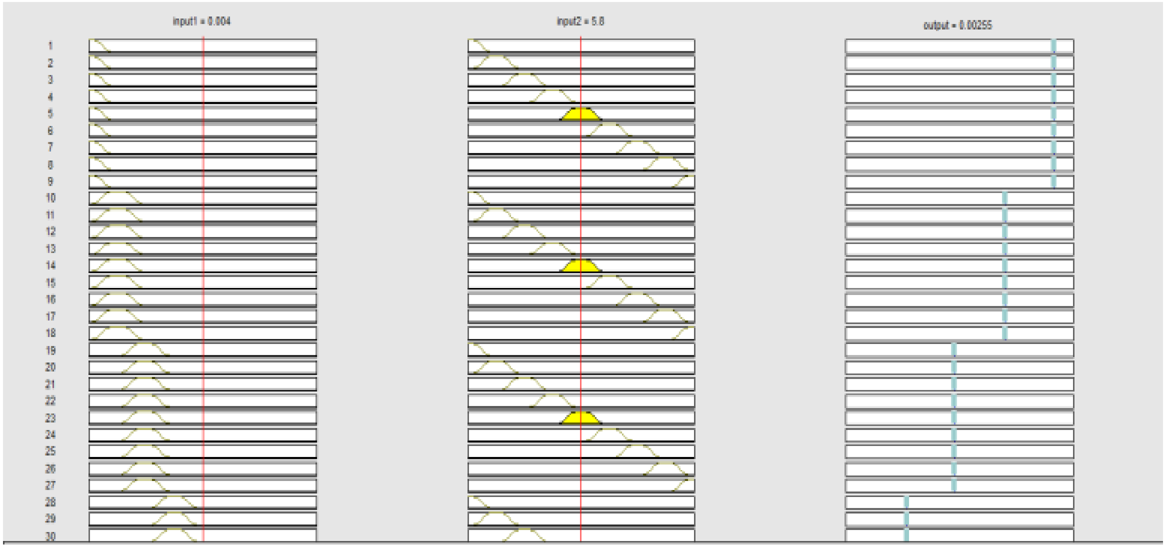


Figure 7. Neuro-fuzzy logic rules

6. SIMULATION STUDY AND RESULTS

The The system study was consists of distribution feeder with "2-branches and SSC" installed in Transmission lin-2 as shown in Figure 8, for controling 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. The simulation start by step changing the load and sensed total current and the current in both branches before compensation. Compensation process done with "inject V_{pq} controllable voltage" which was in make in quadrature to the phase voltage.

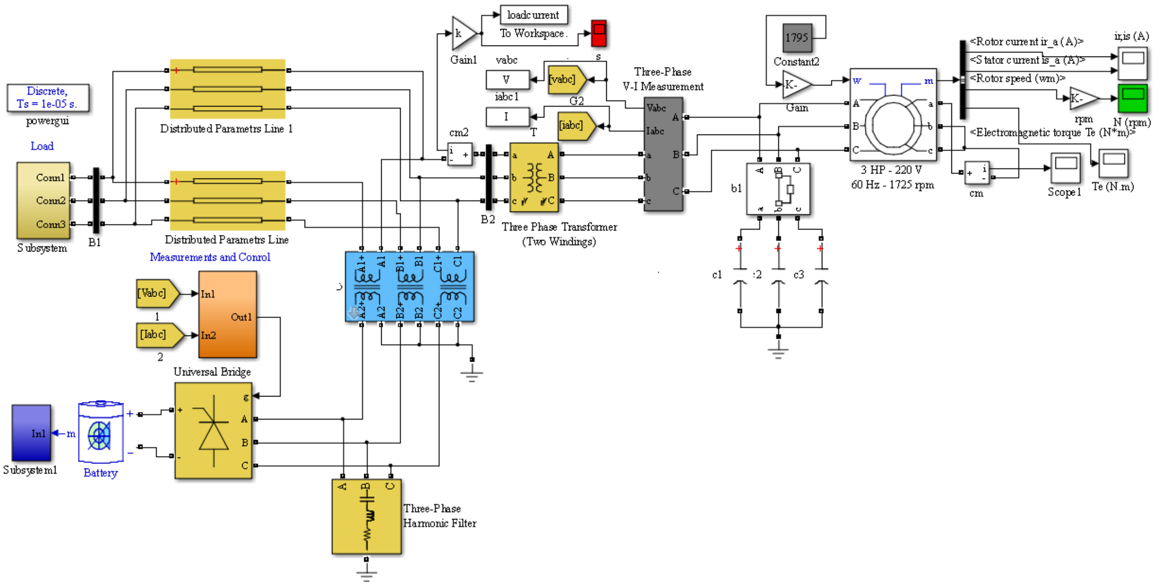


Figure 8. The test model

First the test done by "one step change" in the load, before 0.7 second the power in unbalance between the parallel transmission lines at t=0.7 second SSC inject the controllable voltage the controllable injected voltage shown in Figure 9. The line current of the parallel transmission lines shown in Figure 10, the rms values of both currents shown in Figure 11. Figure 12 and 13 show the change in active and reactive power flow after injection respectively. Figure 14 and 15 show the change in the voltage across the reactance of transmission line V_{TL} after injected the controlled voltage V_{pq}, the results show the decrease the voltage V_{TL} with the V_{pq} and then increase in current. Figure 16 and 17 show the FFT analysis of the injected voltage

V_{pq} and the load voltage after injection, its clear from the result that the total harmonic distortion THD of V_{pq} was 3.11% and the load voltage was 0.15%. Figure 18 show The Characteristic of the energy storage battery model, depending on the control system in Figure 4, the power is taken from ES and compensate the powers on the transmission line. Figure 19 shows the step change response of the system to the "active power". From the figure it is clear that the new controller design (Nuro-Fuzzy controller) has a "smoother response" and also faster than the conventional "PI controller" in reaches the steady state.

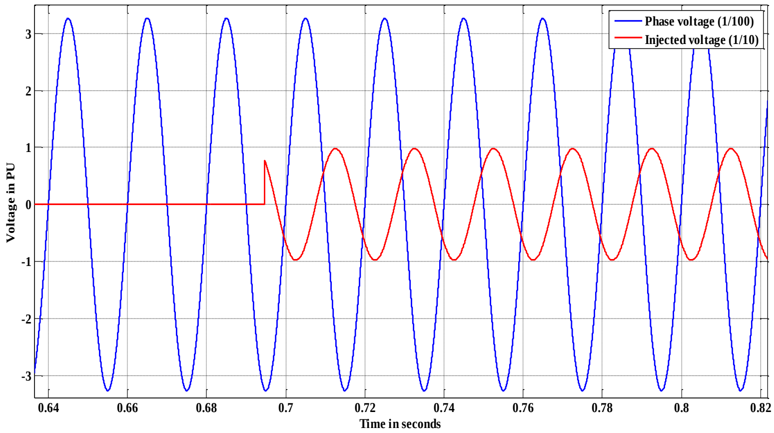
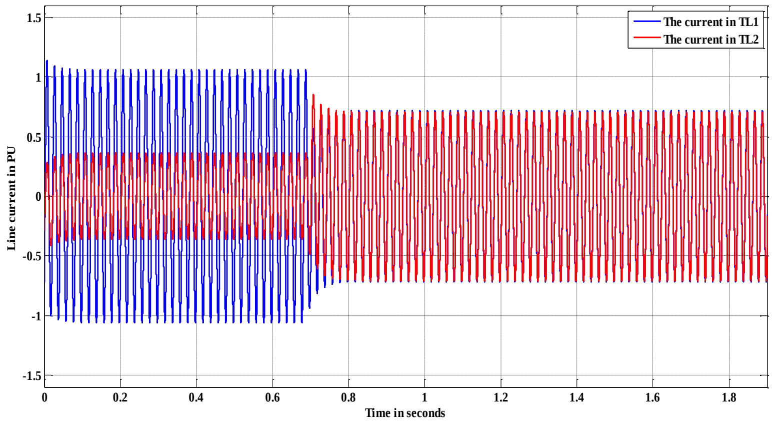
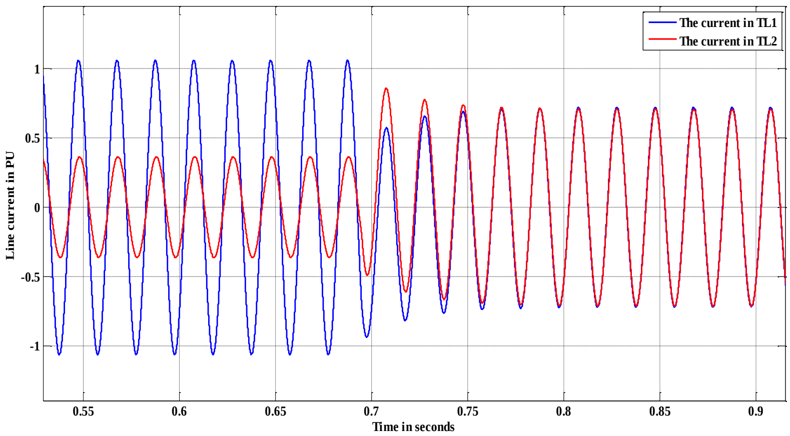


Figure 9. The simulation test



(a)



(b)

Figure 10. The currents before and after compensation, (a) line currents (b) the zooming in

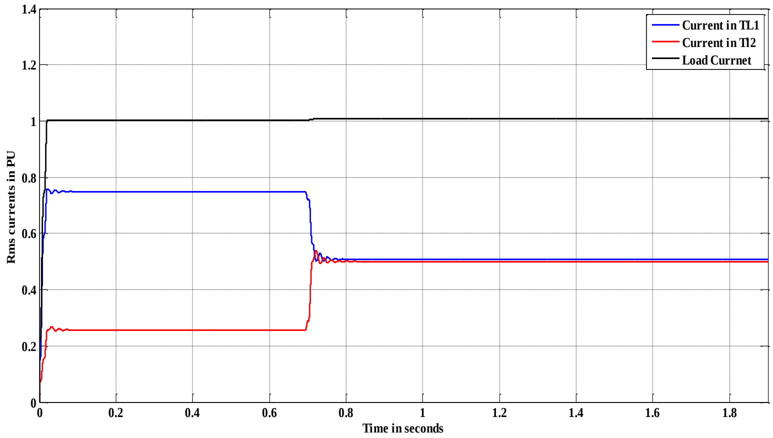


Figure 11. The rms of the line currents

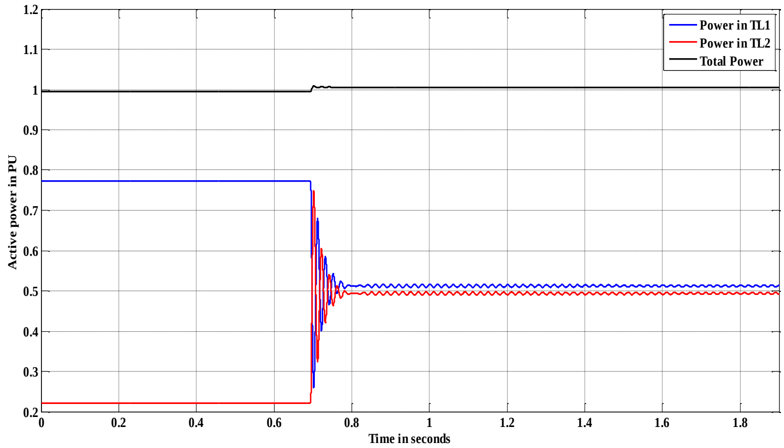


Figure 12. The active power

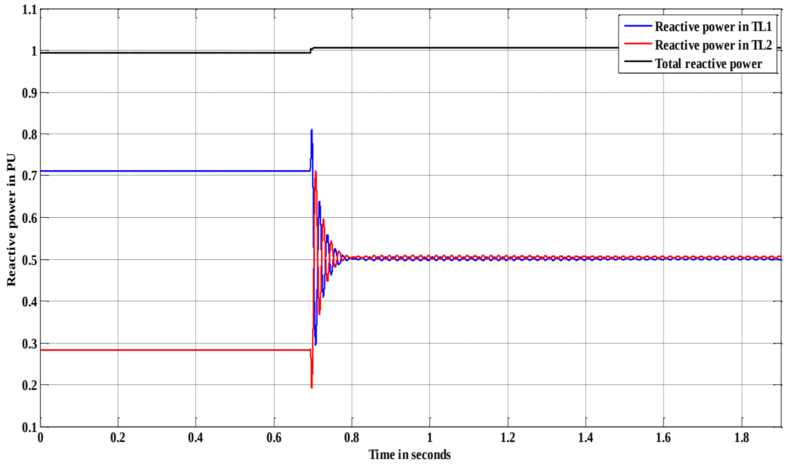
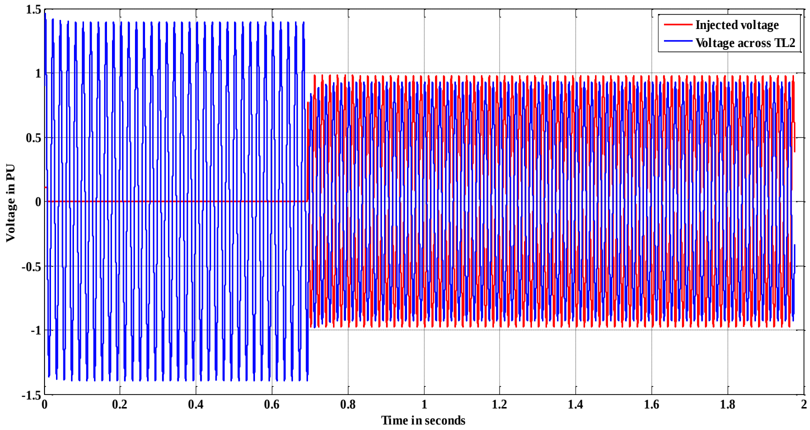
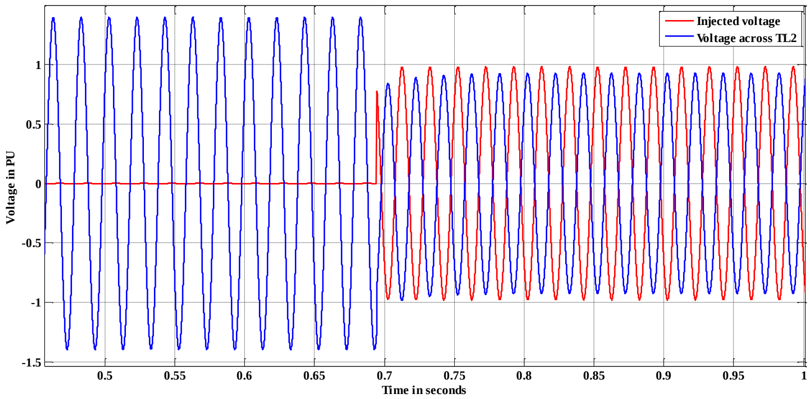


Figure 13. The reactive power



(a)



(b)

Figure 14. The voltage across the transmission line versus injected voltage (a) $V_{TL}$and V_{pq} (b) The zooming in

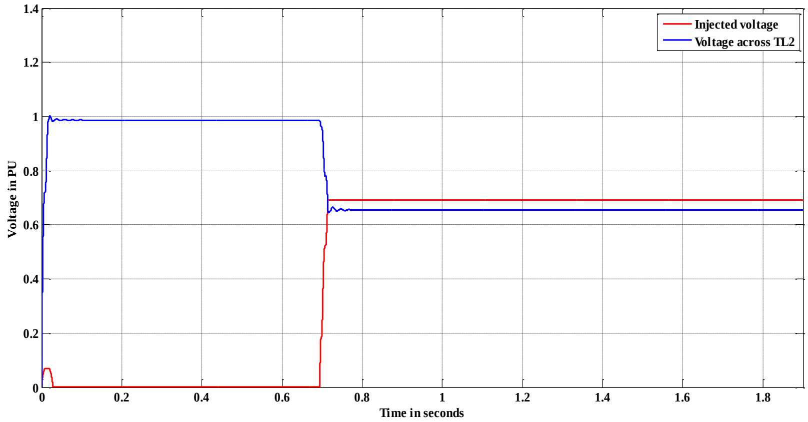


Figure 15. The rms of voltage across the transmission line and the injected voltage

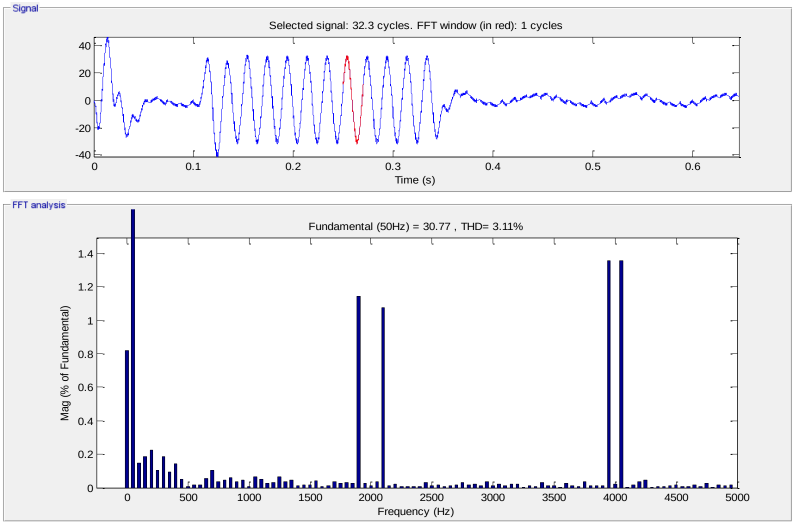


Figure 16. The FFT analysis of the injected voltage

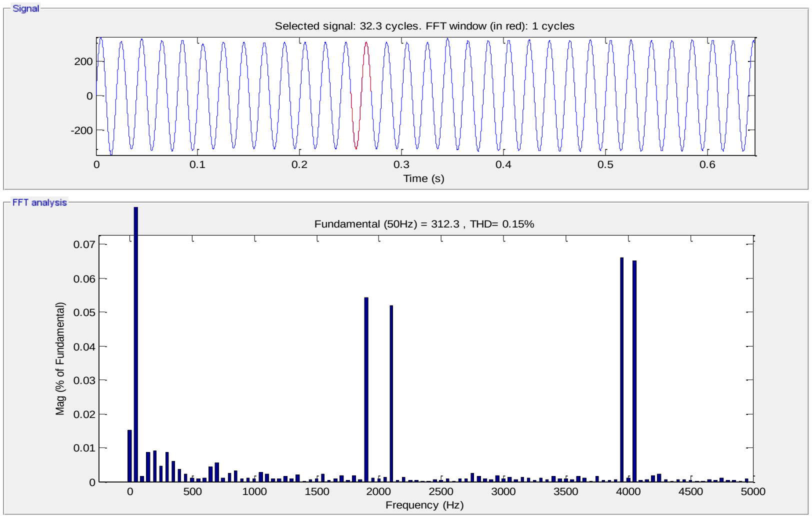


Figure 17. The FFT analysis of the load voltage

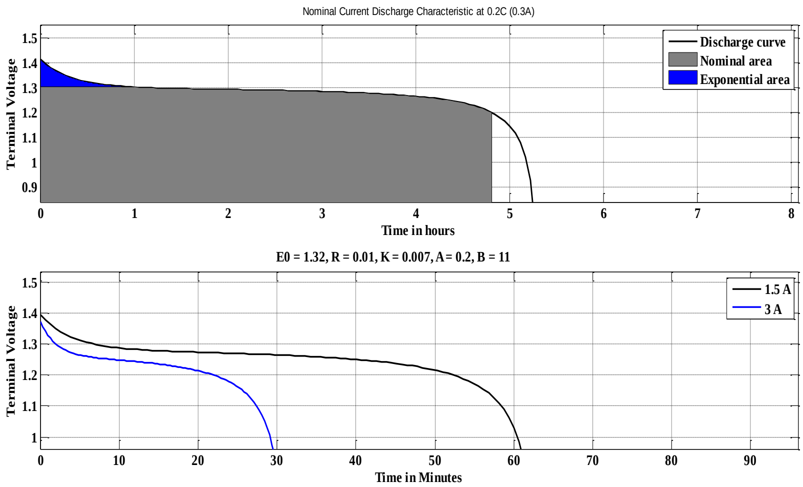


Figure 18. The characteristic of the energy storage model

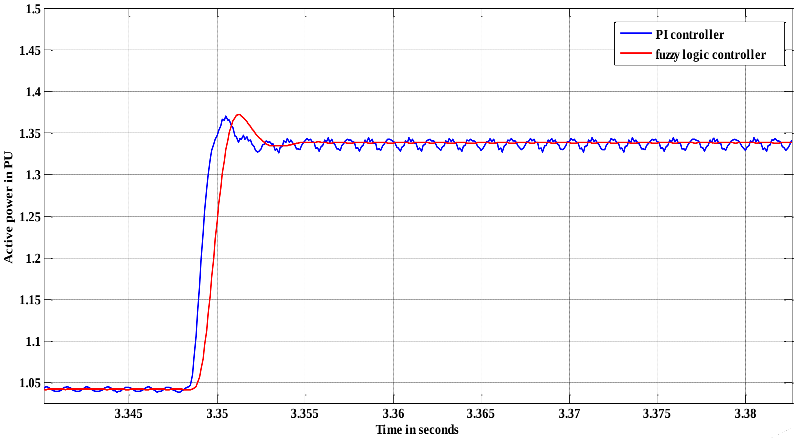


Figure 19. Active power step change

7. CONCLUSION

In this study, a modelling of parallel transmission lines and regulate the active and reactive power control using static series compensator with energy storage is presented. The amplitude and the phase angle of controllable voltage can be adjusted so that can compensate the powers components (active and reactive) and then regulates the powers through the parallel transmission lines. To control the SSC injected voltage a Neuro-fuzzy logic control was designed. Simulation results show that the signifigant management of the active and reactive power in parallel lines is obtained, the FFT of the injected voltage was 3% and the load voltage after injection was 0.15% and this result in accepted ratio also, the energy storage battery was selected to compensate the powers in the rate of about 20% of the line power. The performance of the Nuro-Fuzzy cotroller designed showed the smother and fast in response of about less than one cycle.

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