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Power flow control in parallel transmission lines based on UPFC

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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 unified power flow controller (UPFC) is a FACTS powerful device that can control both active and reactive power flow of parallel transmission lines branches. In this paper, modelling and simulation of active and reactive power flow control in parallel transmission lines using UPFC with adaptive neuro-fuzzy logic is proposed. The mathematical model of UPFC in power flow is also proposed. The results show the ability of UPFC 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 unified power flow controller (UPFC) is a universal AC transmission controller having three main functions those are real and reactive power control, reactive power compensation and voltage regulation. There are several ways to introduce and explain the concept of UPFC. These include mathematical approach, phasor diagrams, or various plots showing graphically relationships among the main transmission parameters, active and reactive power, voltage, line impedance, and transmission angle. The UPFC consists of two converters connected back-to-back, one connected in series and the other in parallel with the transmission line as shown in Figure 1. The shunt type of converter is mainly used to deliver active power demand in the series converter through a common DC link. Shunt converter generate or absorb reactive power, as desired, and thereby provide independent shunt reactive compensation for the line. The voltage with controllable magnitude and phase angle is injected in series with the line via a series converter. The UPFC injection model is derived enabling three parameters to be simultaneously controlled. They are namely the shunt reactive power, magnitude, and phase angle, of the injected series voltage Vs. “The series-connected voltage source” is modeled by an ideal series voltage Vs which is controllable in magnitude and phase. The distributed power in the transmission lines system depends on the transmission line impedance. The UPFC is a member of the 2nd generation of FACTS which uses the concept of synchronous voltage source converter (VSC) for giving a uniquely comprehensive ability for transmission line control [1].

UPFC able to control the independent flow of both active and reactive power [2]. In recent years, new artificial intelligence-based approaches have been proposed to design a FACTS-based power flow [3]. Surya Prakash and Satish Kumar [4] use IUPQC to enhance power quality as well as to exchange power from one line to the other but this system uses four converters. A. Ajami and S.H. Hosseini [5] uses UPFC for current balancing and power control for one line they used the PSCAD simulation program. M. Y. Suliman and R. K. Antar [6] used STATCOM for controlling the power in a transmission line with a neuro-fuzzy algorithm. M.A.M. Manaz, et al [7] show the ability of the control algorithm to minimize power fluctuation is justified using STATCOM like device with considerably small storage could be used at the transformer end to balance the resulting mean zero fluctuation. In [8] the authors proved that the capacity of the series converter is reduced when the series converter is placed on the substation side of the distribution system while the shunt converter is placed on the ending side. The contribution of this study is to use a unified power flow controller for balancing active and reactive power flow in parallel transmission lines with adaptive neuro-fuzzy logic. The results show the ability of UPFC to control the flow of active and reactive power in the controlled line and thus the overall power regulated between lines. Power balancing philosophy is illustrated in Figure 2.

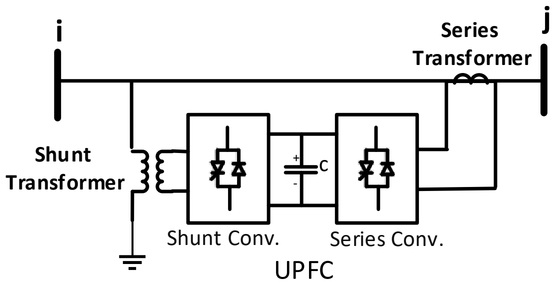

Figure 1. Basic UPFC model

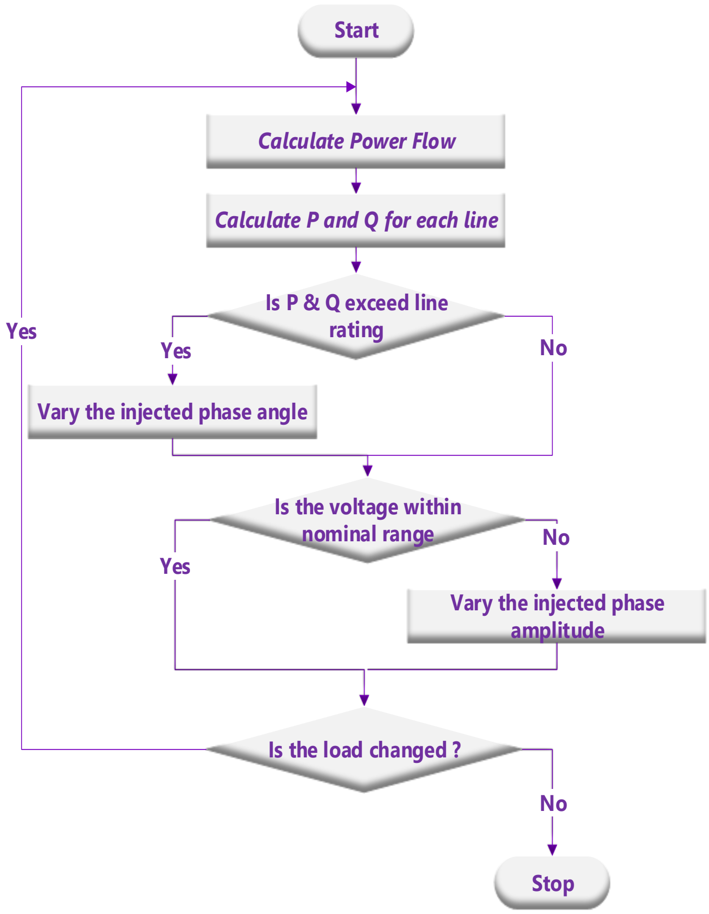

Figure 2. Power balancing philosophy

2. MODELLING OF THE UNIFIED POWER FLOW CONTROLLER

It is convenience to model the UPFC converter as a controllable voltage source is shown in Figure 3. The two ideal series and shunt voltages source equations of the UPFC are:

$$V_{se} = |V_{se}|(cos\theta_{se} + jsin\theta_{se}) \tag{1}$$

$$V_{sh} = |V_{sh}|(cos\theta_{sh} + jsin\theta_{sh}) \tag{2}$$

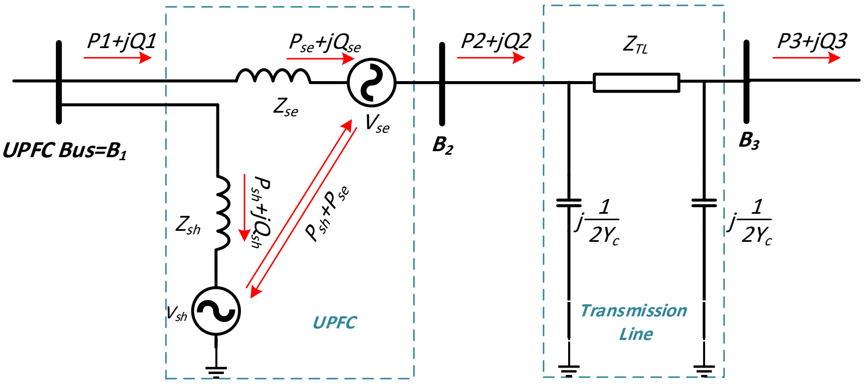

Figure 3. Voltage source model of the UPFC

UPFC operates by adding a controlled voltage of variable magnitude and phase angle at the power system frequency ($V_{injected}$) as shown in Figure 4. UPFC can operate in two modes *reactive compensation* and *load angle control* depending on the reference signal line current or phase voltage [8, 9]. In this paper UPFC operates as a load angle control by taking the phase voltage as a reference for injection, this done by kept the injected voltage phase angle (ψ) in the quadrature phase shift with the system phase voltage instead of the current. consequently, UPFC is controlling the phase angle "load angle" between sending end and receiving ends of the transmission system [10, 11]. The "active and reactive power flow" can be regulated between the two ends of the transmission system by controlling the injected voltage magnitude and phase angle:

$$V_{injected} = |V_{injected}| < \pm\psi \tag{3}$$

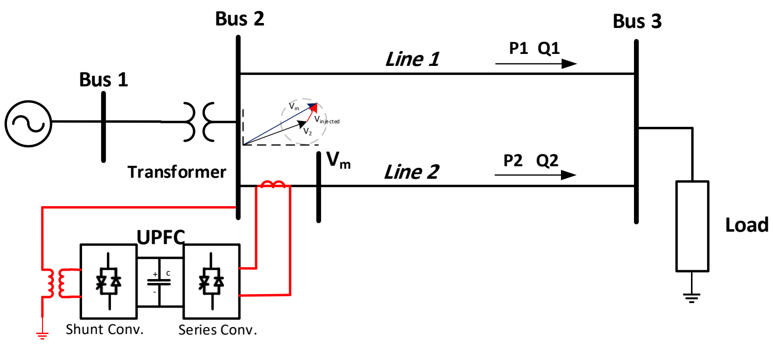

Figure 4. Schematic diagram of UPFC

From Figure 4, the active and reactive power flow in controlled transmission system after inject the controllable voltage ($V_{injected}$=V_s) are:

$$P = \frac{V_m V_3}{X}\sin(\delta \pm \psi) \tag{4}$$

and

$$Q = \frac{V_m{}^2}{X} - \frac{V_m V_3}{X}\cos(\delta \pm \psi) \quad (5)$$

Where V_m is the controlled bus voltage and ψ the phase angle of the injected voltage, V_3 is the receiving end voltage and *X* is the reactance of the transmission line. the connect of the series converter in series with the one of parallel transmission.

The UPFC injects 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. The injected voltage injects a sinusoidal controllable voltage (depending on the frequency of switching devices and configuration of the inverter) with variable amplitude [12]. UPFC can operate in a phase shift regulator and emulate as a controller of power flow [13, 14]. VSI is the main part of UPFC. Shunt VSI is energized by AC line itself, while the series VSC is fed by the shunt VSC through the DC link. The injected voltage V_s has two parameters the amplitude ($0<V_s<V_{smax}$) and phase angle ($0<\psi<360^0$) as shown in Figure 5.

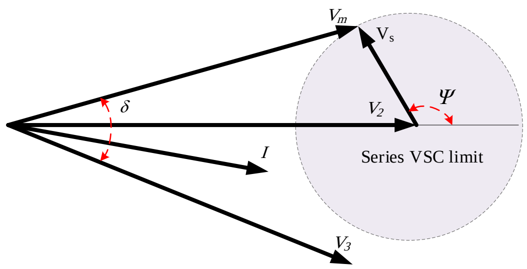

Figure 5. Vector diagram of UPFC function

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

$$P_T = P_2 \pm P_{pq} \quad (7)$$

$$Q_T = Q_2 \pm Q_{pq} \quad (8)$$

where; P_{pq} is the injected active power and Q_{pq} is the injected reactive power.
Depending on (7, 8) the active and reactive power can be regulated by adding or subtracting the injection powers.

3. ACTIVE AND REACTIVE POWER NEASUREMENT AND CONTROL

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 [15]. 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 [16]. The d-q theory implements “park transformation” to transform the a-b-c coordinates (stationary reference) to rotating coordinates or d-q coordinates [17]. The transformation is applied for voltages in the time domain as a standard frame (i.e. v_a, v_b and v_c) is as follows:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\emptyset) & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ -\sin(\emptyset) & -\sin(\emptyset - \frac{2\pi}{3}) & -sin(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\emptyset) & \cos(\emptyset-\frac{2\pi}{3}) & \cos\left(\emptyset+\frac{2\pi}{3}\right) \\ -\sin(\emptyset) & -\sin\left(\emptyset-\frac{2\pi}{3}\right) & -sin(\emptyset+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{10}$$

$$\emptyset = (\omega t + \theta) \tag{11}$$

where $(\emptyset)$ is the phase shift between the rotating and fixed coordinates with respect to time, also (θ) represents the phase shift between the voltage and line current. Two power components compensated can be calculated by:

$$p = V_d I_d + V_q I_q \tag{12}$$

$$q = V_d I_q - V_q I_d \tag{13}$$

4. CONTROL SCHEME OF COMPENSATOR

Figure 6 shows the control scheme of the 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 (9) to (13). From the system, these measured signals in (29, 30) work as inputs to the closed-loop control (as feedback). The desired reference values of active and reactive power p_{ref} and q_{ref} are compared with the calculated values of measured values for generating error signals E_{rrorp} and E_{rrorq}. These signals are processed in the controller where:

$$Erorr_P = p_{ref} - p \tag{14}$$

$$Erorr_q = q_{ref} - q \tag{15}$$

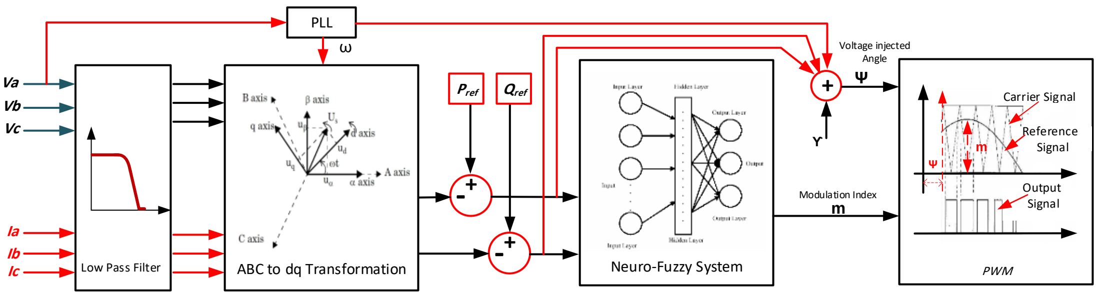

Figure 6. UPFC control system block diagram

Logic control with neuro-fuzzy system is adequate for ununcertain systems, especially to the system with a difficult to derive its model mathematically. Neuro-Fuzzy logic plays an important function in many applications especially the practical [18]. Takagi-Sugeno " TS " choose in this study as inference mechanisms [19]. The artificial neural network (ANN) is used for tuning the TS-controller membership functions. TS-fuzzy logic has variable non-linear gain. The controller provides a wide gain variation. The use of ANN for adapting the fuzzy system parameters which can achieve a better response. 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 [20]. By using the 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 [21]. 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 [22]. The 7-layers outputs emulate ANFIS design procedure referring to [23]. The advantage of using the 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 [24]. A hybrid learning (lease squares estimate-LSE and gradient descent-GD) is used to identify the parameters network [25]. In this study. The inputs are split into 9 trapezoidal membership functions" with overlapping of 50%, so, the two vector inputs a "49-control rule resultant linear functions required to be determined. Figure 7 shows the validation test while Figure 8 shows the tuning TS-rules using ANN. The vector's inputs are Ep and Eq, the output m "modulation index". Figures 9 and 10 show the Fuzzy logic layers and the validation surface of the Fuzzy logic system respectively.

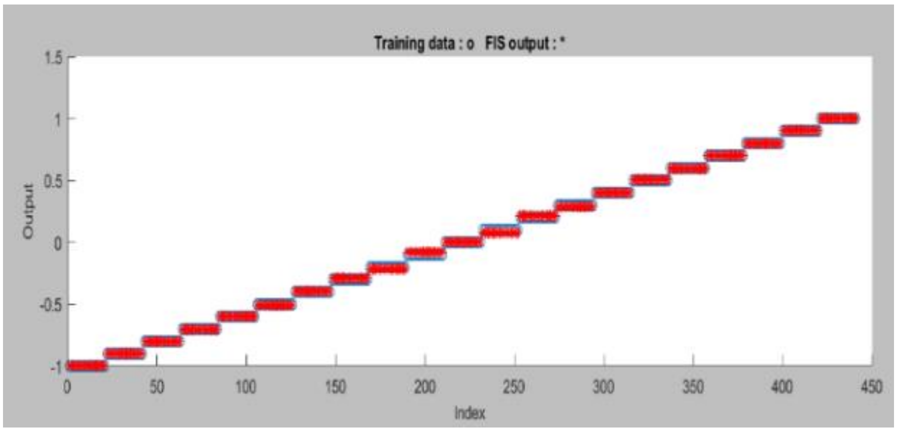

Figure 7. Fuzzy logic validation test

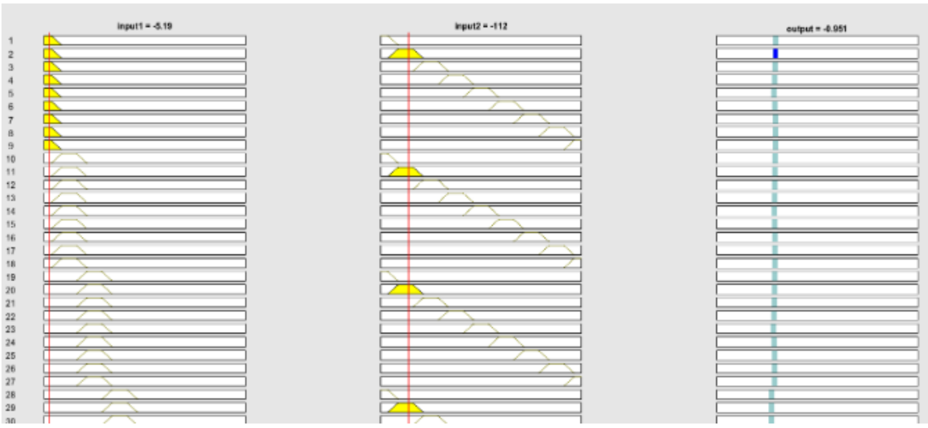

Figure 8. TS-rules using ANN

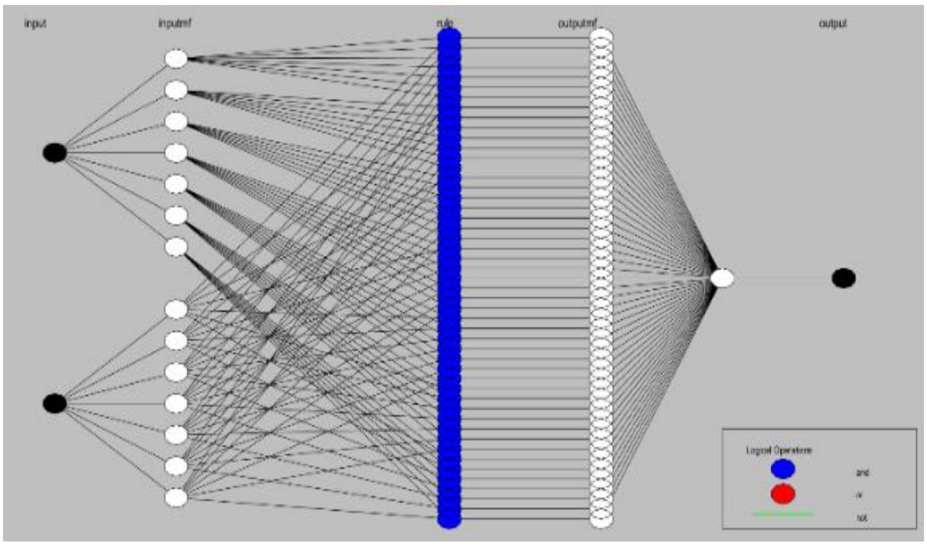

Figure 9. Neuro-fuzzy design

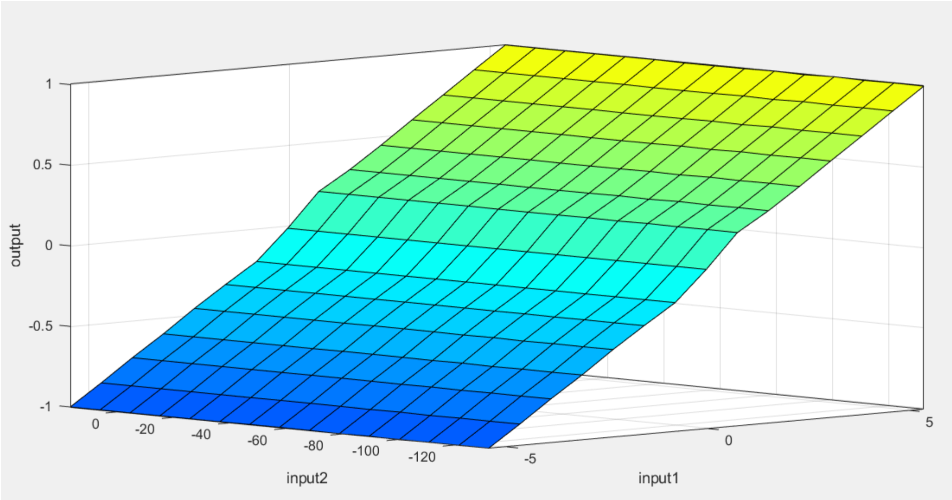

Figure 10. Neuro-fuzzy logic validation surface

5. SIMULATION STUDY

The proposed model study was consisting of a distribution 2-branch feeders with as shown in Figure 11. UPFC installed to control the power in transmission line 2. The compensator is provided by a DC-link that helps in absorbing or feeding the reactive or active power. The test starts by making the bus-2 as PV node then the analysis of load flow through the network using "Newton-Rapheson method", the total power and the powers in both branches without compensation are calculated. The compensation process is done by injecting a control voltage ($V_{injected}$) which was in making with phase voltage in quadrature. First, the model test is done by a "one-step change" in the load, before 5.0 seconds the power in unbalance between the parallel transmission lines at t=5.0 second UPFC inject the controllable voltage the controllable injected current and voltage are shown in Figures 12 and 13 respectively, in the other hand the rms line currents of the parallel transmission lines shown in Figure 14. Figures 15 shows the rms of two-bus voltage. The change in active and reactive power flow after injection are shown in Figures 16 and 17 respectively. All of the results are given in pu.

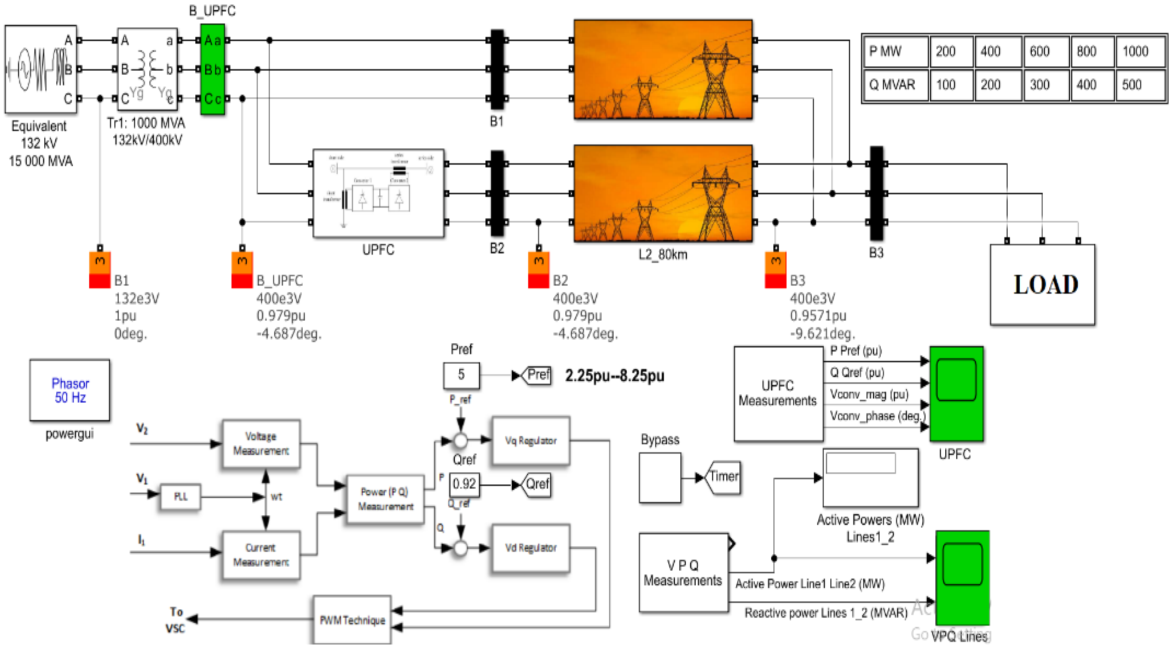

Figure 11. Two lines power control with UPFC

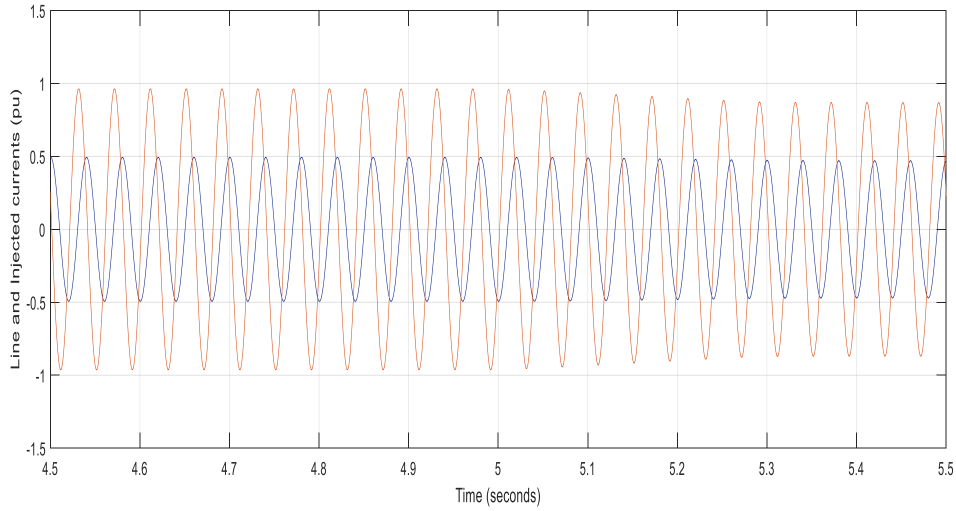

Figure 12. The injected current vs. line current

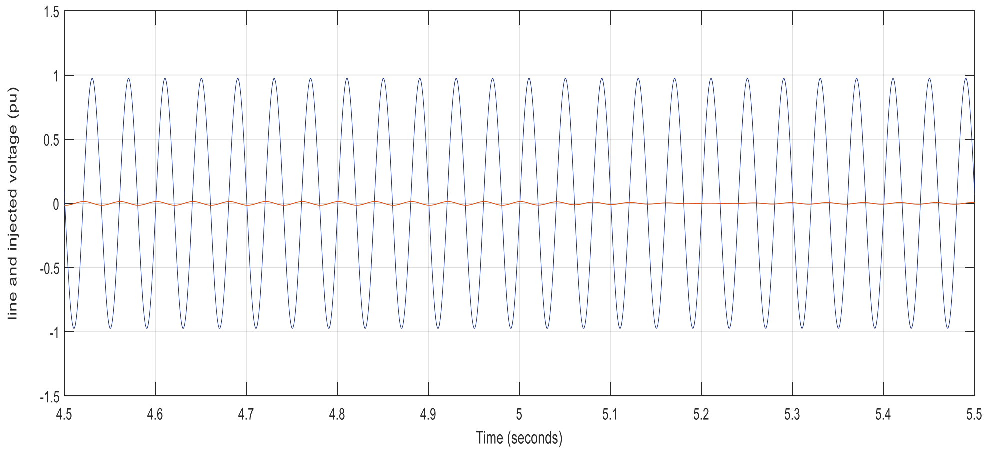

Figure 13. The injected voltage vs. bus voltage

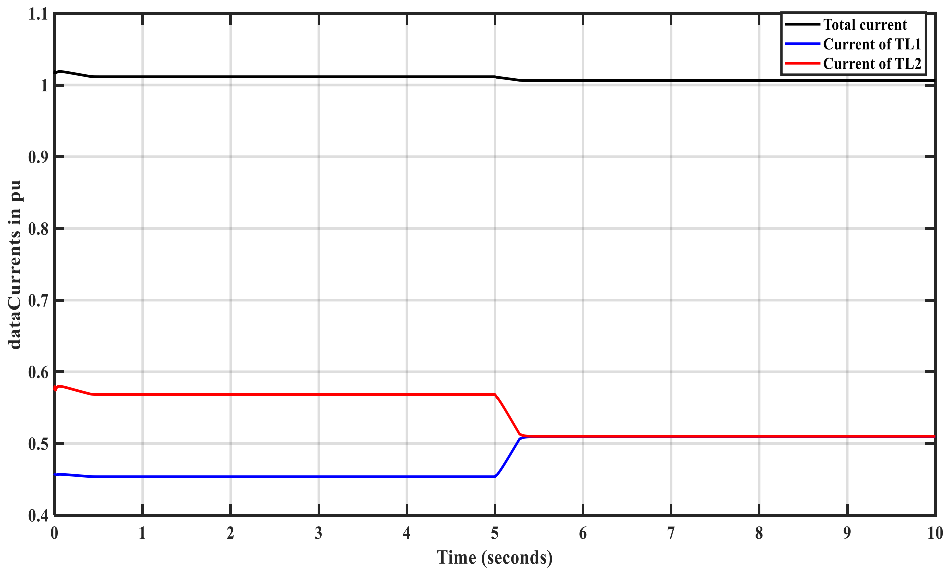

Figure 14. Line currents

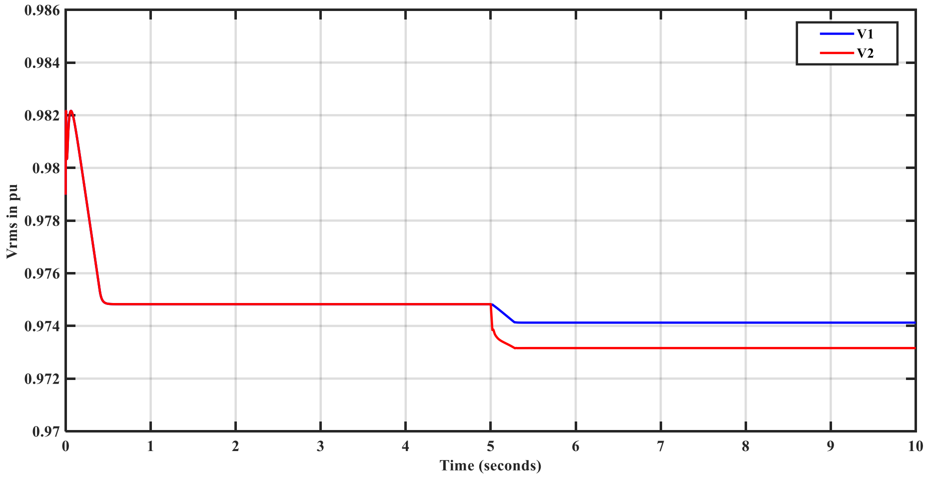

Figure 15. Bus voltages

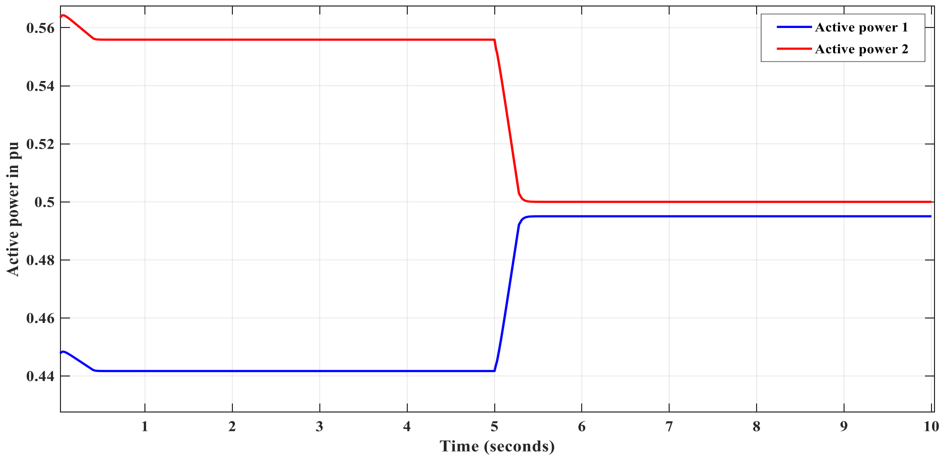

Figure 16. Two-line active power

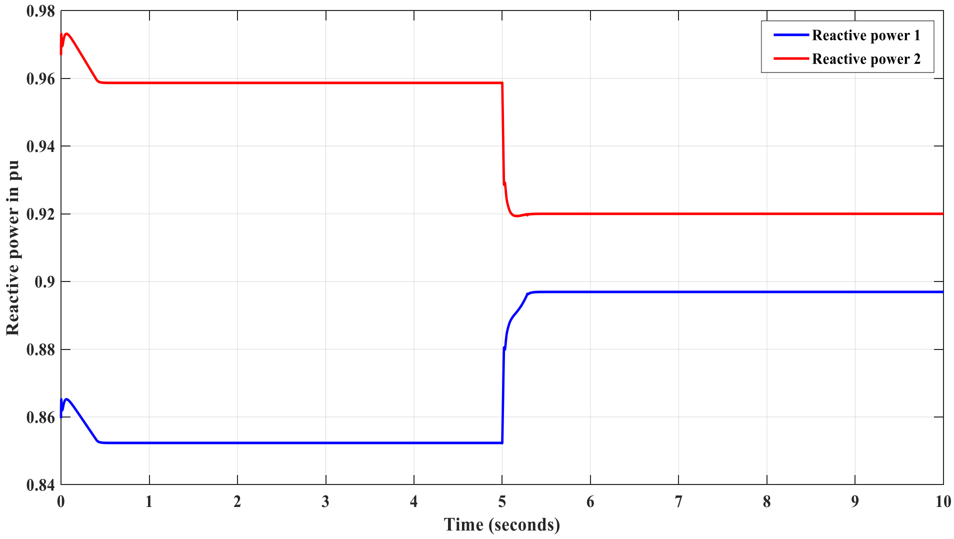

Figure 17. Two-line reactive power

6. CONCLUSION

In this study, modeling of active and reactive power flow control in parallel transmission lines using UPFC is presented. The amplitude and the phase angle of controllable voltage can be adjusted by a series converter of UPFC so that they can inject the controllable voltage that can regulate the components of the power (active and reactive) and then regulates the powers through the parallel transmission lines. To control the UPFC a neuro-fuzzy logic controller was designed. 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.

REFERENCES

[1] Narain G. Hingorani ; Laszlo Gyugyi, “Understanding FACTS, Concepts and technology of flexible AC transmission systems,” Wiley-IEEE Press, pp. 452, 2000.

[2] X. Zhang and C. Rehtanz, “Flexible AC Transmission Systems: Modelling and Control,” Springer press,Verlag Berlin Heidelberg, 2012.

[3] M. T. Alkhayyat1 and S. M. Bashi, “A New Survey for Optimum Power Flow with Facts Devices,” *International Journal of Electrical & Electronic Systems, OMICS*, vol. 5, no. 4, pp. 1-5, 2016.

[4] S. P. Thota and S. K. Peddapelli, "Fuzzy Controller based Interline Unified Power Quality Conditioner (IUPQC) in Multi-feeder Systems," *2019 International Conference on Engineering, Science, and Industrial Applications (ICESI)*, Tokyo, Japan, pp. 1-5, 2019.

[5] A. Ajami and S. H. Hosseini, "Line current balancing using unified power flow controller," *2004 IEEE Region 10 Conference TENCON 2004.*, Chiang Mai, vol. 4, pp. 183-186, 2004.

[6] M. Y. Suliman and R. K. Antar, “Power flow controller based on a new proposed statcom controller,” *International Journal of Engineering & Technology*, vol 7, no 4, pp. 3826-3829, 2018.

[7] M. A. M. Manaz, D. B. W. Abeywardana, M. G. C. P. Mediwaththe, K. M. Liyanage and A. Yokoyama, "Active and reactive power balancing of Ubiquitous power networks considering voltage constraints," *2012 IEEE 7th International Conference on Industrial and Information Systems (ICIIS)*, Chennai, pp. 1-6, 2012**.**

[8] M. Kano, T. Maekawa, T. Takeshita and Y. Kunii, "Comparison of converter arrangement of series and shunt converters in UPFC for distribution system control," *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, Birmingham, pp. 431-436, 2016.

[9] M. Y. Suliman and M. Emad Farrag, "Power Balance and Control of Transmission Lines Using Static Series Compensator," *2018 53rd International Universities Power Engineering Conference (UPEC)*, Glasgow, pp. 1-5, 2018.

[10] N. Kaarunya and J. Muruganandham, "Performance Analysis of Static Synchronous Series Compensator and Interline Power Flow Controller," *2018 International Conference on Communication and Signal Processing (ICCSP)*, Chennai, pp. 0888-0892, 2018.

[11] L. Wang and Q. Vo, "Power Flow Control and Stability Improvement of Connecting an Offshore Wind Farm to a One-Machine Infinite-Bus System Using a Static Synchronous Series Compensator," in *IEEE Transactions on Sustainable Energy*, vol. 4, no. 2, pp. 358-369, April 2013.

[12] Aziz Oukennou, Abdelhalim Sandali, Samira Elmoumen, “Coordinated Placement and Setting of FACTS in Electrical Network based on Kalai-smorodinsky Bargaining Solution and Voltage Deviation Index,” *International Journal of Electrical andomputer Engineering (IJECE)*, vol. 8, no. 6, pp. 4079-4088, part I, December 2018.

[13] S. Panda, and N. P. Padhy, “Comparison of particle swarm optimization and genetic algorithm for FACTS-based controller design,” *Appl. Soft Comput*., vol. 8, no. 4, pp. 1418-1427, 2008.

[14] M. Y. Suliman and S. M. Bashi, "Fast response SSSC based on instantaneous power theory," *2013 International Conference on Electrical Communication, Computer, Power, and Control Engineering (ICECCPCE)*, Mosul, pp. 174-178, 2013.

[15] S. H. Qazi and M. W. Mustafa, “Improving Voltage Profile of Islanded Microgrid using PI Controller,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 3, pp 1383-1388, June 2018.

[16] DiptiMohanty and et al, “Modelling, simulation and performance analysis of FACTS controller in transmission line,” *International Journal of Emerging Technology and Advanced Engineering*, vol 3, no. 5, pp. 428-435, 2013.

[17] V. Ponananthi and B. R. Kumar, "Three-phase statcom controller using D-Q frame theory for a three-phase SEIG feeding single phase loads," *2015 2nd International Conference on Electronics and Communication Systems (ICECS)*, Coimbatore, pp. 926-931, 2015.

[18] E. H. Watanabe, M. Aredes, J. L. Afonso, J. G. Pinto, L. F. C. Monteiro and H. Akagi, "Instantaneous p–q power theory for control of compensators in micro-grids," *2010 International School on Nonsinusoidal Currents and Compensation*, Lagow, pp. 17-26, 2010.

[19] M. Y. Suliman, M. E. Farrag and S. Bashi, “Design of Fast Real Time Controller for the SSSC Based on Takagi-Sugeno (TS) Adaptive Neuro-Fuzzy Control System,” *International Conference on Renewable Energies and Power Quality (ICREPQ’14)*, vol. 1, no. 12, pp 1025-1030, 2014.

[20] M. Y. Suliman, “Voltage profile enhancement in distribution network using static synchronous compensator STATCOM,” *International Journal of Electrical and Computer Engineering (IJECE),* vol. 10, no. 4, pp. 3367-3374, 2020.

[21] M. Y. Suliman and S. S. Al-Juboori, “Design of Fast Real Time Controller for the Dynamic Voltage Restorer Based on Instantaneous Power Theory,” *International Journal of Energy and Power Engineering*, vol 5, no 2, pp. 1-6, 2016.
[22] S. R. Khuntia, "Simulation study of a SSSC-based neuro-fuzzy controller for improvement of transient stability in a three-machine power system," *2012 IEEE Energytech*, Cleveland, OH, pp. 1-6, 2012.
[23] M. Amirian, "Mitigating Sub-Synchronous Resonance Using Static Var Compensator (SVC) Enhanced with Adaptive Neuro-Fuzzy Inference Systems (ANFIS) Controller," *2019 27th Iranian Conference on Electrical Engineering (ICEE)*, Yazd, Iran, pp. 532-538, 2019.
[24] M. Y. Suliman, “Active and reactive power flow management in parallel transmission lines using static series compensation (SSC) with energy storage,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 6, pp. 4598-4609, 2019.
[25] F. Taki, S. Abazari and G. R. Arab Markadeh, "Transient stability improvement using ANFIS controlled UPFC based on energy function," *2010 18th Iranian Conference on Electrical Engineering*, Isfahan, pp. 944-948, 2010.

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