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Adaptive Neuro Fuzzy Inference System (ANFIS) Predictive Control of UPFC for Transient Stability Performance Enhancement of Power System

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Abstract

The increasing complexity of modern power systems, driven by rising electricity demands and limited large-scale energy storage, necessitates advanced strategies for maintaining stability and reliability. This paper explores the application of a FACTS devices to enhance transient stability within power grids specially UPFC. The UPFC provides improved voltage regulation and overall system performance. An Adaptive Neuro-Fuzzy Inference System (ANFIS) is implemented as powerful control strategy, which allows for adaptive and intelligent management of system dynamics and used to augment transient stability. Our findings underscore the importance of integrating advanced control techniques, such as UPFC and ANFIS, to effectively address the challenges posed by modern power system complexities, ultimately ensuring a stable and reliable electricity supply for end-users.

Keywords: Transient Stability (TS), Unified Power Flow controller (UPFC), Adaptive Neuro Fuzzy Inference System (ANFIS).

1. Introduction

An electrical power system is intricate, interconnected network comprising generators, transmission lines, transformers, protective devices, and diverse loads. The growing electricity demand has exacerbated the complexity of these systems, leading to challenges in maintaining stability. Transient stability, a critical issue influenced by continuously varying loads and the potential for overloads on transmission lines, necessitates thorough analysis and enhancement strategies (Kundur, P.,1999). The transient stability study assesses the system's response to large disturbances, such as severe lightning strikes, loss of key transmission lines, and major generation outages. (Hingorani, N.G. 1999). All the findings from these analyses inform the implementation of measures to enhance transient stability, including Automatic Voltage Regulators, Power System Stabilizers, and FACTS devices (Mohan, M.R,2002). The PSS are effective for high-frequency oscillation control, while AVR and FACTS devices contribute significantly to overall system stability. A Ajami, A (2006) has suggested utilization of a fuzzy based controller for stability improvement of transmission system which can significantly make the electrical power systems more reliable and stable and also addresses all challenges posed due to increased complexity

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and variable load conditions.

Table 1: Application wise Comparisons of Different Facts Devices.

Controller	V.R	D.P.O	T.S	R.P.C	Power flow
TCSC	✓	✓	✓		✓
TSSC		✓	✓		✓
SSSC	✓	✓	✓	✓	✓
SVC	✓	✓	✓	✓	
STATCOM	✓	✓	✓	✓	
UPFC	✓	✓	✓	✓	✓

[V.R: Voltage Regulation; D.P.O: Damping Power Oscillations; T.S: Transient Stability; R.P.C: Reactive Power Flow Control; AVR: Automatic Voltage Regulator]

2. UPFC controller

The FACTS controllers are designed to enhance voltage regulation and provide series compensation and phase shifting (Tiwari, S.,2021). The Unified Power Flow Controller is a key FACTS device which allows rapid control of real and reactive power flow in transmission line (Thakur, R.V.,2012). This configuration compromises of two voltage source converter which are connected through a common DC terminal. Converter 1 is linked in parallel to the transmission line through a coupling transformer and the converter 2 is connected in series via an interface transformer. A necessary supply to both converters is provided by common capacitor.

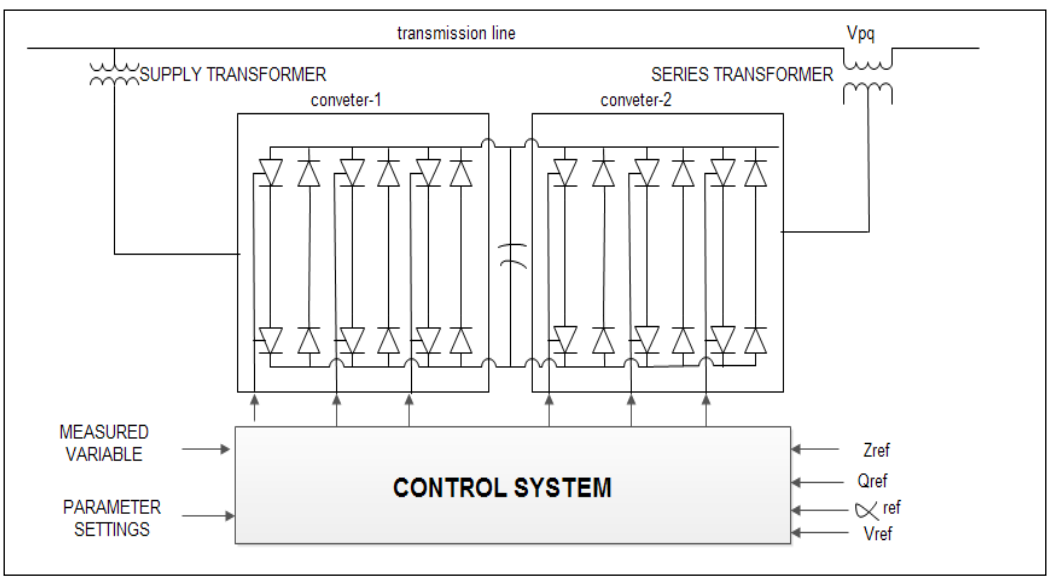


Figure 1: Unified Power Flow Controller

The supply power is controlled by injecting a series phasor voltage in the line and it can be adjusted between 0 and V_{pqmax} by independently varying the phase angle of V_{pq} from 0° to 360°. Additionally, a real power flow is controlled by energy storage device- capacitor, while the series converter manages the supply or consumption of reactive power internally. The shunt-connected converter-1 delivers active power demand of converter-2. DC voltage at the bus is maintained constant by the shunt converter (Salah,

K.,2019). The total active power of the system equals actual losses of both converters and losses of transformers coupling both. The terminal voltage is regulated by providing reactive power support by shunt converter which acts like a STATCOM.

3. Modelling of Unified Power Flow Controller

The transient model of UPFC is shown in figure 2. An equation (1) shows the KVL equation of series inverter

$$V_{sr} - V_{sr1} = R_{sr} I_{sr1} + L_{sr} \frac{d}{dt} I_{sr1} \quad (1)$$

$$V_{sh} - V_{sh1} = R_{sh} I_{sh1} + L_{sh} \frac{d}{dt} I_{sh1} \quad (2)$$

$$I_{dc} = C_{dc} \frac{d}{dt} V_{dc} = I_{shdc} - I_{srdc} \quad (3)$$

Where L_{sh}, are leakage inductances while R_{sh}, R_{sr} represent losses components of inverters and transformers. The N_{shl}/N_{sh2} and N_{sr1}/N_{sr2} are the turn ratio of shunt and series transformers respectively.

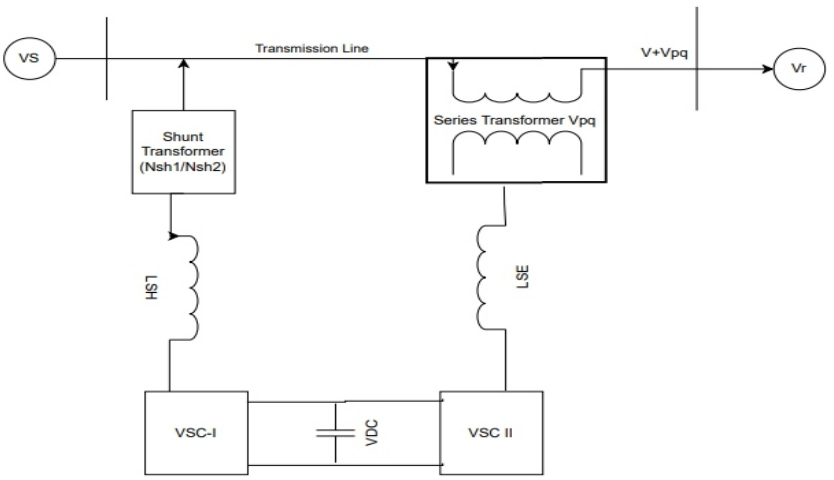


Figure 2: UPFC Transient modelling block diagram

The series inverter injects voltage (V_{ser}) in series with the line and acts as SSSC (Ajami, A ,2006). Equation (2) is a shunt converter circuit equation and equation (3) represents the DC link equation of UPFC. These equations can be converted using d-q transformation equations (4) and (5).

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = T(\theta) \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \ldots \quad (4)$$

Where θ= wt

$$T(\theta) = \frac{2}{3} * \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (5)$$

4. Different control strategies for UPFC

Various equipment like AVR and PSS are mainly used for transient stability enhancement. Advanced AI based control techniques are also used to develop the efficient PSS (Haman,2009). Different types of AI

techniques are used, such as fuzzy logic controllers, ANNs, neuro fuzzy adaptive control, etc. While Boolean or crisp logic handles ambiguous and uncertain problems, fuzzy logic (FL) is more effective for complicated and non-linear systems (Thakur,2012). Fuzzy logic is created by translating the verbal rules of the system into fuzzy sets, which is where fuzzy logic originates. It uses membership functions with values ranging from 0 to 1 (Shair, J., 2021). Taki, F (2010) has presented ANFIS based control of UPFC using energy functions and Bhil, S.K, Kamath A.K (2009) has suggested MPC based TCSC controller for transient stability enhancement of energy system. An artificial neural network (ANN) is a mathematical model that includes feed forward and recurrent neural networks, among other neural network types (Karuppiah,2010). Intermediate signals are propagated forward in a feed forward network because information moves from input to output through a concealed layer of forward lines without any loops. Recurrent neural networks, on the other hand, have numerous cycles (Tiwari,2011).

The fuzzy systems have less ability to learn new things and cannot adjust to new environments. While the neural networks are fast learners and have optimization and adaptation capabilities, they are not transparent to the user (Park, J). Hence, the good qualities of fuzzy control and neural networks have been combined to improve the controller performance (Mishra, S. 2006). It is well evident that fuzzy logic is quite effective for nonlinear, complicated, and well-defined systems. An integrated neuro fuzzy stem has fast capability to learn of neural networks with the human like knowledge presentation and explanation abilities of fuzzy systems. Hence, the system becomes more pellucid and more capable of learning.

5. ANFIS technique

The ANFIS technique uses the fuzzy inference system and adaptive neural network to solve function approximation problems (Salah, K,2019). The system based on Takagi-Sugeno is supported by both ANFIS strategies. It regulates a number of variables, including flux, voltage, current, and angles. As per Taki, F (2010), the ANFIS system lacks training data, external data feeding is necessary to increase system efficiency. The ANFIS system's rules can be changed throughout the training phase and are written in plain language. The Adaptive Network Fuzzy Inference System is depicted in Figure 3 and employs either least squares estimation or back propagation (Bhil, S.2009) The hybrid technique for estimating the membership function parameter involves backpropagation and consists of five layers in total (Alawadhi, A. 2017).

1. First layer contains input variables having triangular and Gaussian type of membership functions which delivers input value [Xi] to the next layer. Node i of each layer is an adaptive node used as membership function (Smith, J.R.,2023).

$$O_{1,i} = \mu_{A,i}(x_i) \text{ where } i = 1,2, \ldots n \qquad (6)$$

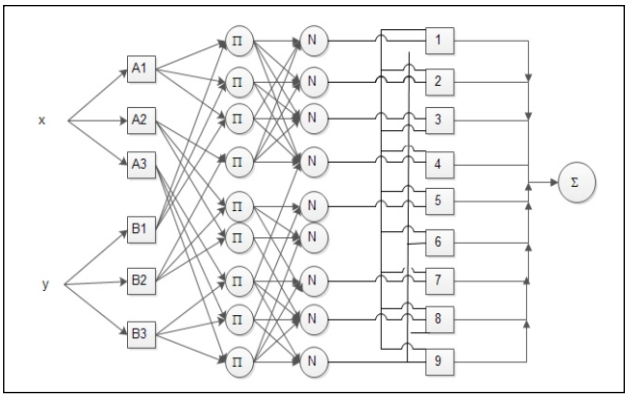


Figure 3: ANFIS layer diagram

Each layer's parameter is seen as a premise parameter, and the membership function can be thought of as an appropriate parameterized function. Every node in this layer performs the fuzzy AND operation by acting as a fixed node whose output is the product of different incoming signals.

$$O_{2,i} = w_i = \mu_{A,i}(x_i)\,\mu_{B,i}(y_i) \qquad (7)$$

2. Normalized matching degree Computation: The nodes of this layer use equations (8) to determine the normalized firing strength of each rule.

$$O_{3,i} = \quad w_i = w_i \Big/ \sum_i \overline{w_i} \qquad (8)$$

3. The defuzzification layer: In this layer, the result of a fuzzy rule inference is calculated. Equation (9), for each adaptive node i, provides the node function.

$$O_{4,i} = \overline{w_i}(P_i x + q_i y + r_i) \qquad (9)$$

4. This output layer combines and transforms each of the layer 4 inputs into a distinct value. Equation (10) is used in a model to aggregate the effects of fuzzy rules.

$$O_{5,i} = \sum_i \overline{w_i}\, fi = \frac{\sum_i w_i fi}{\sum_i \overline{w}_i} \qquad (10)$$

Figure 4. shows specific flow of data for ANFIS control technique used in MATLAB SIMULINK.

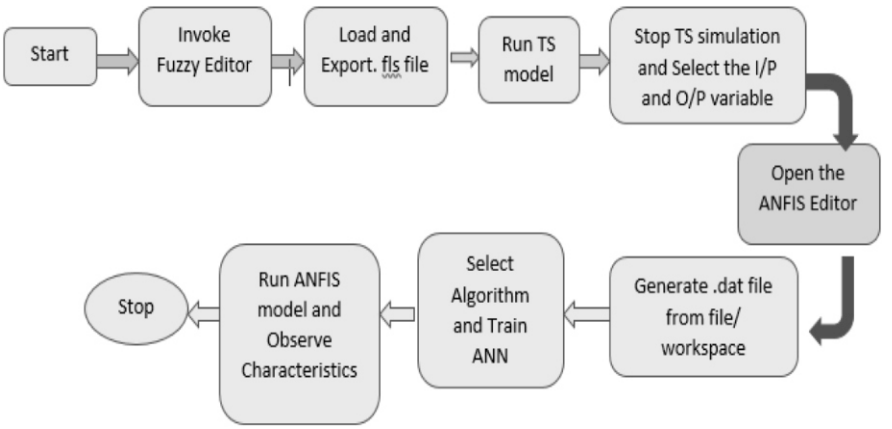


figure 4: Data flow diagram of ANFIS control

6. Simulations and result

Figure 5 displays the one-line schematic for the two-machine system. In Table 2, system specifications are provided. To control the flow of power, the UPFC is connected to a 500/230 KV transmission line. The transmission system used in the study is a connected between two buses B_1 and B_2. Fault is assumed after bus B_2.

Table 2: Power system parameters

	Voltage [kv]	Power [MVA]	F [Hz]	Phase [degree]
Gen. 1	500	400	50	0
Gen. 2	500	400	50	10

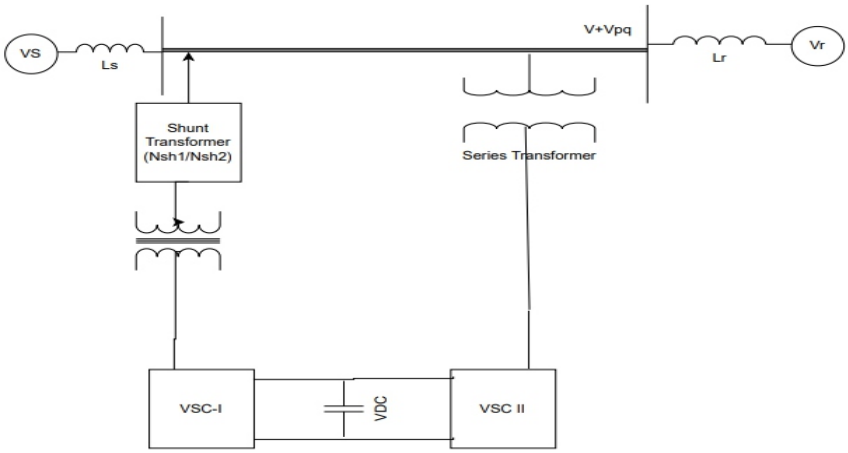


Figure 5: One-line diagram of two machine power system

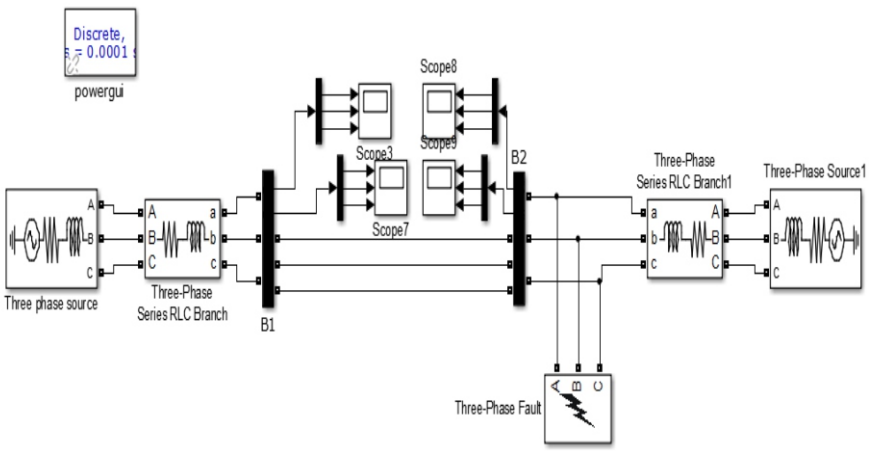


Figure 6: Two machine system without UPFC

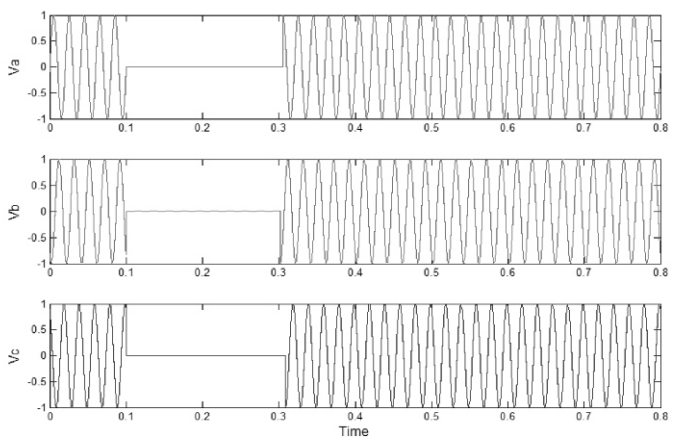


Figure 7: Voltage Waveforms of bus.1, when fault occurs

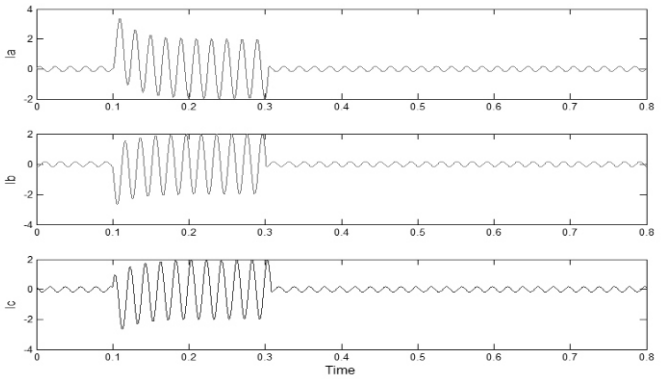


Figure 8: Current waveforms at bus 1, when fault occurs

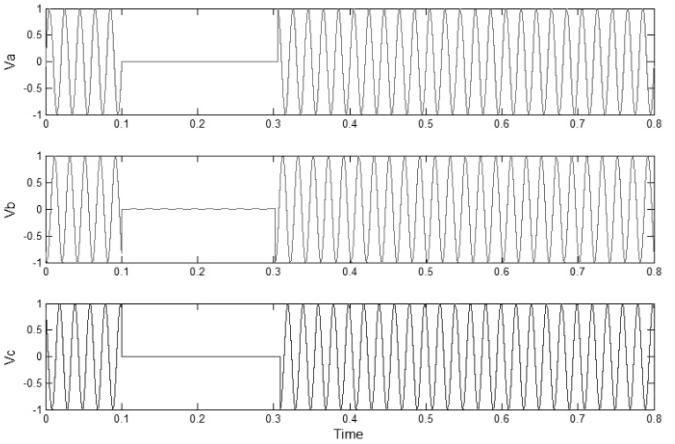


Figure 9: Voltage waveforms of bus.2, when fault occurs

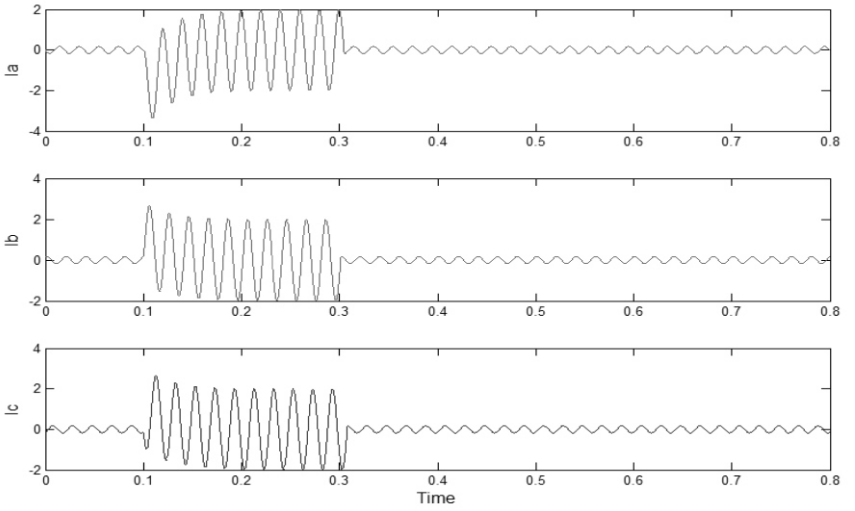


Figure 10: Current waveforms of bus.2 when fault occurs

Figure 11: Real Power Flow in System at bus1

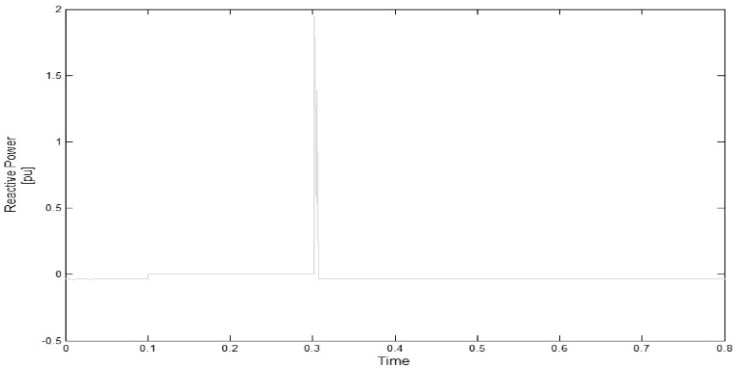


Figure 12: Reactive Power Flow in System at bus 1

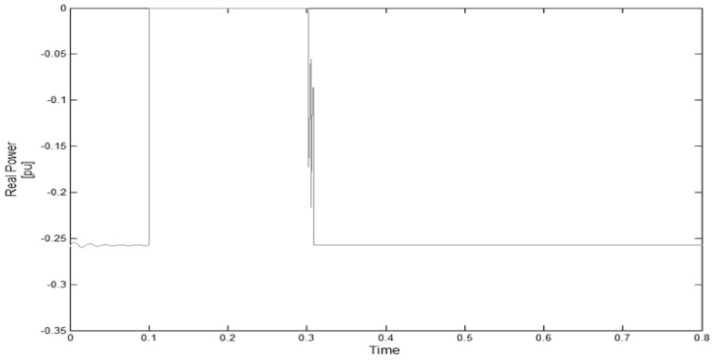


figure 13: Real power flow in system at bus 2

7. Double machine system with UPFC

An UPFC is a device used in power systems to control and optimize power flow. It typically consists of series and shunt compensators that can independently control real and reactive power flows in an AC transmission system. Figure 15 shows the connection diagram and UPFC configuration with the power system. It could depict how the series and shunt components are connected to the transmission lines or buses.

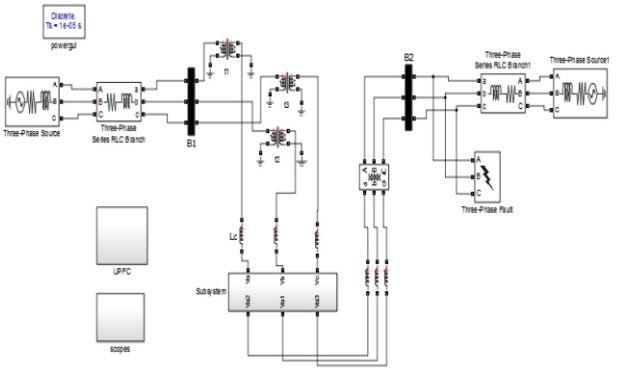


Figure 15: Power system with UPFC

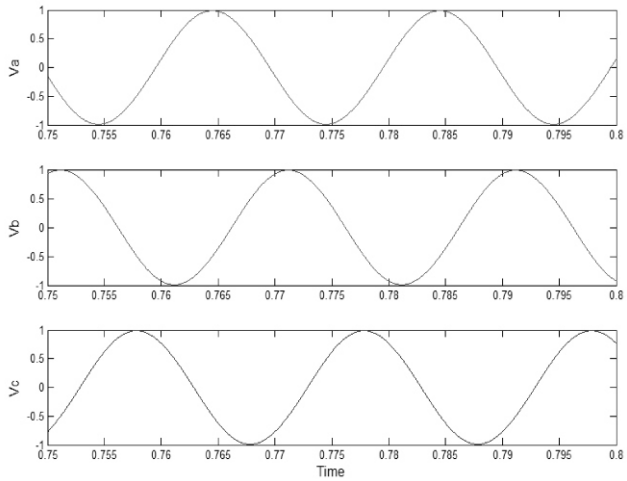


Figure 16: Waveforms of Source Voltages after Connecting UPFC using PWM

The PWM control is commonly used in power electronic devices (like those in UPFC) to regulate the amplitude or frequency of the voltage. The source voltages is controlled by Pulse Width Modulation (PWM) and its waveforms are shown in figure 16 and Figure 17 shows the phase angle characteristic with PWM control. This could indicate how the phase angle between voltages or currents is managed using the PWM technique in the context of UPFC operation.

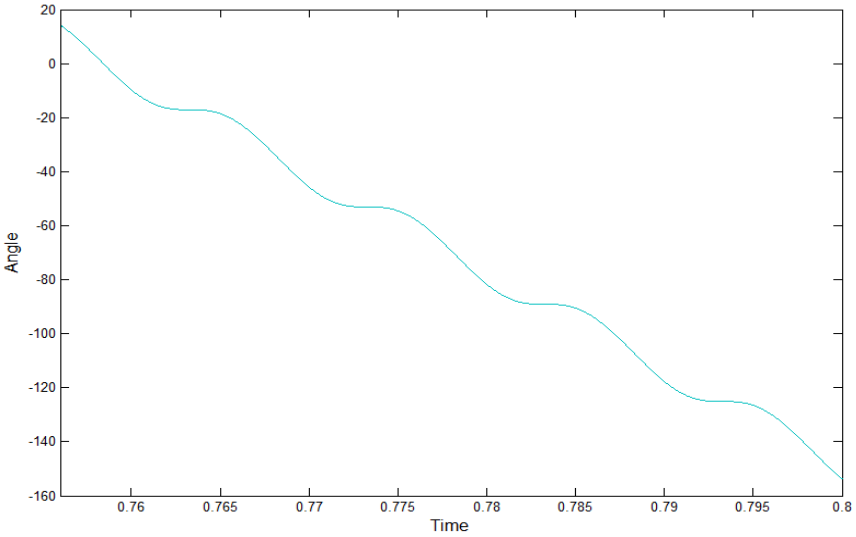


Figure 17: Angle characteristics of power system

The Figure 17 shows crucial characteristics of phase angle variation which indicates the effect of control strategy employed to manage power flow. The active power flow through transmission line is measured and its waveform is shown in Figure 18. These waveform illustrates variation in real power over time in the system and possibly also represents effect of voltage waveform adjustment by PWM control of UPFC and also demonstrate its influences on real and reactive power flows.

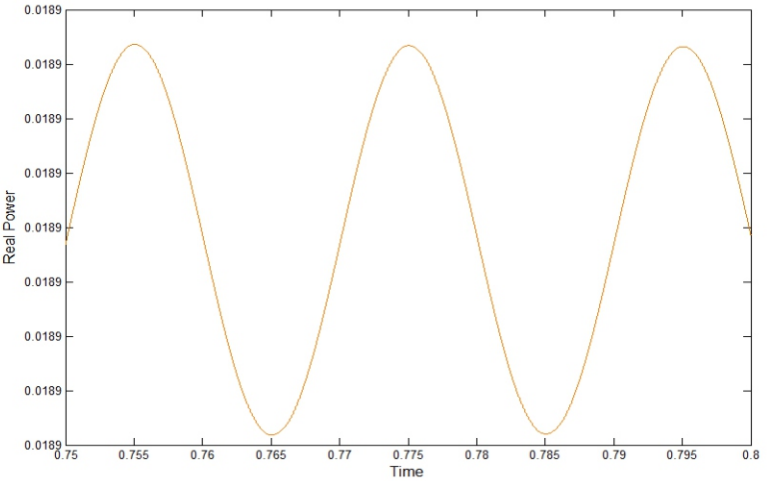


Figure 18: Real Power Flow in System

The waveform shown in Figure 19 is reflecting the reactive compensation provided by the UPFC and represents change in reactive volt-amperes (VAR) changes with respect to time,

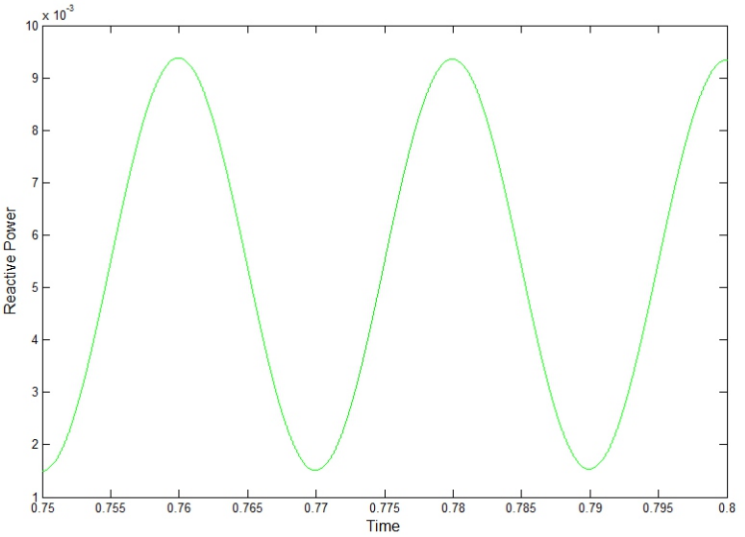


Figure 19: Reactive Power Flow in System

8. ANFIS control strategy

The SIMULINK model of ANFIS controller is shown in Figure 20. The 49 fuzzy rule set has been invoked first from the MATLAB. Initially, the fuzzy file containing the rules is opened in the MATLAB command window and then after the fuzzy editor (FIS) dialogue box is opened.

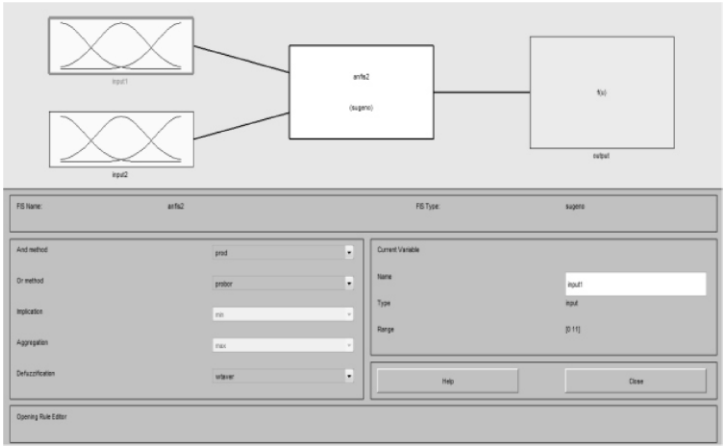


Figure 20: ANFIS editor

The fis file is imported using the command window from the source and then opened in the fuzzy editor dialog box using the file open command.

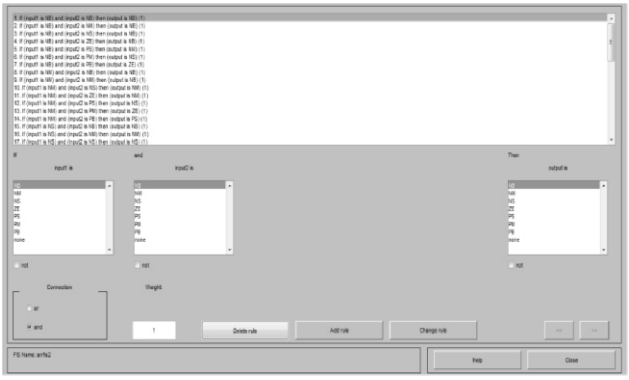


Figure 21: ANFIS rules editor

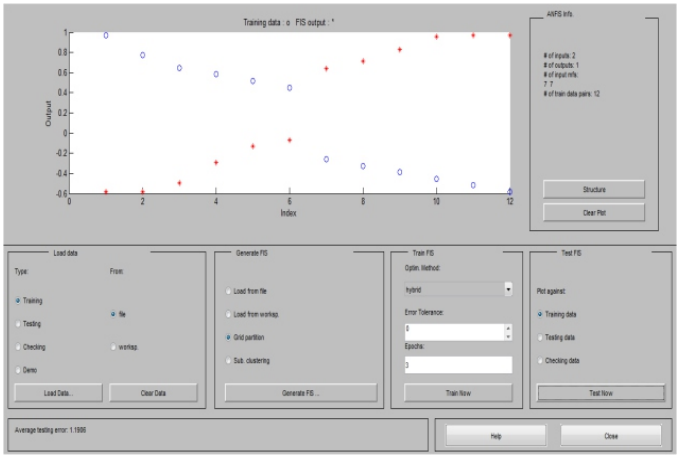


Figure 22: ANFIS output

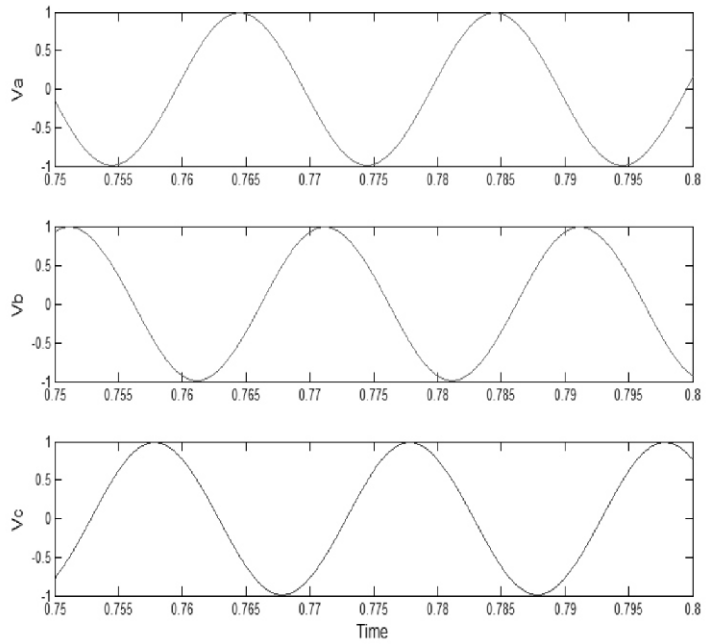


Figure 23: Waveforms of Source Voltages of UPFC with ANFIS control

The TS-fuzzy rules file gets activated and results are obtained. Figure 24 represent phase angle characteristic waveforms with ANFIS controlled UPFC.

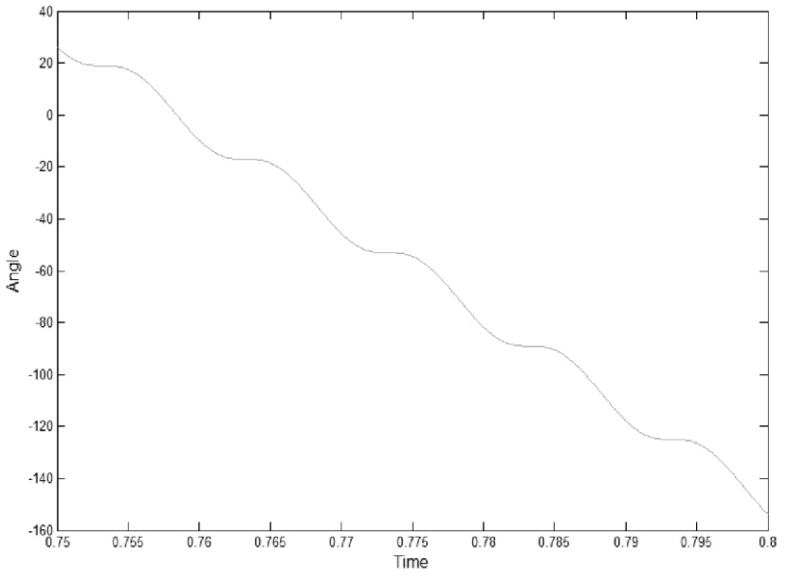


Figure 24: Angle Characteristics of Power System with ANFIS control

Figure 25 and Figure 26 show real power flow and reactive power waveforms after using UPFC with ANFIS controller.

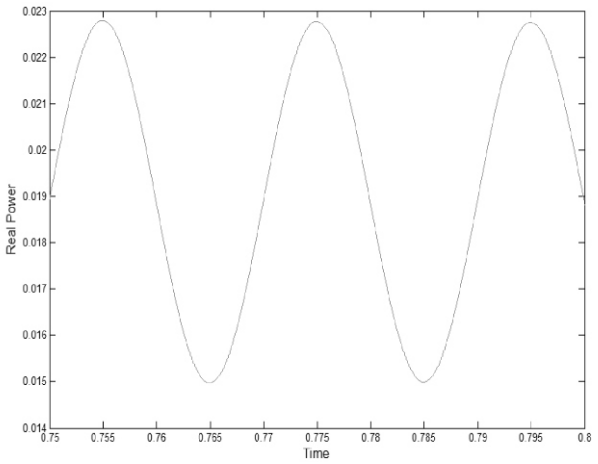


Figure 25: Real Power Flow in System

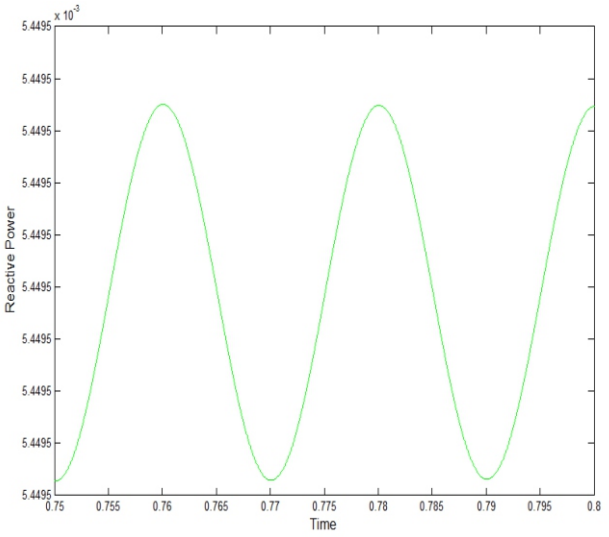


Figure 26: Reactive Power Flow in System

9. Conclusion

The analysis of system is crucial dues to implementation of a UPFC in power system including two machines that experienced a bus failure. It significantly reduced voltage dips under high current loads and failures by stabilizing voltage levels. Additionally, the UPFC allowed for exact control over real power flow and reactive power flow and maximize the efficiency of energy transmission and guaranteeing reliable performance in a variety of scenarios. Above all, it greatly enhanced the transient stability, which made it possible for the system to quickly recover from disruptions and keep synchronism. When comparing control systems, the Adaptive Neuro-Fuzzy Inference System (ANFIS) performed better at improving transient stability, although Pulse Width Modulation (PWM) provided good control. This indicates that ANFIS may dynamically modify control to provide the best possible system response in the face of dynamic events.

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