Controlling the effectiveness of STATCOM using ANFIS based on PI controller

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ABSTRACT

This research achieves two goals, the first is the modelling of the staticsynchronous-compensator (STATCOM) and design of the control circuits for current, voltage and d.c capacitor voltage (Vdc) to improve the power factor (PF) by preparing the reactive power by STATCOM so that its work is similar to the work of a synchronous condenser, and the second goal is to use smart techniques to control the Vdc loop. For comparison, smart technical methods such as fuzzy logic type 1 (FL-T1), fuzzy logic type 2 (FL-T2), and adaptive neuro fuzzy inference system (ANFIS) were used to regulate the Vdc on the capacitor instead of the traditional controller proportional integral (PI). Simulation was performed in MATLAB 2021 to determine the efficiency of the suggested method or approach controllers for STATCOM. The use of the proposed method improves the signal value of both the current and the voltage and the phase difference between them, which reaches almost zero. Proved that an ANFIS technique provides best Vdc response in different values of balance and unbalance load compared with the other methods by obtaining the minimum peak overshoot (P-ov) and minimum settling time (ST).

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1. INTRODUCTION

The speedy growth in the power electronics sector for high endurance has made flexible AC transmission systems (FACTS) a suitable and efficient option for use in both transmission and distribution systems of power systems, such as enhancing power quality, compensating for reactive power, stabilizing voltage, controlling power flow, reducing vibrations, and increasing the system's power factor (PF) [1]. The static synchronous compensator (STATCOM), a static-synchronous compensator, is one of the most commonly employed flexible AC devices. It has the capability to both supply and absorb reactive power, thus preserving voltage stability in electrical power transmission and distribution systems [2]. Recently, FACTS devices have been used, where a STATCOM is used as a voltage source inverter (VSI) with a fix DC capacitor which acts as a substitute for a synchronous condenser, by providing the required VAR control by selecting a fixed set of capacitors, with fast voltage control and improved PF [3].

Numerous research and studies have been completed in STATCOM control field. Research by Yousif and Mohammed [4], put forth a proposal for a STATCOM that utilizes proportional integral (PI) control to regulate the voltage during unexpected scenarios, such as faults or abrupt load changes. Naguyenm *et al.* [5] proposed using an intelligent controller called adaptive neuro fuzzy inference system (ANFIS)-online for a STATCOM system to enhance dynamic voltage stability during three-phase fault conditions. The ANFIS-online controller utilizes an artificial neural network (ANN) and its parameters are continually updated in real-time. The simulation results indicate that this controller is more effective than other controllers like ANFIS-genetic algorithm (ANFIS-GA) and ANFIS-particle swarm optimization (ANFIS-PSO). The researchers used both (PSO) and GA training algorithms to adjust all the adjustable parameters of the ANFIS model so that it accurately reflects the power system training data being studied [6]. In the other research [7], [8] the PI controller gains are designed by a trial-and-error approach with tradeoffs in efficiency and performance. Research by Saxena and Kumar [9] conducted a study on the impact of incorporating an ANFIS controller to adjust the STATCOM parameters in a wind-diesel hybrid power system experiencing frequent disturbances in load and power input. Stephen and Raglend [10] suggested and implemented a PI control model in MATLAB/Simulink environment then the model was tested under various load levels and a series of severe disturbance. Tripathi and Barnawal [11] used in simple design for STATCOM which he was able to overcome the problems caused at the point of common coupling (PCC) due to the presence of non-linear load. The inner control loop utilized the 'modulus optimum' method, while the 'symmetric optimum' method was used to tweak the PI controllers in the outer control loop. In a separate paper, a suggestion was put forward for linear optimal control based on linear quadratic regulation (LQR) control. The success of this control approach is contingent on the designer's ability to choose optimal parameters [12].

This paper proposes a way to control reactive power flow and PF correction in the studied system by cancel the reactive power of the source through STATCOM control methods. A mathematical model of a STATCOM is described. The ANFIS controller used voltage and d.c capacitor voltage (Vd.c) loop is designed and has been compare with traditional PI, fuzzy logic type 1 (FL-T1) and fuzzy logic type 2 (FL-T2) controllers. ANFIS controller has proven its good performance compared to other controllers.

2. STATCOM IN POWER SYSTEM

STATCOM is a one of FACTS devices, consist of a voltage source (Vs) with a reactor. The main work of STATCOM is regulate voltage. The STATCOM supply Q to power system if Vs less than voltage STATCOM. But if Vs greater than voltage STATCOM due to load throw off, the STATCOM observe Q to stabilize the voltage to normal value. Figure 1 represented the essential component of STATCOM, in (1) represent the a.c STATCOM voltage output (Vout) with Vdc in inverter [4], [7].

$$V_{out} = k\,Vd.c \tag{1}$$

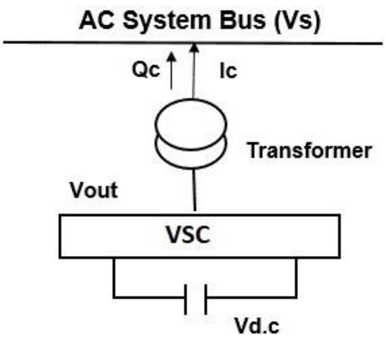

Figure 1. Essential component of STATCOM [7]

The direction of reactive power flow from and to the STATCOM is determined by Vout, which is obtained by adjusting the Vdc through the capacitor by adjusting the phase angle (θ). In (1) outlines this relationship, with the k parameter being influenced by pulse width modulation (PWM) and the design of the inverter and its control circuits. The real power source is responsible for charging the DC capacitor to a desired level of Vdc. The capacitor goes through a charge and discharge cycle for each switching cycle. In a steady state, the mean voltage of the capacitor stays constant. The current injected by the STATCOM (Iac) can be determined using the following calculation:

$$I_{ac} = V_{out} - V_s/x \tag{2}$$

Where x–leakage reactance of coupling transformer. Assuming that the Iac flows from the converter to the AC system:

$$Q = V_{out}(V_{out} - V_s\,cos\theta)/x \tag{3}$$

$$P = V_s\,V_{out}\,sin\theta/x \tag{4}$$

Q and P represented reactive power and real power respectively exchanged between the STATCOM and the power system. Three PI controllers for the STATCOM, two of them for the current control circuit and one for the Vdc control circuit, which in turn generates the direct axis source current Id as depicted in Figure 2 [5], [13].

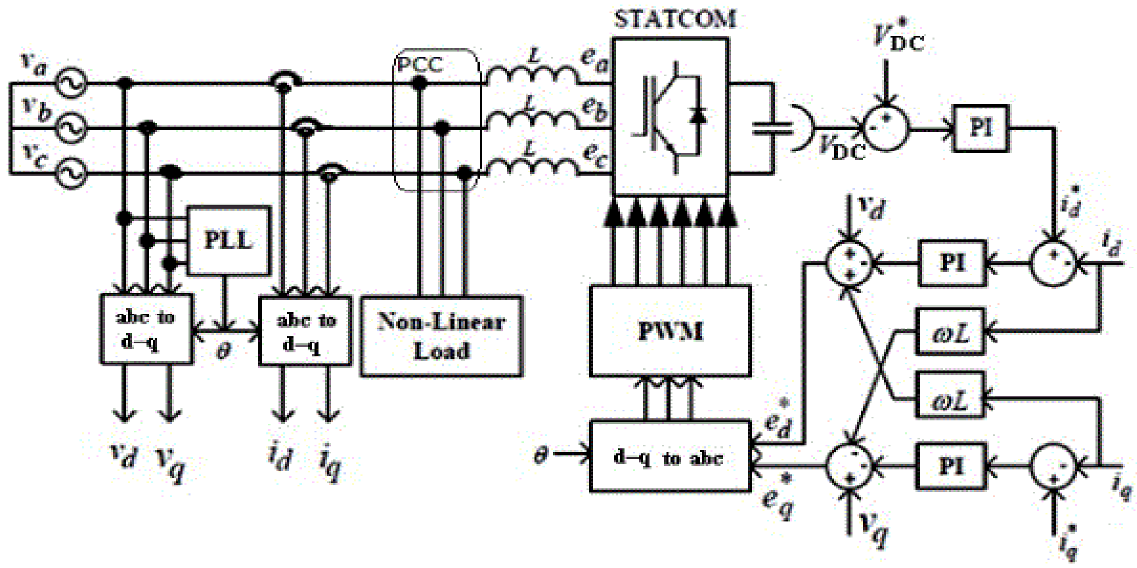

Figure 2. Schematic PI control method [3]

The algorithm illustrates the steps of using PI control method in STATCOM to compensate the reactive power:
- Step 1: measured voltage and current at PCC, furthermore the load current.
- Step 2: using a-b-c/d-q transformation to transform VS, IS, IL into d-q reference frame, the phase angle of (θ) grid is extracted from the output of a phase-closed loop (PLL) [14], [15].
- Step 3: measured the V_{dc}
- Step 4: error signal (e) is generated by difference value of V_{dc} reference and measured value and handle in PI controller to output the reference direct axis source current ($I_{ds\text{-}ref}$).
- Step 5: the difference between $I_{ds\text{-}ref}$ and I_{Ld} (load direct current) resulting a voltage signal processed by inner PI_2 controller (Dvd).
- Step 6: difference between quadrant component of supply current (I_{qS}) with quadrant component reference current (I_q^*) processed by inner PI_3 controller resulting Dvq.
- Step 7: finding the reference values (e_d) and (e_q) of the STATCOM voltages

$$e_d = vd - D_{vd} - I_{ql} * wL \tag{5}$$

$$e_q = vq - D_{vq} - I_{dl} * wL \tag{6}$$

- Step 8: transformed the reference voltages obtained from step 7 into a-b-c reference voltages with phase angle (θ) to create the PWM control signals for the STATCOM [15]. finally signals compared with 10 kHz carrier signal, the output signal represents firing pulses for the inverter.

The primary objective of this study is to produce reactive power from the STATCOM in order to enhance voltage stability and PF. The STACOM control strategy balances the source's quadrature current (Iqs) with the load guardant current (Iql), allowing the STATCOM to supply the reactive power demands of the nonlinear load while the source provides the active power component.

3. SYSTEM CONFIGRATION

PWM switch-based STATCOM is connected to a single infinite bus (SMIB) power system, nonlinear loads connected at (PCC) as shown in Figure 3, parameters are shown as: i) rated power 100 KVA, 50 Hz, ii) grid voltage 415 r.m.s volt L-L, iii) DC capacitor voltage 800 volt, iv) switching frequency 10 kHz, v) DC capacitor 5,600 micro farad, vi) filter inductance 500 mH, vii) filter capacitor 100 micro farad, viii) load inductive reactive power 100 Kvar, and ix) load active power 200 kW. The PI controller are implemented in MATLAB enviroment, the reference current is taken as the q component of the load current to obtain reactive power from stsatcom. A full load simulated with R-L parameters (200 kW+100 kVar) is connected in the grid. The Vdc is charged to 800 V. Figure 4 show the source voltage signal and source current signal. It can have seen that the phase shift between the two signals nearly zero i.e unity PF.

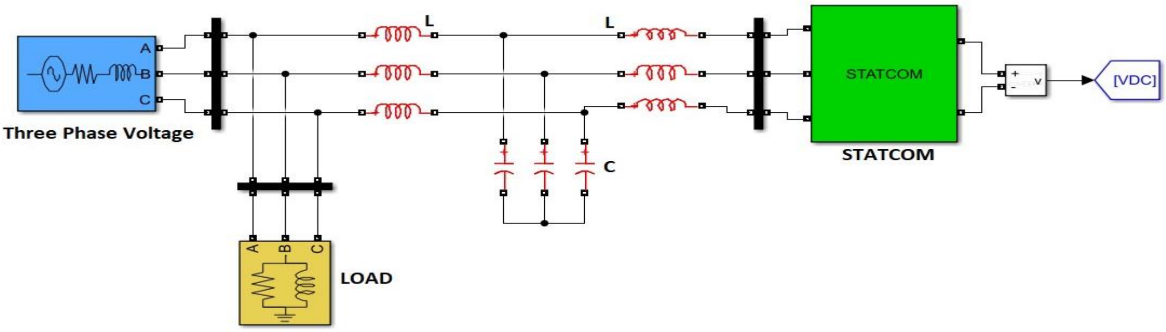

Figure 3. Studeid system

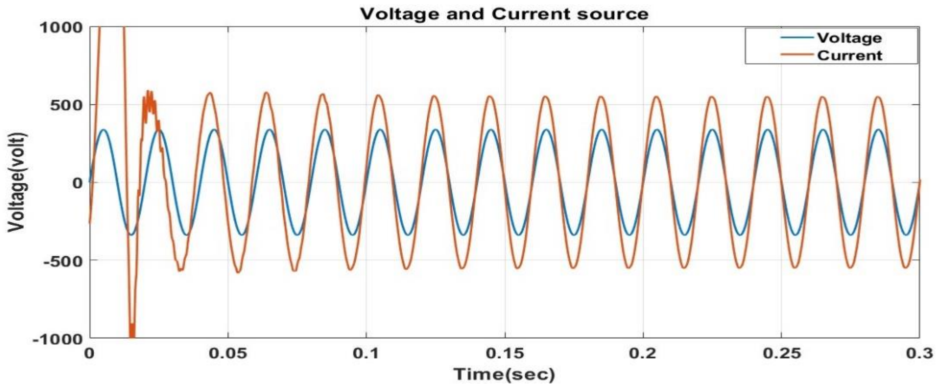

Figure 4. Voltage and current for source

Figure 5 displays the waveforms of active and reactive power for the source, load, and inverter of the STATCOM. Figure 5 demonstrates that the source provides active power to the load, while the STATCOM supplies the reactive power required by the load. This proves that STATCOM works well. Figure 6 displays the active and reactive power for source, load and inverter of STATCOM after adding half of value of load at time (0.3 sec) and outside at time (0.7 sec). It was clear that the reactive power of load compeletly generated by STATCOM and active power has been supplied from source.

Figure 7 illustrate the reactive power of the load and the STATCOM when adding the load from 10-40% from full load value with a step of 10% and adding an unbalanced three phase resistive load with values equal to (100e3, 0.1e3, 70e3) watt and an unbalanced three phase inductive load (90e3, 10e3, and 30e3) var. From Figure 7, we note that the STATCOM is fully responsible for supplying the load with reactive power despite the increase in the load value up to 40% from the value of the full load, and even after adding a non-linear, unbalanced resistive and inductive load, the STATCOM was able to supply the load with reactive power.

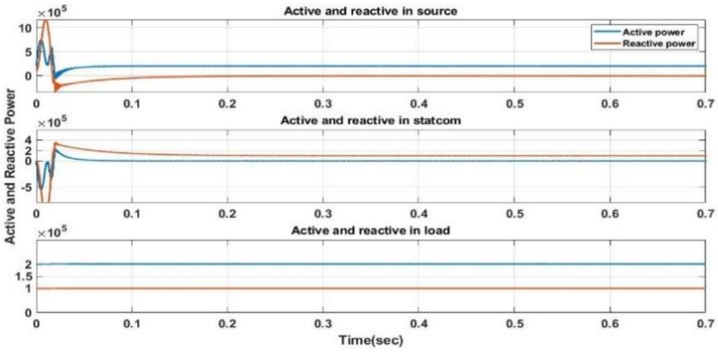

Figure 5. Active power and reactive power for source, load, and inverter of STATCOM in normal load

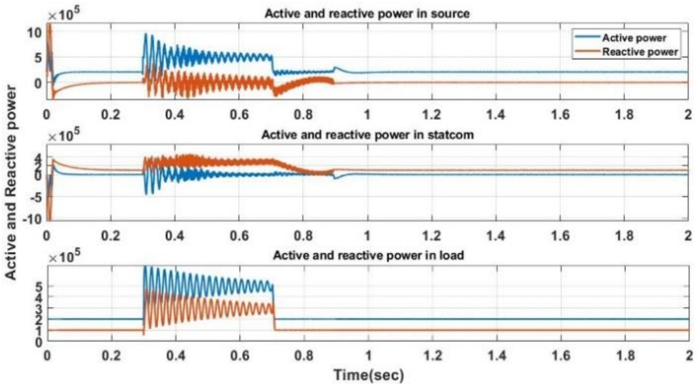

Figure 6. Active power and reactive power for source, load, and inverter of STATCOM after adding half load

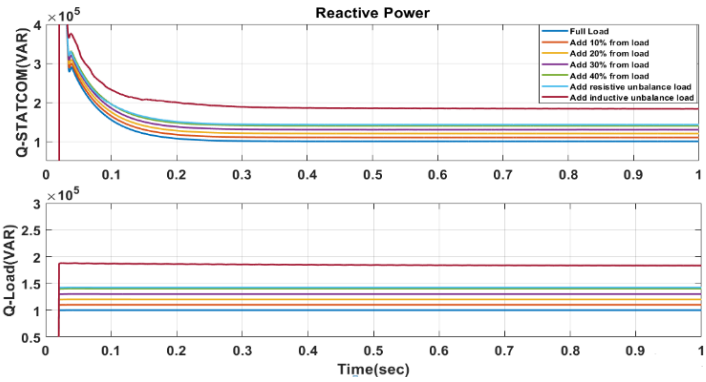

Figure 7. Reactive power for STATCOM and load in different cases

4. DC VOLTAGE CAPACITOR CONTROLLER

The outer loop control in STATCOM done by sensed capacitor voltage and then compared with a reference value (Vdc.ref), which was selected with a value of 800 V, it was calculated as suitable value for the system [3]. The inputs to the PI controller to generate the current reference are the error signal "e" which is calculated as the difference between the desired DC voltage (Vdc.ref) and the actual DC voltage (Vdc), and the change in error signal "Ee (n)" which is found by subtracting the error signal at the previous time step (e (n-1)) from the error signal at the current time step (e (n)). This is depicted in Figure 8 [16]. In this paper, the proposed FL-T1, FL-T2 and ANFIS controllers are implemented for Vdc regulation. The direct axis source current (Idref) command for the inner current loop is guided by the output from the fuzzy controller.

4.1. Type-1 fuzzy logic and type-2 control

FL is one of the artificial intelligence methods, it is a way of thinking. This approach is similar to how humans perform decision-making and includes all possibilities between yes and no. The installation of FL-T1 has four stages: fuzzifier, rule, inference engine (IE), defuzzifier [17], [18]. FL-T2 has almost the same architecture as FL-T1, with the improvement which developed the state of the fog, which has clearly changed the algorithm steps. Type reducer (TR) is represented the essential dissimilarity in output processing stage [19]. The Figure 9 represent structure of two types, using the rules in FL-T1 in FL-T2, the inputs invigorate an IE to get output of FL-T2, then handled via a stage TR that reduces to FL-T1, after that is defuzzified to obtain the fixed output [20], [21]. The three-dimensional MF is the basis for the difference in the structure of FL-T2 from FL-T1 in the presence of the reducer type. MF in FL-T2 has an upper bound for the membership value and a lower bound, which are diffusion in the interval (0, 1) so that (MF) in FL-T2 has a footprint of uncertainty (FOU) [20], [22], [23].

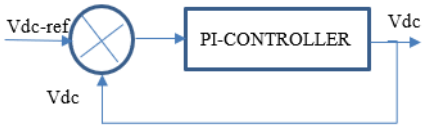

Figure 8. D.c voltage capacitor loop

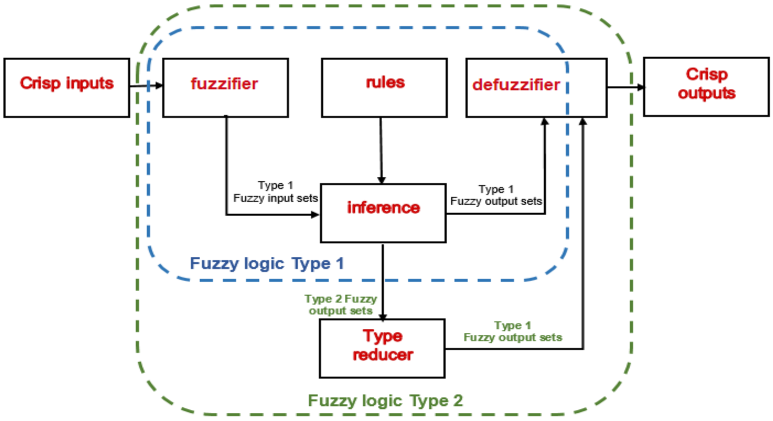

Figure 9. T1-FL and T2-FL schematic

FL-T1 and FL-T2 controllers is designed type Mamdani using MATLAB. The error (e) and change of error (dele) are used input signals to the controller. Each input and output have seven membership functions type triangular form 'trimf' with range (-1,000 and 1,000), the selection of seven fuzzy sets was made, they are: negative-big (NB), negative-medium (NM), negative-small (NS), zero (ZE), positive-small (PS), positive-medium (PM), and positive-big (PB). The membership functions for two inputs, (e) and (dele), and one output are depicted in Figures 10 and 11 respectively.

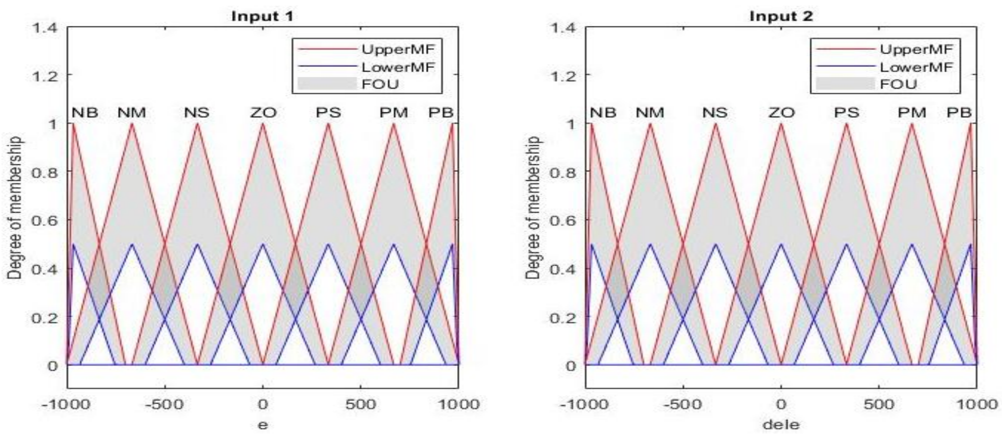

Figure 10. Inputs MFs (e) and (dele) in the amplitude (−1,000 and 1,000) in FL-T2

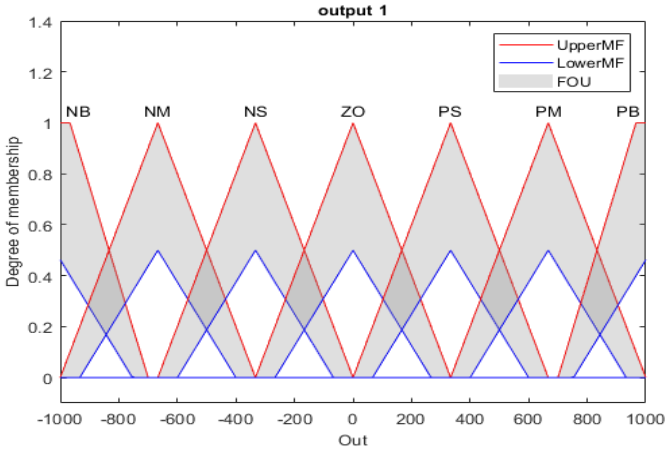

Figure 11. Outputs membership function in the amplitude (−1,000 and 1,000) in FL-T2

MATLAB 2021 is utilized to simulate and operate FL-T2. The lower scale has a value of 0.5, which in MATLAB is defined as a positive scaling factor lower than or equal to 1. The lower lag, which indicates a delay ranging from 0 to 1, is set to 0.2. The upper (MFs) values remain unchanged from the state of FLT1. Finally, 49-rule are chosed for FL-T2 for the best console execution. It is the same as the FL-T1 rules which is presented in Table 1.

Table 1. Fuzzy rule for e and dele

e \ Dele	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	NS	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	ZO	PS	NS	PM	PB	PB	PB
PB	PS	PM	PB	PB	PB	PB	PB

4.2. Adaptive neuro fuzzy inference system

ANFIS combines the characteristics of ANN and FL. It can be differentiated from conventional FL systems by its adaptive parameters that enable both premise and consequent parameters to be altered [21], [24], [25]. The architecture of the ANFIS system used in this case is shown in Figure 12.

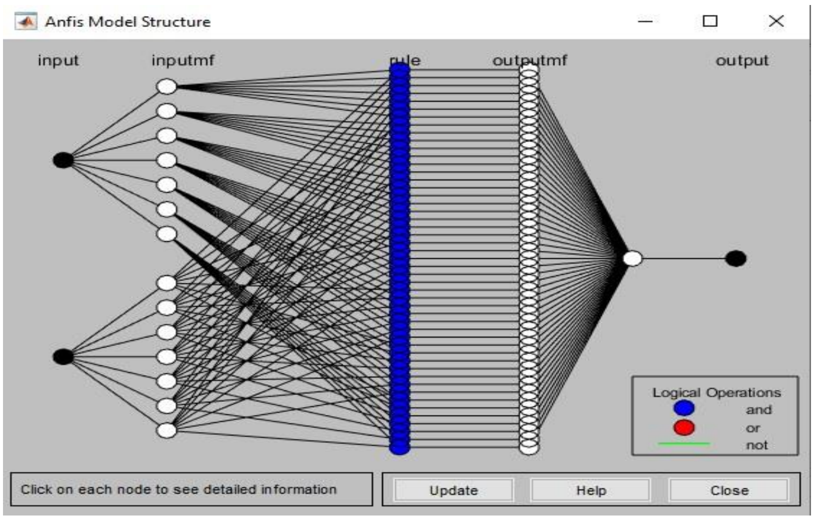

Figure 12. Structure of ANFIS model

The input and output data of the conventional DC voltage controller (PI) is used as input to ANFIS to get the data we need for training [4], this data is collected from the controller PI which gives a pair of data ie. error (e) and change of error (Ee) signals as signals input to the ANFIS environment to adjust or adapt it, while the output represents the DC voltage control signal. The training data should contain a large amount of data about the system's behavior for multiple cases of load disturbance, after that a.fis file is created using "anfisedit" in MATLAB and loads the data that is used in the training and creates the fuzzy inference system (FIS) structure with the appropriate MFs. Finally, train the FIS up to the number of certain epochs. In this study, the PI-ANFIS controller is designed using Sugeno FIS with chosen (100) epochs and (7) MFs type 'trimf' as inputs and one output from linear type.

5. RESULT AND DISCUSSION

After simulating our system (SMIB) using MATLAB 2021 and identifying all its components. Figures 13 and 14 show Vdc signals using four types of STATCOM controllers at full load and 50% full load increased, respectively. We notice from the Figures 13 and 14 that the least deviation of the Vdc is in the case of the ANFIS controller, followed by FL-T2, then FL-T1 and finally the PI controller. Table 2 presented the simulation result for the Vdc signal for three cases such as increasing the half-load, adding an unbalanced resistive load, and adding an unbalanced inductive load. The value of ST time and P-os were relied upon to compare between the four controllers. Table 2 showed that the lowest deviation of P-os is in the case of ANFIS compared to the other controllers for the three studied cases, where the deviation decreased by (13-27%). As for the TS, which represents the speed of signal stability and a fixed range from 2-5% of its last value, it is noted that the fastest ST for all studied cases is in the case of the ANFIS controller, with an error rate ranging approximately (32-92%) compared to other controllers. The above results proved that the ANFIS controller is the best and fastest compared to the rest of the controllers, followed by the FL-T2 controller, then the FL-T1 controller, and the PI controller is in the last rank.

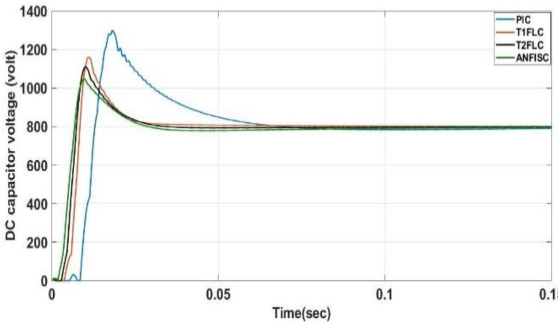

Figure 13. DC voltage signals for different controller

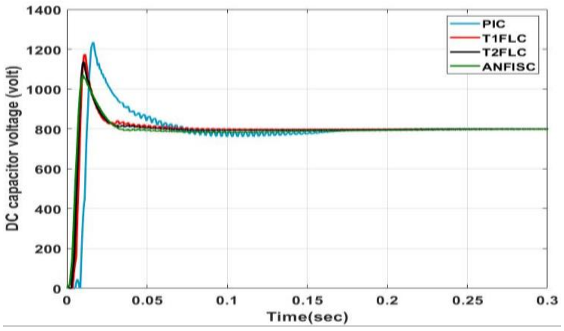

Figure 14. DC voltage signals for different controller

Table 2. Simulation numerical result for the Vdc signal for three cases

Case	Controll-er	Settling time (sec)	Peak overshoot (Kvolt)	Error ST	Error P-os
Increase half load	PIC	0.1662	1.2356		
	T1FLC	0.0519	1.1745	0.687	0.0494
	T2FLC	0.0417	1.1370	0.749	0.0797
	ANFISC	0.0130	1.0711	0.92	0.133
Unbalance resistive load	PIC	0.2980	1.2623		
	T1FLC	0.2695	1.2110	0.0956	0.0406
	T2FLC	0.2197	1.1972	0.2627	0.0515
	ANFISC	0.1998	0.9099	0.3295	0.2791
Unbalance inductance load	PIC	0.4961	1.2971		
	T1FLC	0.2997	1.2355	0.3958	0.0474
	T2FLC	0.2895	1.1885	0.4164	0.0837
	ANFISC	0.2155	0.994	0.5656	0.2336

6. CONCLUSION

In the first part of this paper, a STATCOM was modeled, connected to a power system with a non-linear load, using MATLAB/Simulink to improve voltage stability and PF. The STACOM control strategy adjusts the source's current in order to make the source quadrature current (Iqs) is equalized by the load guardant current (Iql), as a consequence the reactive power demands of nonlinear load are furnished by the STATCOM and the active power component is equipped from the source. The PI controller gave a good response to get a PF equal one for different loads cases. In the second part PI controller in the V_{dc} circuit has replaced with intelligent controllers represented by ANFIS, FL-T_2 and FL-T_1 to control the Vdc voltage. The ANSFIS controller has proven its high ability to control the voltage of Vdc when compared to other controllers, where the P-os of the V_{dc} has been reduced to a value ranging between (13-27%) and a ST between (32-92%) for different loads.

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