
ABSTRACT

The higher power demand and competitive environment of electric power industries has forced the electrical equipment usage to its maximum capacity which raises the serious power quality issues such as voltage sag or swell problems in the electrical power system. The power quality issues can be effectively solved in minimum time by properly installing the FACTS devices such as FC-TCR and STATCOM in the model of the system with control strategy based on advanced intelligent control. This paper presents the effective solution of power quality issues using the FC-TCR and STATCOM in the model of the system. The ANFIS and fuzzy logic based control are designed and implemented in a closed-loop fashion and the application results of improvement are presented through various simulation results. The conventional PI is also designed for the considered power system; however, its performance is not up to the acceptance level whereas the system performance improves significantly through the combination of FACTS with intelligent control schemes.

KEYWORDS: FC-TCR, Statcom, Conventional PI, ANFIS, Fuzzy logic.

INTRODUCTION

Due to development of modern society and higher living standards has led to the facilitation of increased and economic power demand of the modern power customers. Further, higher industrial power demands and competitive deregulation environment of electric power industry has forced the electrical equipment's to use at their maximum capacity while maintaining the system reliability and the acceptance level of the standard. On the other side, the electrical equipment's are much sensitive to disturbances and less tolerant to power quality problems such as voltage sag, swells and harmonics. When reactive power absorption is more than the generation the voltage becomes less than the normal value and this result in voltage sag whereas when reactive power generation is more than the absorption then voltage becomes more than the normal value and this results in voltage swell. The problems associated with voltage dip are considered as one of the most severe disturbances in the electrical energy system which further raises the several threats to the stability of the power system [1].

The power electronic industry development and its effective applications to solve the problems of real power system operation is a major issue of the concern i.e. FACTS. The FACTS devices controls the power flow increased the power transfer capability and further improve the overall security and system stability without requiring the expansion in transmission and generations. The applications of FACTS controller such as unified power flow controller (UPFC) and the Static Synchronous Compensator (STATCOM) have shown the successful results in [2]. In [3-8], it has been shown that FACTS can give better flexibility stability margins to electrical energy system and hence improves the power transfer capability limit in shunt or either series compensation. It is observed from the available research that the application of various FACTS devices are increasing in real power system to solve the various issues in the power system in a more effective and efficient manner. However, the application of FACTS such as fixed capacitor thyristor control reactor (FC-TCR) as a static VAR compensator (SVC) and static compensator (STATCOM) in power quality problem i.e. voltage sag or swell have not been explored so far by the researchers and electric power engineers

worldwide. These FACTS devices are used to maintain reactive power balance in the system and hence solve the voltage sag and swell problem in a more efficient and effective manner. FC-TCR works on the principle of variable impedance and it contains no source whereas STATCOM contains voltage or current source. Further, the design of fuzzy logic based control as well as artificial neuro fuzzy inference (ANFIS) are also used with the application of above mentioned FACTS to improve the power quality problem of the system and the investigation results of voltage and current wave form for different case studies are analyzed and presented.

MODELLING OF FC-TCR

A thyristor-controlled reactor (TCR) is a reactance connected in series with a bi-directional thyristor valve. The thyristor valve is phase controlled which allows the value of delivered reactive power to be adjusted to meet the varying system conditions. Thyristor controlled reactors can be used for limiting voltage rises on lightly loaded transmission lines. The current in the TCR is varied from maximum (determined by the connection voltage and the inductance of the reactor) to almost zero by varying the firing delay angle. The representation of the TCR is shown in Fig. 1. The controlling element is the thyristor controller shown as two back-to-back thyristors which conduct on alternate half-cycles of the supply frequency. If the thyristors are gated into conduction precisely at the peaks of the supply voltage, full conduction results in the reactor, and the current is the same as though the thyristors controller were short-circuited.

The current is essentially reactive lagging the voltage by nearly 90° . It contains a small in-phase component due to the power losses in the reactor, which may be of the order of 0.5-2% of the reactive power. Full conduction is shown by the current waveform in Fig. 2 (a). If the gating is delayed by equal amounts on both thyristors, a series of current waveforms is obtained, such as those in Fig. 2(d). Each of these corresponds to a particular value of the gating angle α , which is measured from the zero-crossing of the voltage. Full conduction is obtained with a gating angle of 90° . Partial conduction is obtained with gating angles between 90° and 180° . The effect of increasing the gating angle is to reduce the fundamental harmonic component of the current. This is equivalent to an increase in the inductance of the reactor, reducing its reactive power as well as its current. So far as the fundamental component of current is concerned, the TCR is a controllable susceptance and can therefore be applied as a static compensator in the power system.

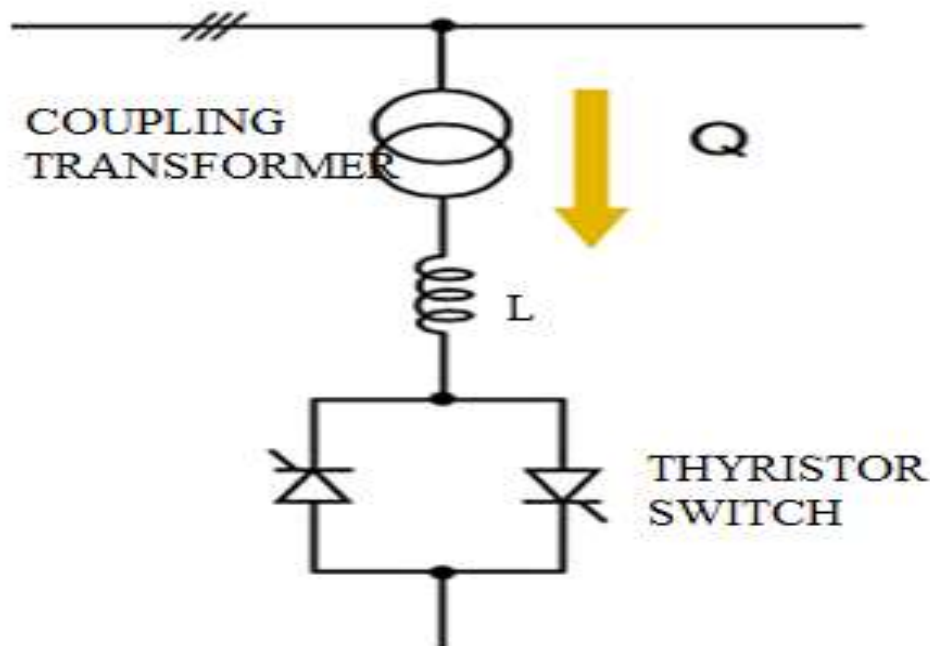


Fig. 1 Basic FC- TCR topology

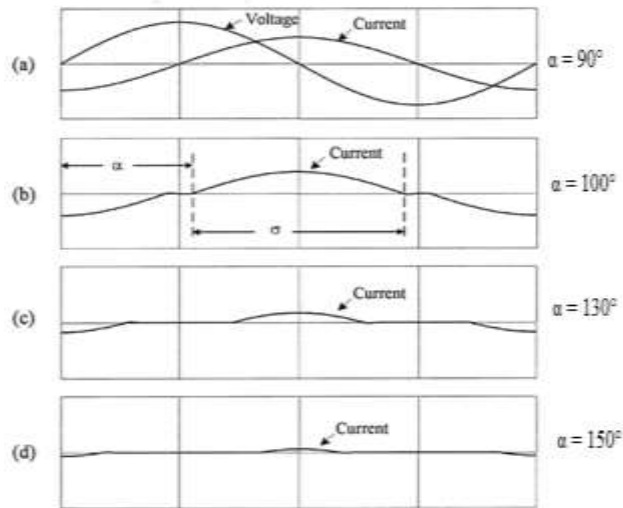


Fig. 2 (a- d) Voltage and current waveforms of TCR at different firing angle

The instantaneous current i is given by:

$$i = \frac{\sqrt{2}V}{X_L} (\cos\alpha - \cos\omega t), \alpha < \omega t < \alpha + \sigma \quad (1)$$

$$i = 0, \quad \alpha + \sigma < \omega t < \alpha + \pi \quad (2)$$

Where V is the rms voltage; $X_L = \omega L$ is the fundamental-frequency reactance of the reactor (in Ohms); $\omega = 2\pi f$; and α is the gating delay angle. The time origin is chosen to coincide with a positive-going zero-crossing of the voltage. The fundamental component is found by Fourier analysis and is given by:

$$I_1 = \frac{\sigma - \sin\sigma}{\pi X_L} V A_{rms} \quad (3)$$

Where, σ is the conduction angle, related to α by the equation

$$\alpha + \frac{\sigma}{2} = \pi \quad (4)$$

Equation 3 can be written as;

$$I_1 = B_L(\sigma) V \quad (5)$$

Where, $B_L(\sigma)$ is an adjustable fundamental-frequency susceptance controlled by the conduction angle according to the law

$$B_L(\sigma) = \frac{\sigma - \sin\sigma}{\pi X_L} \quad (6)$$

This control law is shown in Fig. 3. The maximum value of B_L is $1/X_L$, obtained with $\sigma = \pi$ or 180 , i.e. full conduction in the thyristor controller. The minimum value is zero, obtained with $\sigma = 0$ ($\alpha = 180^\circ$). This control principle is called phase control.

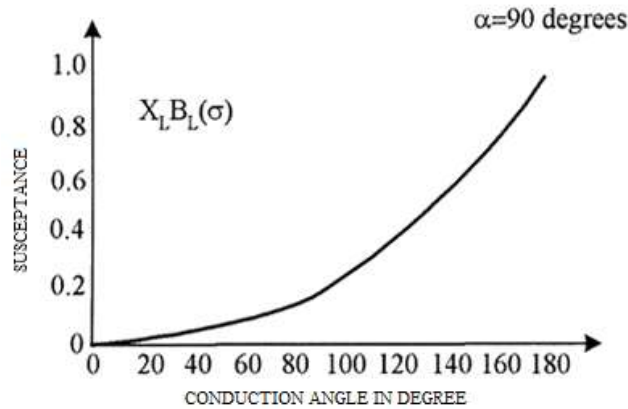


Fig 3 Control law of FC- TCR

MODELLING OF STATCOM

The STATCOM is modeled by a voltage source connected to the power system through a coupling transformer. The source voltage is the output of a voltage-sourced converter (VSC) realizing the STATCOM as given in Fig. 4. STATCOM is assumed at the midpoint of the transmission line. The phase angle of the source voltage is equal as that of the midpoint voltage. Therefore, there is exchange of only reactive power and no real power flows between the STATCOM and the AC system.

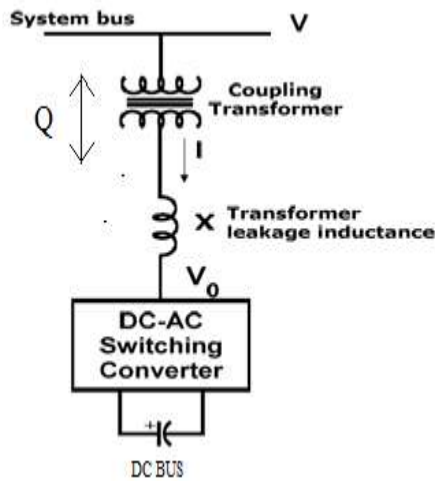


Fig. 4 Model of STATCOM

The expressions for the current flowing from the STATCOM to the system and the reactive power injection are given as:

$$I = \frac{(V_{sc}-V_m)\angle\theta_m}{jX_l} \tag{7}$$

$$Q = V_m^2 \frac{(V_{sc}-1)}{jX_l} \tag{8}$$

Where, V_m is the magnitude of the voltage at the mid-point of the line and V_{sc} is the magnitude of the voltage of the voltage-sourced converter, θ_m is the phase angle of the mid-point voltage, and X_l is the coupling transformer leakage reactance. The magnitude of the voltage of the voltage-sourced converter determines the direction and nature of the

reactive power flow. If it is greater than the magnitude of the line midpoint voltage, then reactive power is injected into the AC system whereas if the line midpoint voltage magnitude is greater than the reactive power will be drawn from the AC system. Only the reactive power injection mode of operation is considered for the analysis. The leakage reactance of the coupling transformer is taken as 0.1 p. u. During fault conditions a constant value of source voltage magnitude may cause a very high value of current drawn from the STATCOM (I_{sc}). For this, a maximum limit, denoted by I_{max} , is set for the STATCOM current. For a practical system, this current limit is decided by the rating of the STATCOM. When the current reaches the limit I_{max} , STATCOM behaves like a constant current source.

To include this feature in the simulation, V_{sc} is kept constant at the pre-specified value (denoted by V_{sco}) when $I_{sc} \leq I_{max}$. But, whenever the value of I_{sc} exceeds I_{max} , the value of V_{sc} is adjusted such that I_{sc} becomes equal to I_{max} . The STATCOM is used to control power flow of the power system by injecting appropriate reactive power during dynamic state. The STATCOM is a voltage-sourced-converter (VSC)-based shunt-connected device. By injecting a current of variable magnitude in quadrature with the line voltage, the STATCOM can inject reactive power into the power system. The STATCOM does not employ capacitor or reactor banks to produce reactive power as does the SVC, but instead uses a capacitor to maintain a constant dc voltage for the inverter operation. An equivalent circuit for the STATCOM is shown in Fig. 5.

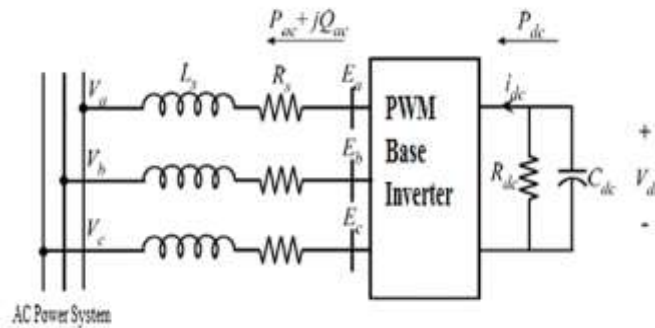


Fig 5 Equivalent circuit of STATCOM

Where R_s and L_s represent the STATCOM transformer losses, E_{abc} are the inverter ac side phase voltages, V_{abc} are the system-side phase voltages, and i_{abc} are the phase currents. The output of the STATCOM is given by:

$$E_a = kV_{dc} \cos(\omega t + \alpha) \quad (9)$$

Where, voltage across the V_{dc} is the dc capacitor, k is the modulation gain. By defining a proper synchronous reference frame, the dynamic model can be simplified. The reference frame coordinate is defined in which the d-axis is always coincident with the instant system voltage vector and the q-axis is in quadrature with it. By transforming the system model to this reference frame, the STATCOM equations at bus i can be written as:

$$\frac{1}{\omega_s} \frac{d}{dt} i_d = -\frac{R_s}{L_s} i_d + \frac{\omega}{\omega_s} i_q + \frac{K}{L_s} \cos(\alpha + \theta_i) V_{dc} - \frac{V_i}{L_s} \cos\theta_i \quad (10)$$

$$\frac{1}{\omega_s} \frac{d}{dt} i_q = -\frac{R_s}{L_s} i_q + \frac{\omega}{\omega_s} i_d + \frac{K}{L_s} \sin(\alpha + \theta_i) V_{dc} - \frac{V_i}{L_s} \sin\theta_i \quad (11)$$

$$\frac{C_{dc}}{\omega_s} \frac{d}{dt} V_{dc} = -k \cos(\alpha + \theta_i) i_d - k \sin(\alpha + \theta_i) i_q \frac{V_{dc}}{R_{dc}} \quad (12)$$

Where i_d and i_q are the injected dq STATCOM currents, V_{dc} is the voltage across the dc capacitor, R_{dc} represents the switching losses, R_s and L_s are the coupling transformer resistance and inductance, respectively

ANFIS DESIGN

The artificial neuro fuzzy inference system (ANFIS) is an intelligent technique having the intelligence of fuzzy and the learning capability of neural in order to get the exact and desired output in various conditions as required in the

system. The idea behind the concept of fuzzy inference system (FIS) is that it can deal with linguistic expressions and the advantage of neural networks that can be trained and so can self-learn and self-improve the performance of the system. In 1993 Jang, a Japanese Scientist proposed the combined concept of fuzzy and neural networks known as ANFIS in order to design a system that uses a fuzzy system to represent knowledge in an interpretable manner and has the learning ability derived from a neural network that can adjust the membership functions parameters and linguistic rules directly from the data in order to enhance the dynamic system performance. The model of control scheme is shown in Fig. 6.

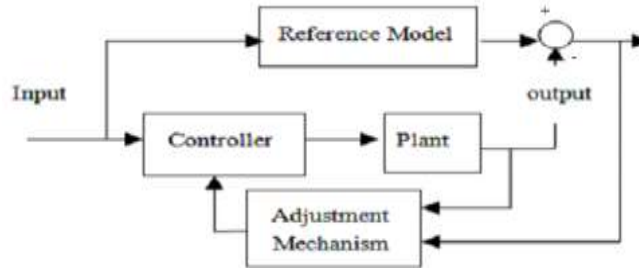


Fig 6 Basic diagram of ANFIS control

ANFIS is a hybrid intelligent system which implements a Sugeno fuzzy inference system for a systematic approach to generating fuzzy rules from a given input- output data set. One of the methods proposed by Jang to update the parameters of the networks uses a combination of gradient descent and least squares estimator (LSE). ANFIS uses two sets of parameters: a set of premise parameters and a set of consequent parameters. ANFIS uses a hybrid learning algorithm to tune the parameters of a Sugeno-type fuzzy inference system (FIS). The algorithm uses a combination of the least-squares and back-propagation gradient descent methods to model a training data set. ANFIS also validates models using a checking data set to test for over fitting of the training data and the system performance improves significantly. However, ANFIS needs proper training with different number of epochs and the rigorous training runs were performed and the best trained model is used to improve the power quality issues in the power system

SIMULATION RESULTS AND DISCUSSION

Brief description of the power system considered in this work:

A radial power system is considered for the research and investigations. Power system has a source of 25KV, 100MVA connected to a step up transformer of 25/ 220KV, 100MVA. A substation local load of 30KW is also considered. A 200 Km transmission line is considered between the source and the load end in order to transfer the power from source to load end. Receiving end of the system contains a variable load. There is a use of circuit breaker to attach and de-attach the load as per the system conditions. One load is 40 MW whereas the other load is of 10 MW. In addition to this, a dynamic load of 10 MW is also used. The reactive power compensation device is connected at the centre of the transmission line. The thyristor controlled reactor with fixed capacitor banks (TCR-FC) and static compensator (STATCOM) as reactive power management devices are used to improve the power quality problems. The power Circuit of FC-TCR consists of the reactor connected in series with anti-parallel thyristor. Each branch of TCR is star connected. A three phase star connected capacitor bank of rating 43.92MVAR is connected in parallel with TCR. The combination of TCR and fixed capacitor is connected to bus in parallel whose voltage profile is to maintained flat. FC-TCR is basically a Static VAR Compensator (SVC) FACTS device. SVC is a variable impedance type FACTS device and does not contain any source. On the other hand STATCOM is static compensator which contains a source. STATCOM may contain voltage source converter or a current source converter. In our Simulink model, we have used voltage source converter based STATCOM. The output of the inverter is given to a LC filter to remove the harmonics of the system. Transformer is of 250MVA 220/100 KV rating. A battery at the input side of the inverter is also used. Modern practice is to use IGBT in the inverter circuitry. However, thyristor can also be used in place of IGBT but a separate commutation circuitry will be required. Practically, choice between IGBT and thyristor depends on the rating of the STATCOM. The reactive power injected into the system can be controlled by controlling the inverter. Here inverter is controlled by Pulse Width Modulation Technique (PWM). There are many types of PWM technique available in the literature. However, we have chosen Sinusoidal PWM technique because of its simplicity as well as it is capable of reducing the lower order harmonics. The Carrier signal used is of 5000Hz.

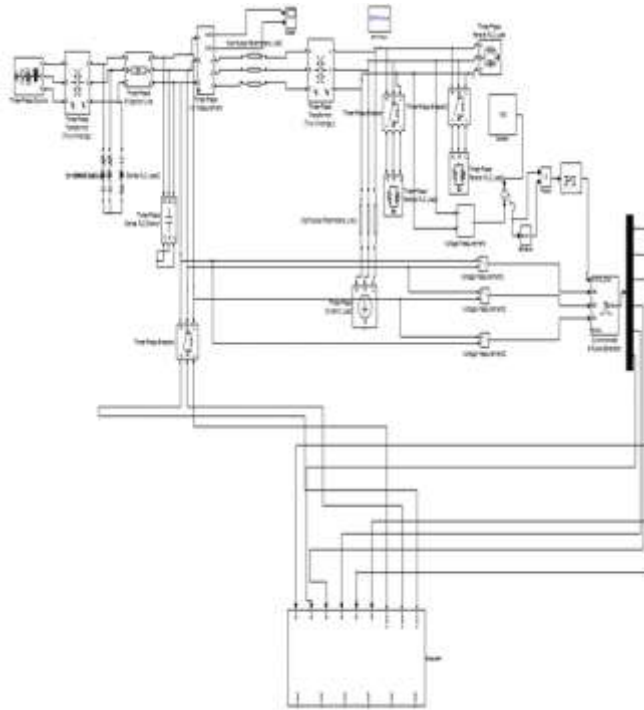


Fig 7 MATLAB Simulink model of Power System

In order to have the analysis and investigations, the MATLAB Simulink model was run for 0.1 Seconds. The dynamic load and load of 40MW remain connected throughout the simulation. After 2 cycles, load of 10MW was connected in the system and it was removed from the system at the beginning of the 5th cycle. There is a use of circuit breaker to attach and de-attach the load. In the first simulation as shown in Fig. 7 where no compensation was used, we noticed a sag in the voltage profile at the mid of bus. At the beginning of 3rd cycle, when a load of 10MW was switched on, a decrease in load voltage and a corresponding increase in load current were noticed from the simulation results and the voltage profile become 1 p. u. when load was disconnected at the beginning of 5th cycle.

In second set of simulations we have used FC-TCR as a compensation device to improve the voltage profile of the system. We have used FC-TCR in a closed loop control system. The control strategy based conventional PI, fuzzy and ANFIS are designed and the comparative analyses in terms of achieved results were presented. Since PI controller is a non-adaptive controller whose effective gains are find through hit and trail method hence, it is effective for only up to 80% sag. Beyond 80% of sag, its results were not satisfactory. On the other side fuzzy is an intelligent controller and its effectiveness can be clearly seen from the results achieved, it is very much effective in removing sag up to 65% with steady state error in acceptable range of the system. But in this case, the THD of voltage waveform is poor. THD was found to be 3.7%. However, the further improvements were observed with the help of ANFIS control design. As discussed earlier, the considered ANFIS control is trained with the help of Back propagation learning algorithm with suitable number of epochs and the best trained model is used for the simulations.

In third set of simulations, STATCOM was used as a reactive compensation device. Again it contains various sets of simulations. Different controllers were used in this work. Performance of PI controller, Fuzzy controller and ANFIS were tested on MATLAB SIMULINK platform. From the analysis of the results, it is observed that PI Controller is known to reduce the steady state error to zero. But it makes the system sluggish. Further, it requires effective gain through proper tuning methods. Hence, we require intelligent controllers. The simulation results are shown in Fig. 8 to12. PI controller tuned for 90% sag gives satisfactory results for 75% sag. For 75% sag, steady state error was found to 2.9%.

The fuzzy logic based control is also designed for the system having STATCOM. The Mamdani based fuzzy logic control scheme is used with two inputs and one control output. One input is error and other is rate of change of error. In both the inputs, seven triangular shaped membership functions were used, 49 fuzzy, if then rule base was constructed to get the desired control action. It is tested on the considered model. It is observed that, it removes sag up to 65% with steady state error under acceptable limits (0.73%). THD of bus voltage was found to be 1.43%. The drawback of fuzzy logic based scheme is complex rule base and slow operation because every time it has to scan 49 rule base in order to get the desired action.

The ANFIS controller is also tried to overcome the drawbacks of fuzzy and to get more improved results. ANFIS controller is basically an adaptive fuzzy controller. In this controller, membership function is not fixed but variable or adaptive. ANFIS controller was trained first by using 200 data sets. After its proper training, it was used to control STATCOM. The results of ANFIS are much better as compared to fuzzy and conventional PI. Even for sagging condition up to 75%, the steady state error was 0.23% and THD of bus voltage waveform is 0.28%. The low value of THD implies low harmonic contents in voltage waveform. However, the low harmonic content is always advantageous in any power system and the investigations shows the design of ANFIS is much superior in all aspects to improve the voltage profile of the system as compared to that obtained with conventional and fuzzy based control.

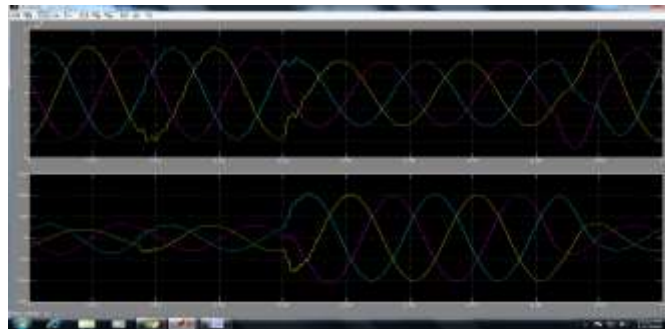


Fig 8 Waveform of voltage and current during Sag and Swell without any FACTS device

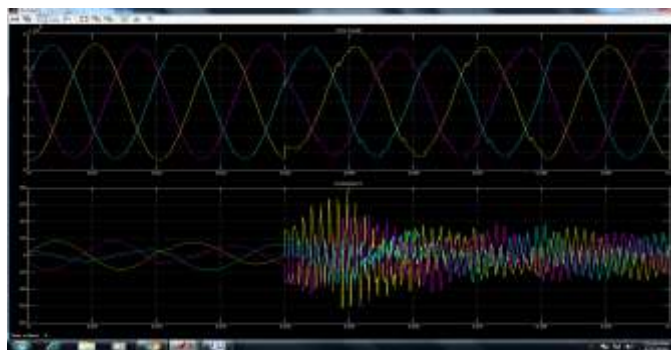


Fig 9 Waveform of voltage and current with FC-TCR

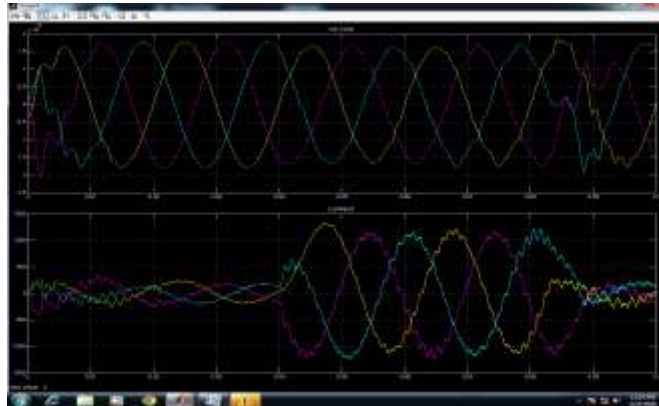


Fig 10 Waveform of voltage and current with PI Controller (STATCOM)

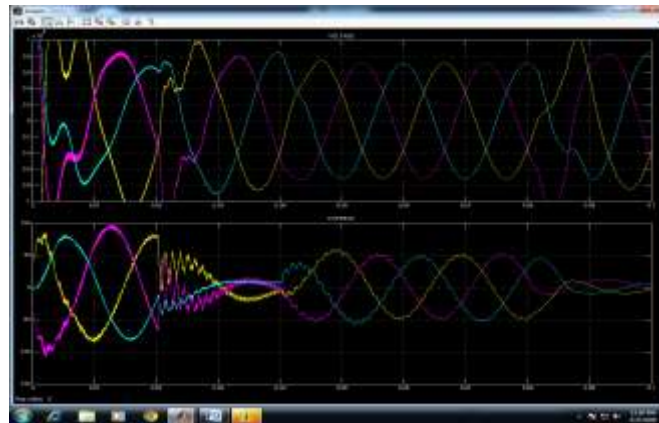


Fig 11 Waveform of voltage and current with Fuzzy controller (STATCOM)

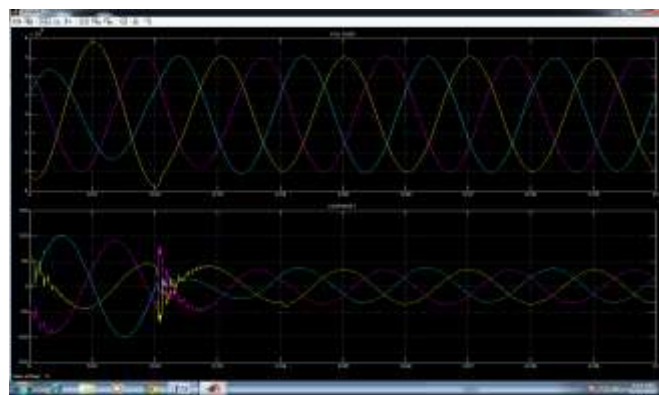


Fig 12 Waveform of voltage and current with ANFIS controller

CONCLUSION

This paper presents the design and implementation of FC-TCR and STATCOM based FACTS controller in the model of the system to solve the problem of voltage sag and swell in the electrical power system. The simulations were performed on standard MATLAB software and the applications results are presented:

- [1] The conventional PI based control scheme in a closed-loop fashion is designed and tested on the considered system with the applications of FC-TCR. However, its performance is not up to the acceptance level as it is effective for only up to 80% sag.

- [2] The fuzzy based design is much effective in removing sag up to 65% with steady state error in acceptable range of the system. But in this case, the THD of voltage waveform is poor. THD was found to be 3.7%. However, the further improvements in the system results were observed with the help of ANFIS control design and the promising system results were obtained.
- [3] The application results of STATCOM are also presented using the combination of conventional PI, fuzzy and ANFIS. The ANFIS controller is tried to overcome the drawbacks of fuzzy and to get more improved results.
- [4] The results of ANFIS are much better as compared to fuzzy and conventional PI. Even for sagging condition up to 75%, the steady state error was 0.23% and THD of bus voltage waveform is 0.28%. The low value of THD implies low harmonic contents in voltage waveform. However, the low harmonic content is always advantageous in any power system and the investigations shows the design of ANFIS is much superior in all aspects to improve the voltage profile of the system as compared to that obtained with conventional and fuzzy based control.

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