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STUDY OF TOTAL HARMONIC DISTORTION IN THYRISTOR CONTROLLED REACTOR EMPLOYED IN STATIC VOLTAGE COMPENSATOR

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ABSTRACT

The present work is based on finding the range of firing angle of SCR used in Thyristor Controlled Reactor (TCR) at which harmonic distortion can be minimized. A three-phase controlled rectifier is designed and an accurate statistical method is proposed to calculate its input current, harmonic components and THD with simulation at various firing angles. Influence of firing angle variations on harmonic currents is investigated. Finally a harmonic current database of rectifier is obtained in terms of firing angle. The application of TCR based compensator is then implemented in the transmission line. Least harmonic distortion was observed in specified range of firing angle. The effectiveness of result has been shown using MATLAB/SIMULINK.

Key words: CR, Active and Reactive power, Harmonics, Total Harmonic Distortion.

INTRODUCTION

Most of the electronics equipments are supplied by DC, and the power generation is in AC. So the AC to DC conversion has become universal.

For this conversion Diode rectifier or rectifier having electronic switches have become popular. They affect the system with high Total Harmonic Distortion which may cause low performance, excess heat and large ripple factor. Low power factor leads high reactive power requirement and reduce voltage at the load. As a result line and equipment losses are increased. For stable and reliable operation loads require regulated DC voltage. In this respect switching regulators are available to perform regulation of DC voltage.

Recent works have been proposed on switching regulators with single phase or three phase diode bridge rectifier, single and three-phase AC to DC converters between sources and loads. But non sinusoidal input current, high harmonic distortion, low power factor, large ripple and lower efficiency are the major drawbacks of these regulators. The problem can be solved by adding filter in input and output side of regulators.

Thyristor Controlled Reactor

Fig.1 shows the scheme of a static compensator of the thyristor controlled reactor (TCR) type. A compensator includes a fixed capacitor and a filter (for lower order harmonic). Each of the three phase branches includes an inductor L, and the thyristor switches Th_1 and Th_2. Reactors may be both switched and phase-angle controlled [2],[3].

A continuous range of reactive power consumption can be obtained by phase-angle control technique which results in the generation of odd harmonic current components during the control process. Full conduction is achieved with a firing angle of 90^0 whereas with firing angle between 90^0 - 180^0 partial conduction can be achieved. On increasing the thyristor firing angle causes fundamental reactor current component to decrease. It should be noted that adjustment is limited to once per half cycle and it limits the change in reactor current at discrete points of time. Hence static compensators of the TCR type are characterized by the ability to perform continuous control, maximum delay of one half cycle and practically no transients.

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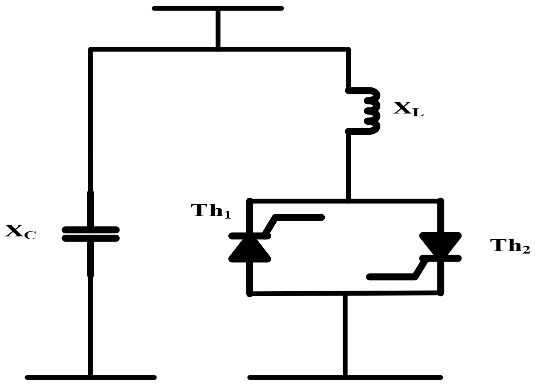

Fig. 1 The Thyristor-Controlled Reactor configuration

The relation between the fundamental component of the reactor current and the phase-shift angle α [4] is given by (1):

$$I_{rms} = \frac{V_{rms}}{\omega L}(1 - \frac{2}{\pi}$$

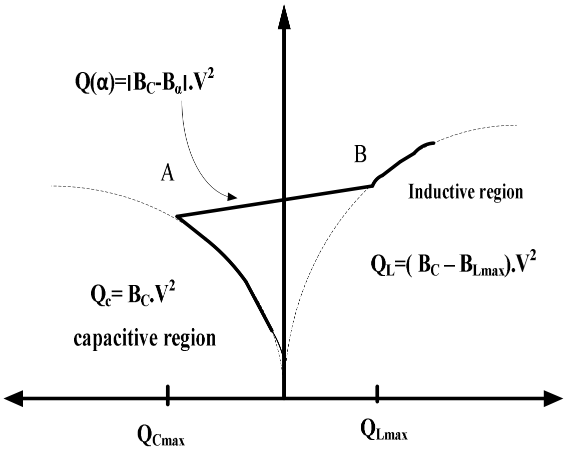

Fig. 2 Voltage – Reactive Power Characteristic of a FC-TCR.

As firing angle varies from 0 to 90^0, the current waveform deviates from its original sinusoidal form and for balanced load condition it starts generating odd harmonics. By connecting the TCR in delta, the third harmonic currents ("Triplen harmonics") flow only around the delta and do not escape into the connected AC system. However, the 5th and 7th harmonics (and to a lesser extent 11th, 13th, 17th etc.) must be filtered in order to prevent excessive voltage distortion on the AC network. Tuned passive and active filters were being used to eliminate these harmonics [5]-[7] but there are some limitations on their application. They offers very low impedance path to the odd harmonic component of currents. Besides this the design of the filter components depends upon the ac source impedance (short circuit level), higher the short circuit level, higher is the rating of the filter circuit component. In addition, these filters are sensitive to the adjacent harmonic generating circuits in the power system network therefore, they may be less efficient.

This characteristic shows the amount of reactive power generated or absorbed by the FC-TCR, as a function of the applied voltage. At rated voltage, the FC-TCR presents a linear characteristic, which is limited by the rated power of the capacitor and reactor respectively. Beyond these limits, the Q-V_{Th} characteristic is not linear, which is one of the principal disadvantages of this type of VAR compensator.

Active and Reactive Power

In general the rate at which energy is transferred or transformed is known as "Power". So, in an electric circuit the rate at which an electric energy is transferred by an electric circuit is known is electrical power. In alternating current (AC) circuits, there are three basic elements are used, which are resistor, capacitor and inductor. Among these three, resistor is the only energy absorbing element where as inductor and capacitor are energy storing device. These storing elements may cause periodic reversals of the energy flow direction. The portion of power that averaged over a complete cycle of the AC waveform, results in net transfer of energy in one direction is known as real power and denoted by P. It is also known as "active power" , "true power" or simply "power" Where as the portion of power due to stored energy, which returns to the source in each cycle, is known as " reactive power" and is denoted by Q.

In a simple alternating current (AC) circuit consisting of a source and a linear load, both the current and voltage are sinusoidal. If the load is purely resistive, the two quantities reverse their polarity at the same time which means phase difference between voltage and current is zero. At every instant the product of voltage and current is positive; indicating that the direction of energy flow does not reverse. In this case, only real power is transferred.

In the case of purely reactive loads (either inductive or capacitive), the voltage and current are 90 degrees out of phase. For each half cycle, the product of voltage and current is positive, but on the other half of the cycle, the product is negative; on average, exactly as much energy flows toward the load as flows back. Net energy flow over one cycle is null. In this case, only reactive energy flows there is no net transfer of energy to the load.

Practically in our power system network, loads have resistance, inductance and capacitance, so both real and reactive power will flow to real loads. Thus the apparent power is measured by the magnitude of the vector sum of real and reactive power. Apparent power is the product of the root-mean-square of voltage and current.

Need of Reactive power Compensation?

Reactive power affects power system operation in following different ways:

1. Loads consume reactive power, so this must be provided by some sources.
2. The delivery system (transmission lines and transformers) consumes reactive power, so this must be provided by some source (even if the loads do not consume reactive power).
3. The flow of reactive power from the supplies to the sinks causes additional heating of the lines and voltage drops in the network.
4. The generation of reactive power can limit the generation of real power.

In the transmission network generators are generally required to support reactive power flow. Transmission system generators are required to supply their rated power between the limits of 0.85 power factor lagging and 0.90 power factors leading at the designated terminals. The system operator have to perform switching actions to maintain a secure and economical voltage profile while maintaining a reactive power balance equation, given as follows:

[Generator MVARs + System gain + Shunt capacitors] = [MVAR Demand + Reactive losses + Shunt reactors]

The 'System gain' is an important source of reactive power in the above equation of power balance, which is generated by the capacitive nature of the transmission network itself. By making decisive switching actions in the early morning before the demand increases, the system gain can be maximized early on, helping to secure the system for the whole day. Pre fault reactive generators may be required some times to balance the equation. Other sources of reactive power can also be used including shunt capacitors, shunt reactors, Static VAR Compensators.

Harmonics

Harmonics are a mathematical way of describing distortion to a voltage or current waveform. The term harmonic refers to a component of a waveform that occurs at an integer multiple of the fundamental frequency.

Fourier theory tells us that any repetitive waveform can be defined in terms of summing sinusoidal waveforms which are integer multiples (or harmonics) of the fundamental frequency. For the purpose of a steady state waveform with equal positive and negative half-cycles, the Fourier series can be expressed as follows:

$$f(t) = \sum_{n=1}^{\infty}$$

Where

f(t) = the time domain function ,

n = the harmonic number (only odd values of n are required)

A_n = the amplitude of the nth harmonic component,

T = time period in seconds,

Harmonics are a steady state phenomenon and repeat with every 50(or 60) Hz cycle. Harmonics should not be confused with spikes, dips, impulses, oscillations or other forms of transients. A common term that is used in relation to harmonics is THD or Total Harmonic Distortion. THD can be used to describe voltage or current distortion and is calculated as follows:

$$\% \mathrm{THD} = \sqrt{I_{D1}^2 + I_{D2}^2 +}$$

where, I_{Dn} is the magnitude of the nth harmonic as a percentage of the fundamental (individual distortion). Another closely related term is Distortion Factor (DF) which is essentially the same as THD.

Harmonics (or distortion in wave form) has always existed in electrical power systems. It is harmless as long as its level is not substantial. However, with the recent rapid advancement of power electronics technology, so-called nonlinear loads, such as variable frequency drives for motor power/speed control, are increasingly finding their way to industrial as well as domestic applications. Harmonics induced by these nonlinear loads are a potential risk if they are not predicted and controlled.

Effect of Change in Firing Angle of the Thyristor

The current in the reactor is varied by varying the firing angle of the thyristor. The method is known as firing delay angle control method. The variable VAR absorption of the thyristor capacitor reactor opposes the variable VAR generation of the fixed capacitor to give the total VAR output. The thyristor controlled reactor is off at the maximum capacitive VAR output. For decrement of the capacitive VAR output the current in the reactor is increased by decreasing the delay angle.

The change in power flow with change in the value of firing angle of the thyristor is studied. The thyristor angle was varied from 0^0 to 180^0 and the corresponding changes in the values of reactive power and the current through the thyristor controlled reactor were noted down and tabulated in Table 1 :-

TABLE I: Variation in I_{TCR} and Q with Firing Angle

S. No.	Firing Angle (Degree)	Current through TCR (Amp)	Q (VAR)
1	30^0	90	33570
2	60^0	78	33580
3	90^0	50	33600
4	120^0	22	33620
5	150^0	7	33640
6	180^0	0	33650

From Table I it is seen that with the increase in firing angle the current varies from maximum value to zero. Subsequently the real power and the reactive power increase on increasing the firing angle.

Simulation Model

A three phase Thyristor Controlled Reactor simulation model has been implemented. The current in the reactor can be controlled from maximum to zero by firing angle control. Thus by this technique closure of thyristor valve is delayed in each half cycle with respect to peak of the applied voltage.

The conduction angle range control results in a non sinusoidal current waveform in case of single phase TCR, thus generates harmonics. For identical positive and negative current half cycle of waveform, only odd harmonics are significant. Its amplitude is given by the following equation as a function of α:

$$I_{La} = \frac{V}{\omega L}\frac{4}{\pi}\left[\frac{\sin\alpha\cos n\alpha - n}{n(n^2}\right.$$

The maximum amplitude of the most significant harmonics, third, fifth, seventh, ninth, eleventh and thirteenth are 13.78%, 5.05 %, 2.59 %, 1.57 %, 1.05 % and 0.75 % respectively of the maximum fundamental current.

But in case of three phase system TCRs are connected in delta connection and in balanced condition, the triplen harmonics circulates in delta connected TCR only and could not enter in to the power system. Other remaining harmonics can be eliminated by filtering and many other techniques.

A three phase delta connected TCR with SSR is shown in the Fig. 3. With six different coils as follows [1]:

L1 =305mH; L2 = 320 mH; L3 =329mH;
L4 =330 mH; L5 =313 mH; L6 =330 mH;
R1=10.3Ω; R2=11.23 Ω; R3=10.5 Ω;
R4= 10.3 Ω; R5=10.83 Ω; R6=11.3 Ω;

The reactor coil in the phase is split in two halves as shown in the Fig. 3 to prevent the full AC voltage appearing across the SSR. The display of all the line and phase currents waveforms are carried out for firing angles α = 90^0, 99^0, 108^0, 117^0, 126^0, 135^0, 144^0, and 153^0. Since all the inductors vary in their magnitudes, results in slight asymmetrical operation.

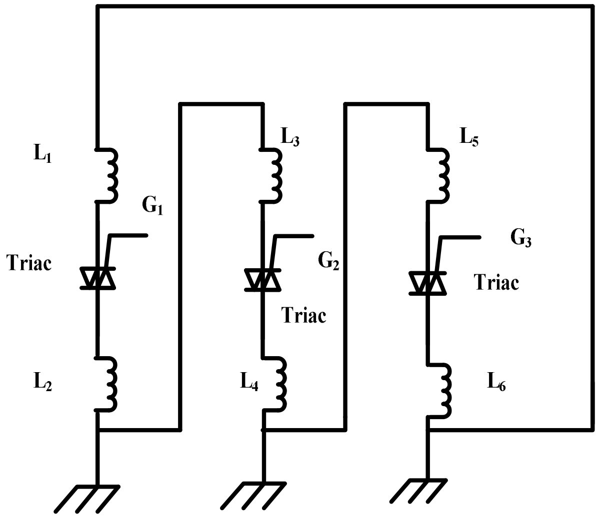

Fig 3 Delta Connected TCR

The model for TCR simulation is shown in Fig 4. A 3 phase AC to DC converter is supplied by 3 phase power. In each phase 2 thyristor are connected in anti-parallel configuration. Each thyristor is provided with an individual pulse generator with pulse of 10 seconds. The result can be obtained from scope.

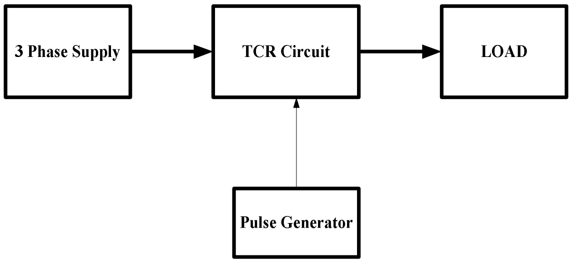

Fig. 4 Block Diagram for TCR Simulation

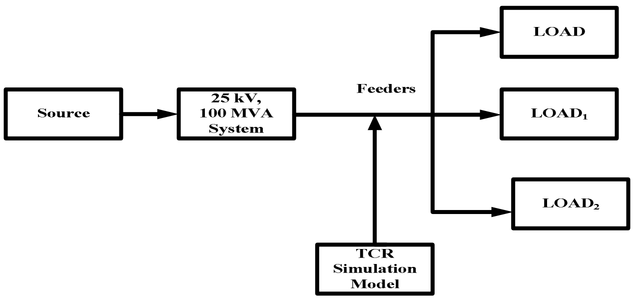

Fig. 5 Implementation of TCR Simulation Model in Transmission Line

Now this model is employed in the transmission line. The waveform after the implementation can be observed from the measurement block for feeders B_1, B_2, B_3, B_4, B_5, B_6 and B_7. After stepping down the power for distribution, load if fed from feeder B_5, B_6 and B_7. For further controlling a 3 phase circuit breaker is connected between the load and the line for $load_1$ and $load_2$ whereas the load is directly connected to the feeder. The operation can be controlled through the circuit breaker.

Simulation Results

The Table II, shows the various fundamental rms magnitudes as well as percentage of harmonic current generated with respect to fundamental component of the current for firing angle α varying from 90^0 to 153^0. The data for various firing angles α was collected. The various parameters noted are fundamental current component, % THD, active and reactive power values.

The implementation of TCR simulation model in transmission line is at feeder B_4. The power curves at different feeders can be observed from the scope of measurement block implemented in the Simulation model.

TABLE II: Simulation Result of TCR at various Firing Angle

Firing Angle (α)	**Fund. Current (A)**		**DC Current Component (A)**		**% THD**		**P**	**Q**
	L	**P**	**L**	**P**	**L**	**P**	**W**	**VAR**
90^0	3.30	1.89	4.26	2.41	6.76	7	1.9	4.09
99^0	2.27	1.376	5.25	3.11	12.11	20.79	1.99	2.81
108^0	1.79	1.080	5.40	3.00	16.02	31.41	1	2.30
117^0	1.395	0.835	4.22	2.51	13.98	39.52	0.795	1.74
126^0	0.832	0.507	4.93	3.02	16.35	59.07	0.52	1
135^0	0.512	0.299	4.88	1.88	32.03	80.18	0.4	0.7
144^0	0.252	0.150	5.52	2.59	57.92	133.4	0.15	0.29
153^0	0.066	0.043	9.07	4.66	180.0	243.5	0.025	0.07

he Fig. 6(a) shows the active and reactive power waveform for TCR model. Due to this current, KVAR compensation can be controlled. From the Table 2, it can be observed that because of asymmetrical operation all triplen harmonics are not eliminated totally but their magnitudes are reduced considerably. In normal circumstances, harmonics with such reduced magnitude are insignificant. This asymmetrical operation results in generation of DC component which has been listed in the Table 2. In addition to the harmonics, small in phase component of current (approximately 0.5 to 2%) of fundamental frequency flows in TCR which represents copper losses in TCR winding. The quality factor for TCR coil QF be accounting for these losses.

Air cored reactor suitable for delta connected TCR to be operated in conjunction with a capacitor bank in five binary sequential steps are designed, tested and simulation studies are carried out. TCR is the heart of a typical static VAR compensator and problem of harmonics is very severe. A comprehensive work is carried out through simulation studies with the sole purpose of fixing firing angle range so as to minimize triplen, characteristic and even harmonics on the line side. Thoroughly investigation ravels the firing angle range between 85 to 130 degrees which gives very satisfactory performance with regard to harmonics, real and reactive powers, D.C. components and other variables. A scheme dealt in this paper is practically implemented on live system and the results are matching with simulation study values.

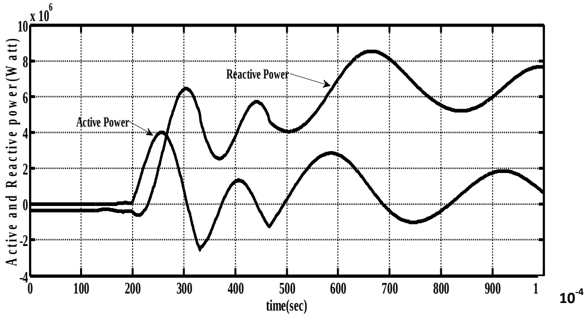

Fig 6(a) Instantaneous Active and Reactive Power for TCR simulation model

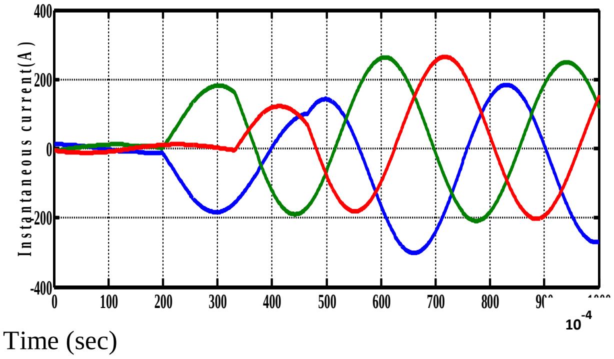

Fig 6(b) Three Phase Current

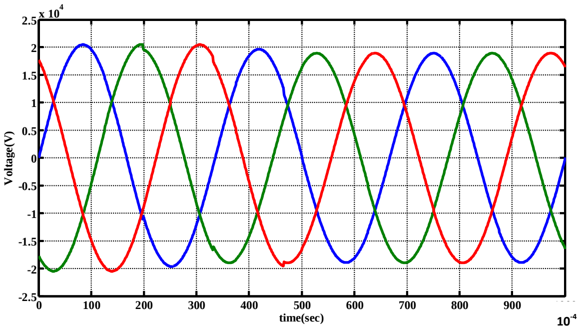

Fig 6(c) Three Phase Voltage

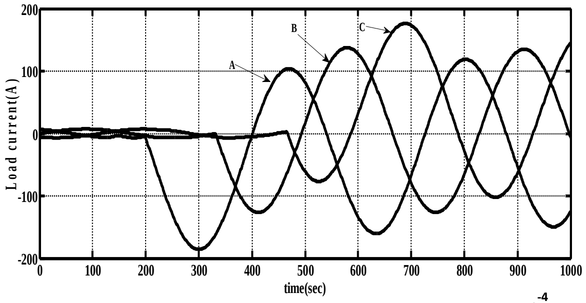

Fig 6(d) Load current

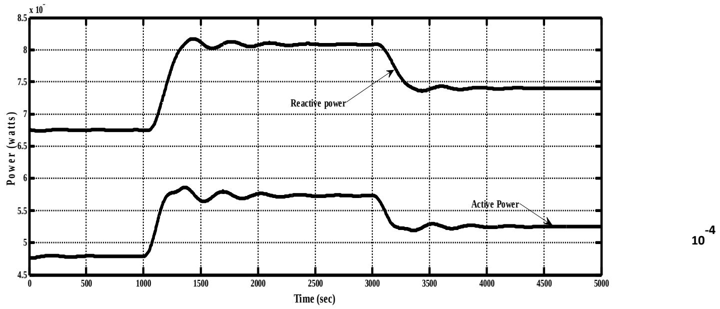

Fig 7(a) Active and Reactive Power at Feeder B_1

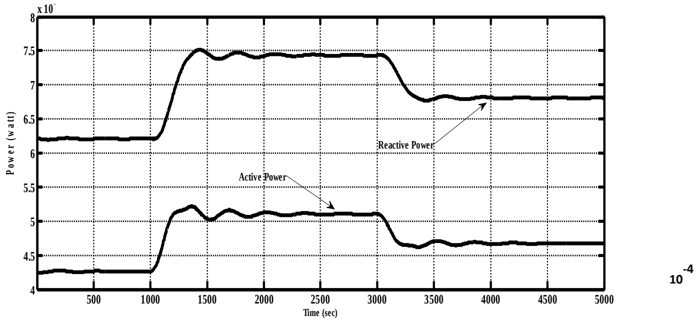

Fig 7(b) Active and Reactive Power at Feeder B_2

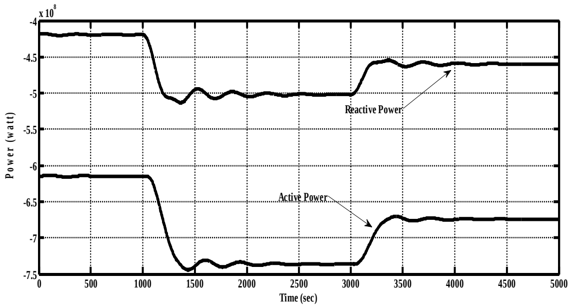

Fig 7(c) Active and Reactive Power at Feeder B_4

Fig 7(a), Fig 7(b) and Fig. 7(c) shows the waveform for the feeder B_1, B_2 and B_4. Feeder B_1 and B_2 are located near sending point of the line where as B_4 represents the point at which TCR simulation model is connected to the transmission line.

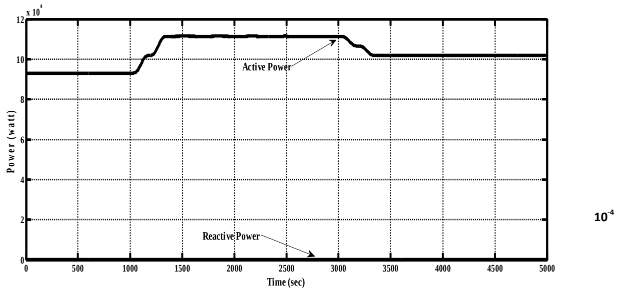

Fig 7(d) Active and Reactive Power at Feeder B_5

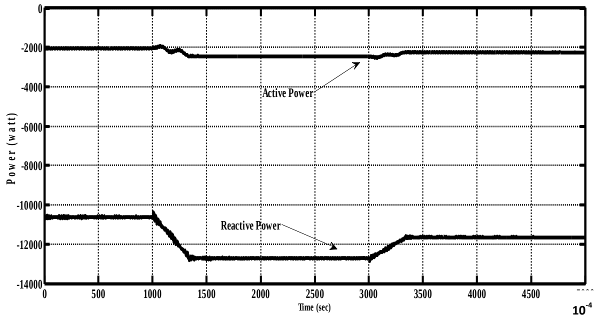

Fig 7(e) Active and Reactive Power at Feeder B_6

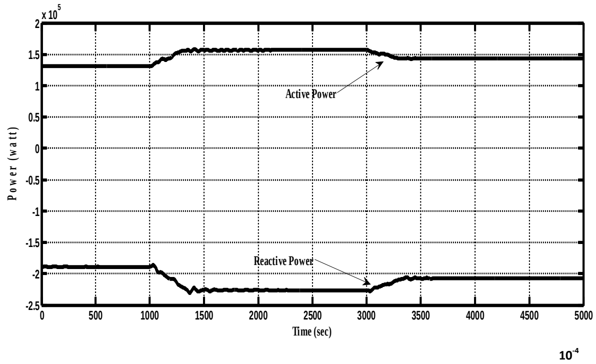

Fig 7(f) Active and Reactive Power at Feeder B_7

Similarly Fig. 7(d), Fig 7(e), Fig 7(f) shows the waveform of active and reactive power at Feeder B_5, B_6 and B_7, which are the points at which 3 loads are connected. The difference in the variation before the implementation of TCR and after the implementation can be observed from these figures. This implementation gives the smoother and stable output with reduced distortion.

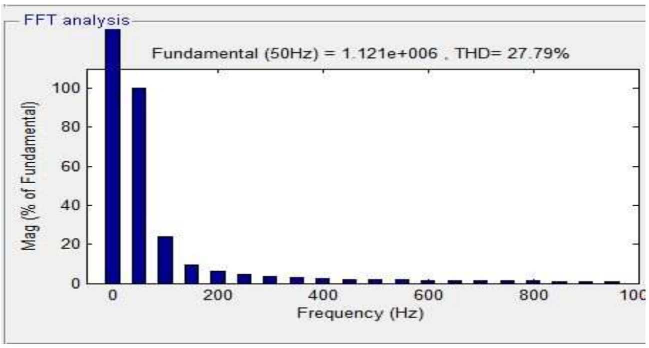

Fig 8(a) Harmonic Spectrum at Feeder B_1

FFT analysis for percentage THD in the form of harmonic spectrum has been shown in Fig. 8(a), Fig 8(b), Fig 8(c), Fig 8(d), Fig 8(e) and Fig 8(f). It can be observed that at feeder B_1, B_2, B_3 and B_4, % THD is 27.79 %, 27.92 %, 27.94% and 27.97% respectively where as at B_5, B_6 and B_7 78.20% and 71.79%. of THD is obtained.

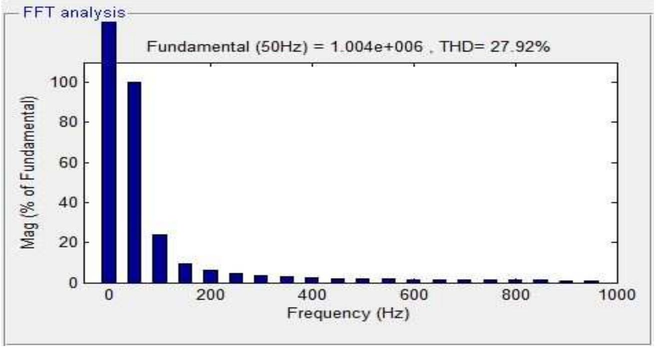

Fig 8(b) Harmonic Spectrum at Feeder B_2

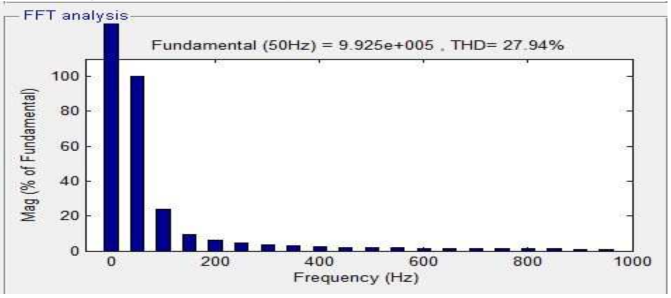

Fig 8(c) Harmonic Spectrum at Feeder B_3

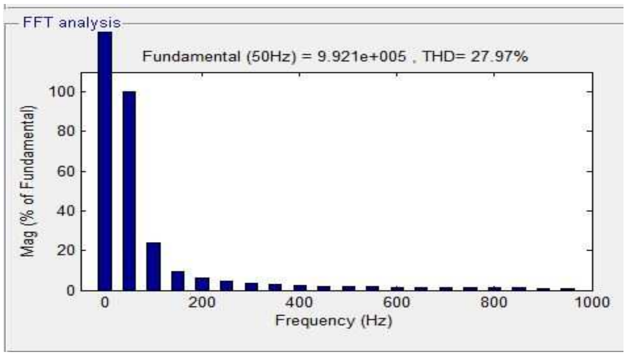

Fig 8(d) Harmonic Spectrum at Feeder B_4

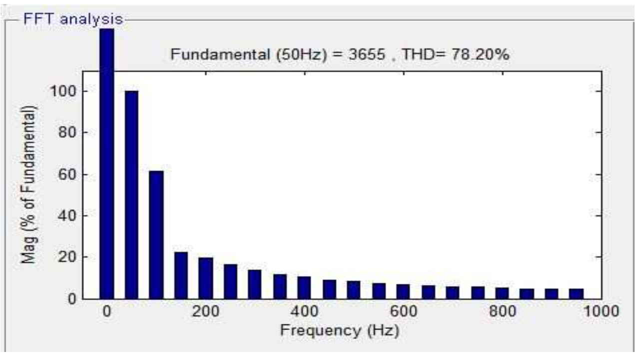

Fig 8(e) Harmonic Spectrum at Feeder B_5

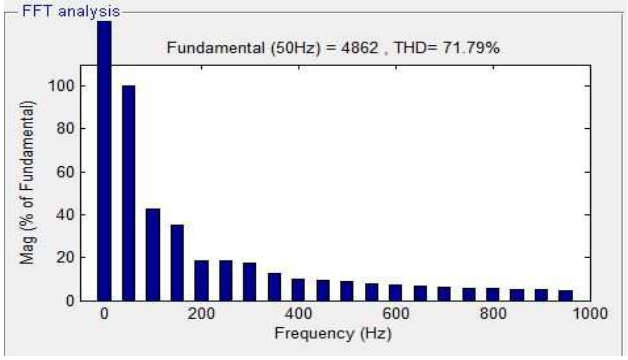

Fig 8(f) Harmonic Spectrum at Feeder B_7

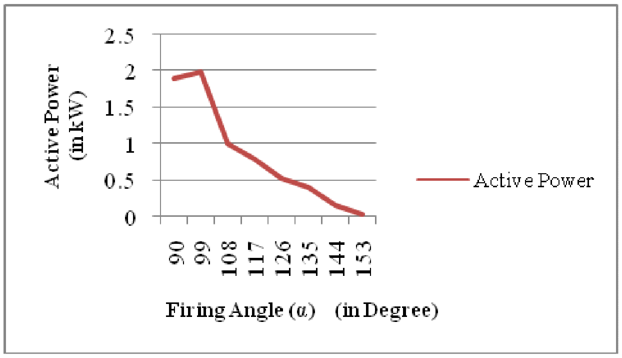

Fig 9(a) Active Power v/s Firing Angle

The plot of active and reactive power variation with respect to firing angle α is also considered in Fig 9(a) and 9(b). While, Fig. 9(c) shows the percentage THD variation with respect to firing angle α. As the angle α approaches to 180^0, the %THD goes on increasing. It is observed that the safe operating region of TCR operation without significant harmonics is in between 90^0 to 130^0. For various firing angles, as listed earlier, different wave forms are recorded. The waveforms are: 3 phase line & phase currents, total active and reactive power.

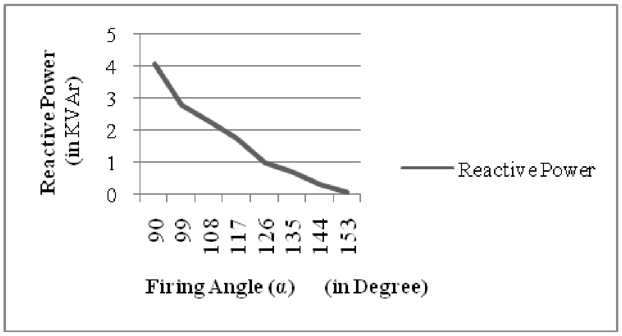

Fig 9(b) Reactive Power v/s Firing Angle

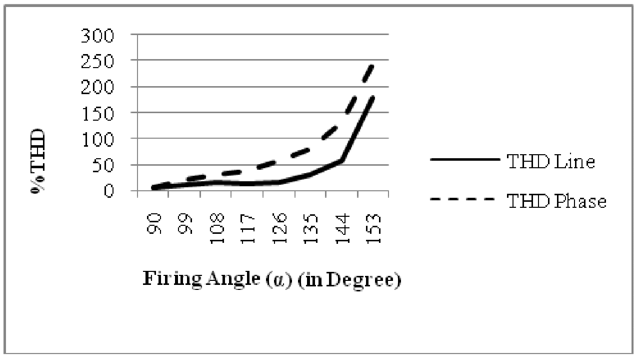

Fig 9(c) % THD v/s Firing Angle

CONCLUSION

The problem of harmonic has become more severe now days and requires more attention for solving to protect the system from damages. This report demonstrates the effect of harmonic distortion at the device. Air cored reactor suitable for delta connected TCR is designed to be operated in conjunction with a capacitor bank in five binary sequential steps. The configuration is tested and simulation studies have been carried out. It is an important element of the static VAR compensator.

The purpose of performing the test is to find the range of firing angel of thyristor used in TCR in SVC. A satisfactory performance of the compensator; from the point of view of harmonic distortion, DC components, real and reactive power and other variables is obtained in the firing angle range of thyristor between 85^0 to 120^0 . From the analysis of the obtained data, it can be concluded that the safest operating area from the point of view of distortion we should use the firing angle of the thyristor used in TCR can be varied from 85^0 to 120^0. Also when the firing angle is about 117^0 the total harmonic distortion is at considerable range from the point of view of economy for the system. On further increasing the firing angle above this limit % THD increases abruptly which may cause serious damage to the system and the personnel as well. All odd, even and triplen harmonics are obtained and from the result analysis it is concluded that all triplen harmonics can be eliminated completely but can be reduced up to a considerable limit.

Future scope

The present model is implemented for finding the region or the range of firing angle in which system total harmonic distortion is at its minimum and can be operated with least losses. On future this model can be implemented for:

- The analysis of higher order harmonics.
- Optimisation can be done with the safe operating region.
- Artificial Intelligence Techniques [such as Artificial Neural Network (ANN) and Fuzzy Logic] can be employed to improve the system performance.

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