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# Harmonic Analysis of Three-phase Fixed Capacitor–thyristor Controlled Reactor under Balanced and Unbalanced Conditions

**Jayababu Badugu[1], Y. P. Obulesu[2], Ch. Saibabu[3]**
[1] Departement of Electrical and Electronics Engineering, VLITS, India
[2] Departement of Electrical and Electronics Engineering, KL University, India
[3] Departement of Electrical and Electronics Engineering, JNTUK, India

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**ABSTRACT**

Three-phase Fixed Capacitor Thyristor Controlled Reactor is widely used for reactive power compensation in power systems because of reduced cost and high reliability. The problem with FC-TCR is that to generate current harmonics when it is partially conducting. When this harmonic current is interacted with system impedance, voltage waveform will distorted. This harmonic pollution is undesirable in power systems. Therefore, it is important to know the harmonic behaviour of three-phase FC-TCR before they can be used in a power system network. This paper presents the harmonic analysis of three-phase FC-TCR operating under balanced and unbalanced conditions. This analysis is useful to design the harmonic filter to reduce the harmonic pollution in power systems.The proposed work is implemented in MATLAB environment.

***Corresponding Author:***

Jayababu badugu1,
Department of EEE,
VLITS, Guntur,
Andhra Pradesh, India.
Jayababu.badugu@gmail.com

## 1. INTRODUCTION

Ideal power system network is expected to operate with sinusoidal voltages and currents of a single frequency and constant amplitude. This ideal operation is not possible in realistic power systems because of increasing use of power electronics devices in modern power system network. Nonlinear components and loads, such as power converters, Flexible AC Transmission Systems (FACTS) devices, nonlinear saturation and hysteresis in components with magnetic cores represent the main contribution harmonic distortion. Flexible alternating current transmission systems devices are widely used in transmission network to improve electrical and economic performance. But they are nonlinear devices, they generate undesirable distortions in voltage or current waveforms. Distorted waveforms contain unwanted harmonics. This harmonic distortion creates many problems such as misoperation of protective devices, reduces the life of electrical equipment, and increases losses in the power systems [1].Considerable progress has been made in the development of correct apparatus to monitor the harmonic behaviour of power systems. However, in system planning and system analysis problem must be considered separately because measurements may not be economic or the system may not be available. In such situations, computer simulations based on the mathematical modelling provide the workable alternative to physical measurements [1]. Many works have been proposed mathematical models of nonlinear devices to determine waveform distortion in power systems. To study the steady-state voltage and current waveform distortion, time domain simulation has been developed many years back. This technique usually takes long simulation run times to calculate the harmonic content of distorted waveforms even for small systems. This is because time domain technique first finds steady state condition after that harmonic content of distorted waveform is found using the Fast Fourier Transform (FFT). The complications in time domain provided motivation for developing the frequency domain techniques. Frequency domain techniques take less simulation time as compare to the time domain techniques. The most fruitful frequency domain technique is Harmonic Domain (HD) technique which is used for both analysis and modelling of harmonic sources. Complex Fourier Series (CFS) and Norton equivalent circuit formulations are used in Harmonic domain technique. HD solution process have presented in reference [1].

HD has been applied to obtain steady state response of the power system components such as synchronous machines, the power transformer, arc furnaces, Fluorescent lamps, Thyristor Commutated Reactors (TCRs) .The Harmonic Domain Technique has been applied to model the Thyristor Controlled Series Capacitor (TCSC) for both stability analysis and steady state analysis. In this paper, Harmonic Domain approach is used for the harmonic analysis of three phase delta connected Fixed Capacitor-Thyristor Controlled Reactor operating under balanced and unbalanced conditions. The paper is organized as follows. Basic operation of Single phase FC-TCR is presented in the second section. The third section describes modelling of three phase FC-TCR in HD approach. Test system description is given in the fourth section. Simulation results are presented in the fifth section.

## 2. BASIC OPERATION OF SINGLE PHASE FC-TCR

This section gives the main components of FC-TCR and basic operation of single phase FC-TCR. Figure 1 shows the single phase FC-TCR used to supply variable reactive power support at a specific location in Power systems. Basically, single FC-TCR consists of fixed capacitor, reactor and two thyristors. Connections of basic elements are shown in Figure 1. It is possible to operate the FC-TCR in both capacitive mode and inductive mode with help of firing signals given to thyristors. Firing angle $\alpha$ plays important role to control reactive power. Firing angle $\alpha$ is varied from $90^0$ to $180^0$. TCR is full conducting state at $\alpha=90^0$.

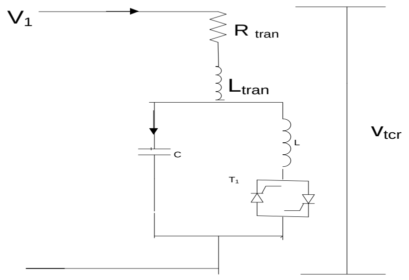

Figure 1. Single phase FC-TCR

TCR is said to be full conducting mode when firing angle ($\alpha$) $is$ $90^0$ Figure 2 shows the TCR current ($\mathbf{I}_{tcr}$) and TCRvoltage ($\mathbf{V}_{tcr}$) waveforms when the TCR is in full conducting mode.

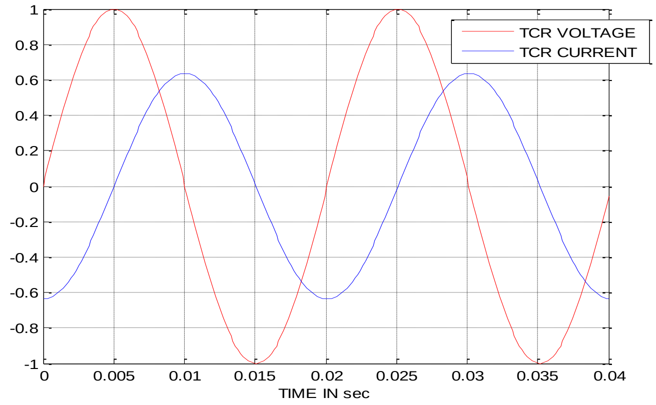

Figure 2. TCR Voltage and TCR current waveforms when $\alpha=90^0$

It is clear from Figure 2 that there is no distortion in current waveform. No current harmonics are generated when TCR in full conduction mode. TCR is said tobe non-conducting mode when firing angle $(\alpha)$ $is$ $180^0$. Figure 3 shows the TCR current and TCR voltage waveforms when TCR is non-conducting mode.

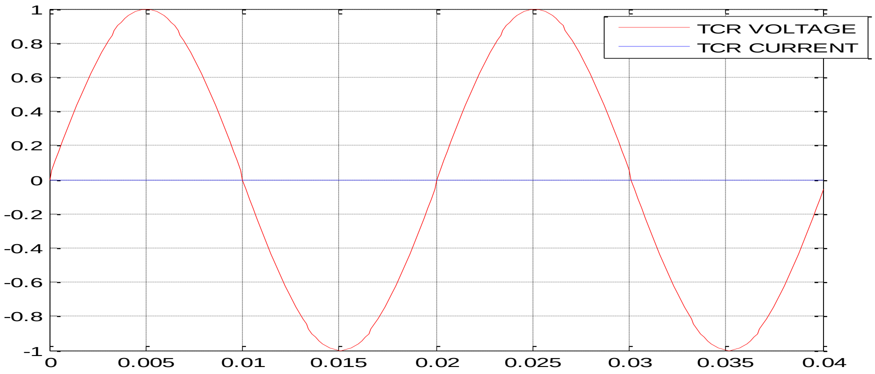

Figure 3. TCR Voltage and TCR current waveforms when $\alpha$=$180^0$

It is clear from Figure 3 that there is no current flowing in TCR branch. Because both thyristers are non conducting. TCR is said to be partially conducting mode when firing angle is varied between $90^0$ to $180^0$ Figure 4 shows the TCR current and TCR voltage waveforms when TCR is partially conducting mode.

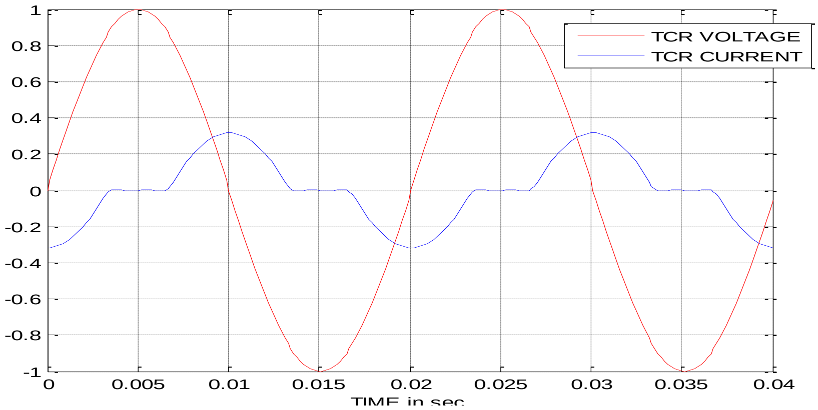

Figure 4. TCR Voltage and TCR current waveforms when $\alpha$=$120^0$

It is clear from Figure 4 that there is distortion in current waveform. When TCR is partially conducting, it will generate the harmonics at connection point. One way to obtain harmonic content generated by FC-TCR is measurement by power quality analyser. We can predict harmonic content of FC-TCR using computer simulation.Simulation techniques does not requires the costly power quality analysers.

## 3. MODELLING OF THREE PHASE FC-TCR

Peter wood proposed the switching function concept to determine the harmonic content of converters. Later Bohmann and Lasseter the same switching function method applied to basic TCR circuit to compute the harmonic content of TCR. The main drawback of this method is that switching instants are fixed. Acha introduced the Norton equivalent circuit model of TCR. Harmonic content of switching function depends on conduction of thyristors. The switching function of TCR is a function of TCR voltage and firing angle$\alpha$. The TCR voltage zero crossing is appropriated as the reference for giving the firing signal. Mathematical modelling of TCR should include the thyristors turn-on and turn-off instants. Harmonic domain model of single phase FC-TCR is given by the following Equation (1).

$$\mathbf{Y}_{FC-TCR} = \mathbf{Y}_{TCR} + \mathbf{Y}_{C} \quad (1)$$

$\mathbf{Y}_{TCR}$ is admittance matrix of TCR which represents the steady state operation of TCR as shown in Equation (2) and (3).

$$\mathbf{Y}_{TCR} = \frac{\mathbf{1}}{\mathbf{L}}\mathbf{D}^{-1}(jh\omega)\mathbf{S} \quad (2)$$

$$\mathbf{Y}_{C} = C\mathbf{D}(jh\omega) \quad (3)$$

**S** is harmonic switching vector. **D** is differention operator. Practical power systems, three phase FC-TCR consists of three single-phase TCR are connected in delta and three capacitors are connected in star.The equations for three phaseTCR is given by Equation (4).

$$\begin{bmatrix}\mathbf{I_R}\\ \mathbf{I_Y}\\ \mathbf{I_B}\end{bmatrix}=\frac{\mathbf{1}}{\mathbf{3}}\begin{bmatrix}Y_{TCR}^{RY}+\mathbf{Y}_{TCR}^{BR} & -Y_{TCR}^{RY} & -\mathbf{Y}_{TCR}^{BR}\\ -\mathbf{Y}_{TCR}^{RY} & \mathbf{Y}_{TCR}^{YB}+\mathbf{Y}_{CR}^{RY} & -\boldsymbol{Y}_{TCR}^{YB}\\ -\mathbf{Y}_{TCR}^{BR} & -\mathbf{Y}_{TCR}^{YB} & \mathbf{Y}_{TCR}^{BR}+Y_{TCR}^{YB}\end{bmatrix}\begin{bmatrix}\mathbf{V_R}\\ \mathbf{V_Y}\\ \mathbf{V}_B\end{bmatrix} \quad (4)$$

## 4. SIMULATION RESULTS

Three phase FC-TCR model developed in section 3 is tested on two bus system shown in Figure 5. The system contains the FC-TCR at bus 2. Figure 5 is reduced to simple circuit as shown in Figure 6.

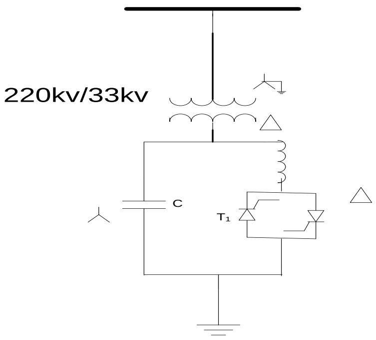

Figure 5. Test system under consideration

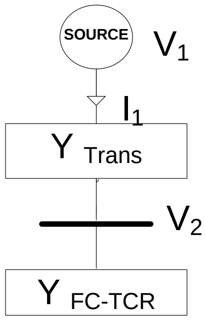

Figure 6. Equivalent circuit of two bus system

$V_1$ is source voltage. $V_2$ is voltage at bus2.Three phase FC-TCR is connected at bus 2. $V_2$ is unknown which can be deternine form network equations. Network Equations can be written for Figure 6 as follows

Network Equation (5)

$$\begin{bmatrix} \mathrm{I}_{1,\mathrm{RYB}} \\ 0 \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{t,11} & \mathbf{Y}_{\boldsymbol{t},\mathbf{22}} \\ \mathbf{Y}_{t,21} & \mathbf{Y}_{t,22} + \mathbf{Y}_{FC-TCR} \end{bmatrix} \begin{bmatrix} \mathrm{V}_{\mathbf{1RYB}} \\ \mathbf{V}_{\mathbf{2RYB}} \end{bmatrix} \tag{5}$$

$\mathrm{V}_{1\mathrm{RYB}}$ is source voltage. $\mathrm{V}_{2\mathrm{RYB}}$ Can be determine from Equation (6) iteratively

$$\mathbf{V}_{2\mathrm{RYB}} = -\langle \mathbf{Y}_{t,22} + \mathbf{Y}_{FC-TCR} \rangle^{-1} \mathbf{Y}_{t,22}\, \mathrm{V}_{1\mathrm{RYB}} \tag{6}$$

The following parameters are used to simulation. The Transformer parameters: Star/delta, 220kv/33kv, 10% of impedance, 100 MVA. FC-TCR rating: (0-80) MVAR. Three cases are considered here and simulation results have been presented.

### 4.1. Balanced Operation of FC-TCR

Three phase voltage magnitude are equal and phase displacement is $120^0$. Results are presented for two firing angles under this case.

#### 4.1.1. Firing angle=$95^0$

Figure 7 shows tha harmonic content of voltages at bus 2.Magnitude of Fifth harmonic is more as compared to the other harnonics.This because of TCR current waveform, 5th harmonic is dominant which is clear from the Figure 8. Fifth harmonics is dominating in capacitor current waveform as copmpare to the other harmonics.

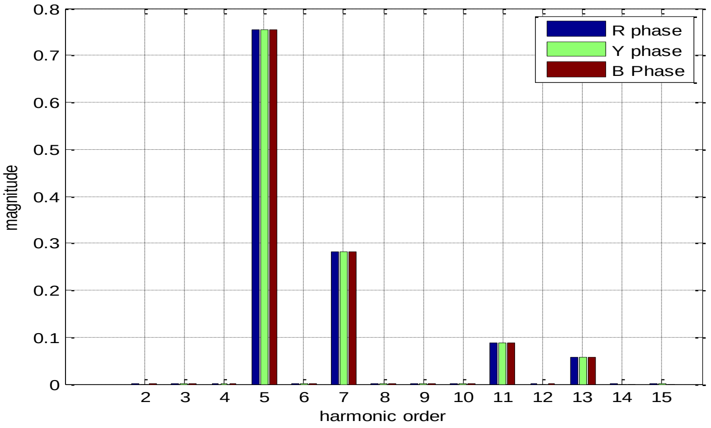

Figure 7. Three phase voltages harmonic spectrum at bus 2

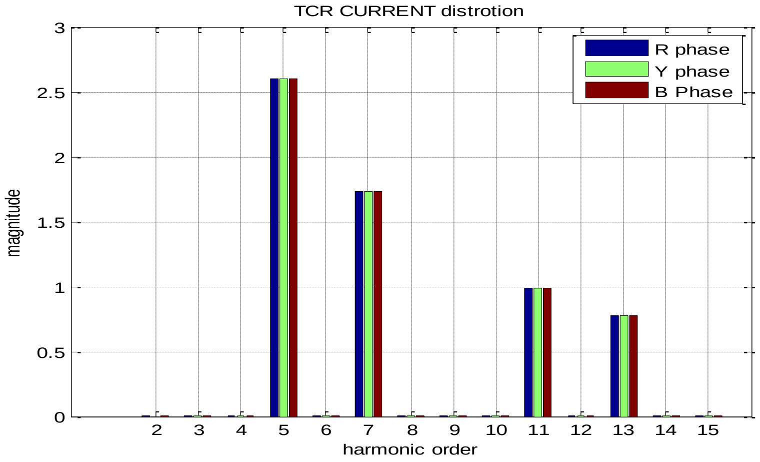

Figure 8. Three phase TCR currents harmonic spectrum

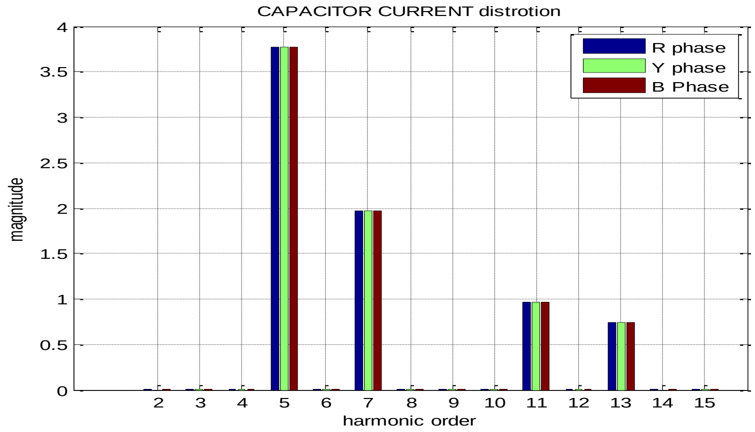

Figure 9. Three phase Capacitor currents harmonic spectrum

### 4.1.2. Firing angle=100$^0$

Fifth harmonic is dominating here also.magnitude is more as compare to previous case. This because of TCR current waveform becomes more nonsinusoidal as firing angle increases. It is also observe from Figure 7 to Figure 12 that 3$^{rd}$ harmonic is not appeared because 3$^{rd}$ harmonic produced in TCR is circulated in delta connected TCR under balanced condition.

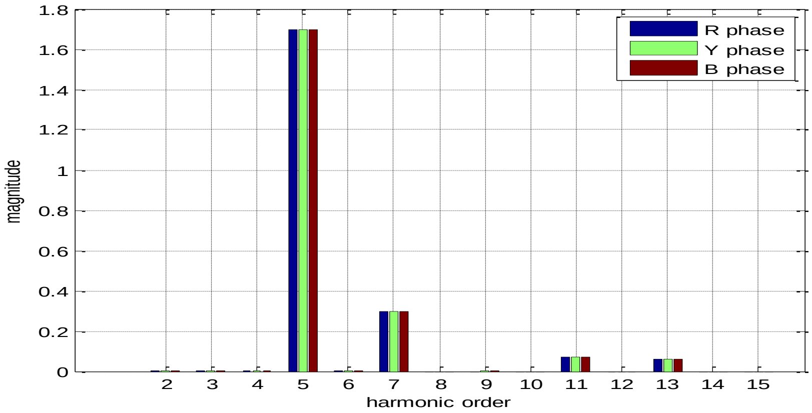

Figure 10. Three phase voltages harmonic spectrum at bus 2

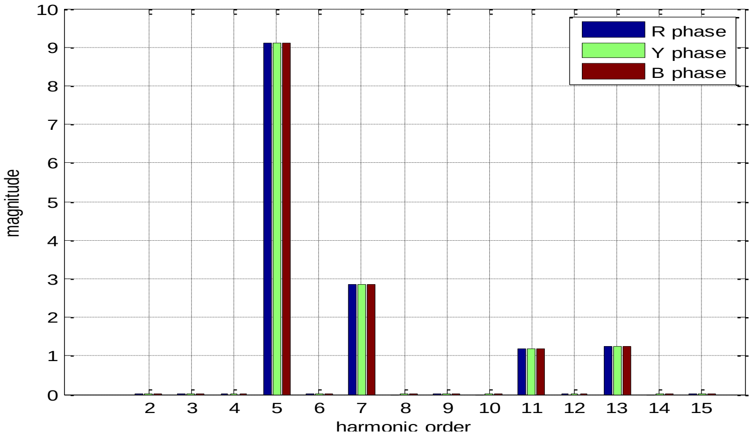

Figure 11. Three phase TCR currents harmonic spectrum

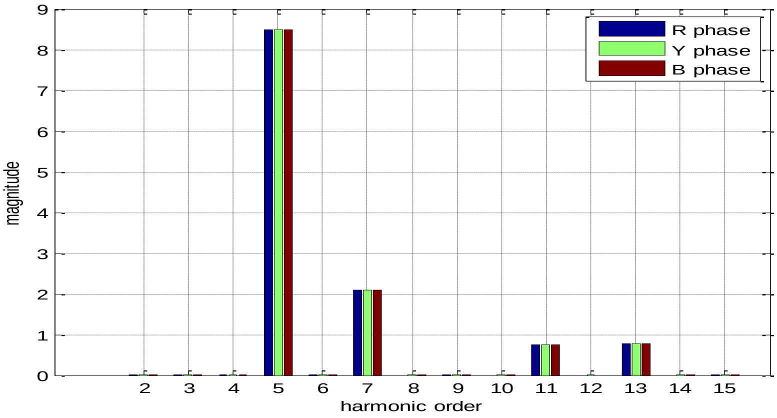

Figure 12. Three phase Capacitor currents harmonic spectrum

### 4.2. Unbalance in Voltage Magnitudes

Unbalance in voltage magnitudes assume voltage magnitude values in three phase voltages as $V_{R=}$1 P.U, $\mathbf{V}_Y$=0.95pu, $\mathbf{V}_B$=1.2pu values and Firing angle=$100^0$ are considered. Harmonic content of voltages at bus2, TCR currents, capacitor currents are shown in Figure 13, Figure 14 and Figure 15 respectively.

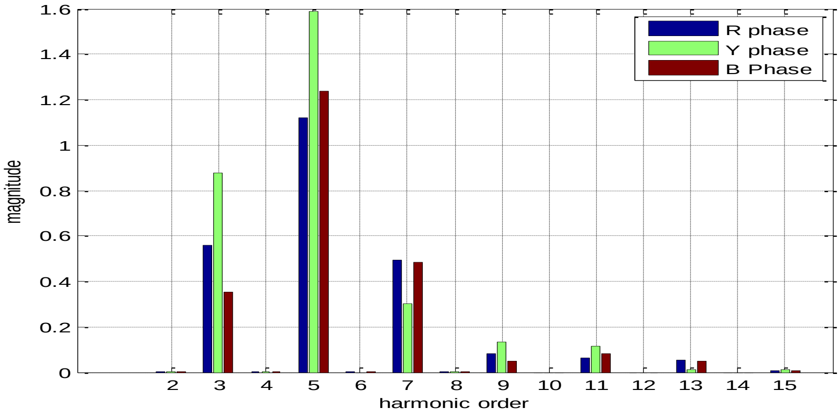

Figure 13. Three phase voltages harmonic spectrum at bus 2

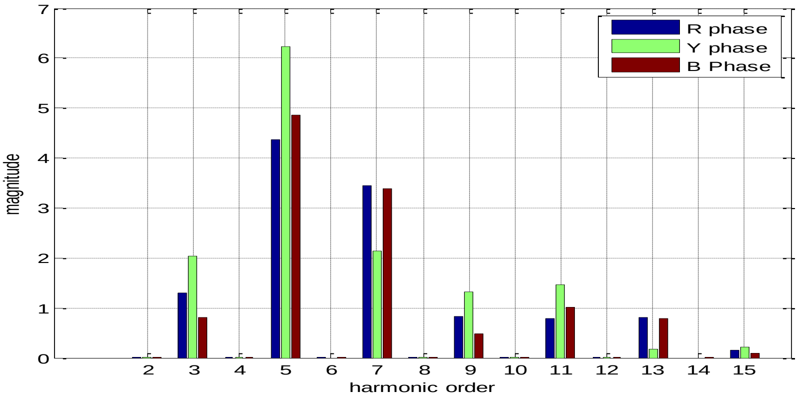

Figure 14. Three phase TCR currents harmonic spectrum

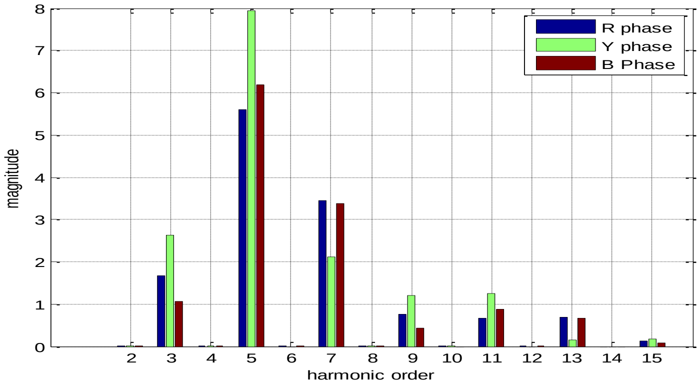

Figure 15. Three phase Capacitor currents harmonic spectrum

It is clear that 3rd harmonic is appeared when there is unbalance due to voltage magnitudes and magnitude of 3rd harmonic is less as compared to the 5th harmonic magnitude.

### 4.3. Unbalance in Firing Angles

Unbalance in firing angles votage magnitude of all three phase voltages are equal and different firing angles are considered in this case. Firing angle in R phase =$95^0$, Firing angle in Y phase =$100^0$, Firing angle in B phase =$120^0$, and equal voltage magnitudes (1pu) are used in simulation. Results are presented in Figure 16, Figure 17 and Figure 18.

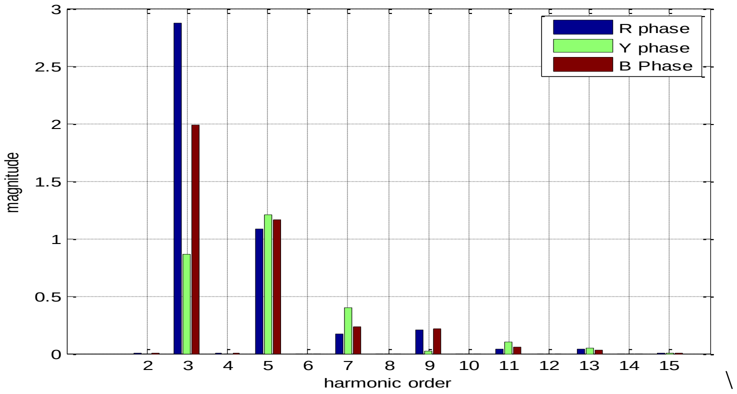

Figure 16. Three phase voltages harmonic spectrum at bus 2

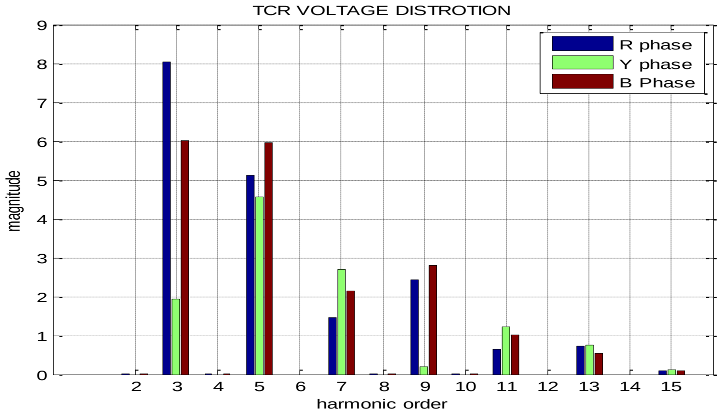

Figure 17. Three phase TCR currents harmonic spectrum

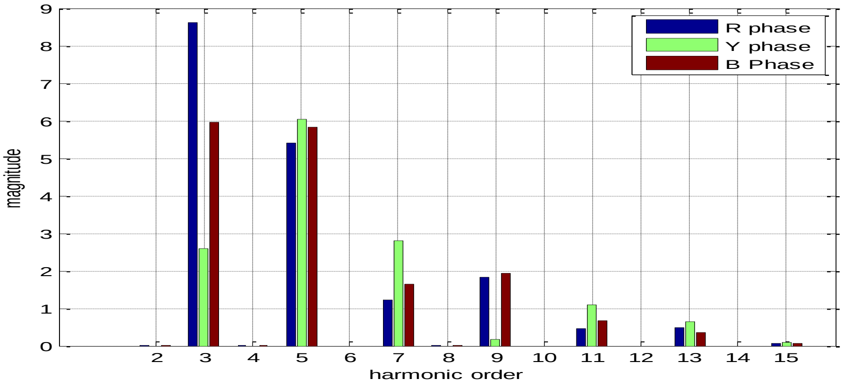

Figure 18. Three phase Capacitor currents harmonic spectrum

It is clear that 3rd harmonic is also appeared here also and magnitude of 3rd harmonic is more as compared to the 5th harmonic magnitude.

## 5. CONCLUSION

Harmonic analysis of three-phase fixed capacitor-Thyristor Controlled Reactor working under balanced and unbalanced conditions has been investigated using HD approach. The results shows that significant amount of 5th harmonic appears in voltage waveform at connection point of FC-TCR, TCR per phase current and capacitor line current when system is operating under balanced conditions. 3rd harmonic is not appeared when system is operating under balanced condition. Third harmonic is appeared when there is unbalance due to voltage magnitudes and magnitude of 3rd harmonic is less as compared to the 5th harmonic magnitude. Third harmonic is also appeared when there is unbalance due to firing angles and magnitude of 3rd harmonic is more as compared to the 5th harmonic magnitude. This work is useful to design the filters to mitigate the harmonics under different operating conditions. Steady state harmonic analysis is carried out in this paper. Future scope of this work is to determine harmonics of given system under transient conditions.

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## BIOGRAPHIES OF AUTHORS

B.JAYABABU received his B.TECH. degree in Electrical and Electronics Engineering in 2001 from Nagarjuna University,Guntur, India and M.Tech degree from NIT Calicut, India in 2003.His fields of interests are Flexible Ac transmission systems , power quality.

Y.P.Obulesu received his B.E. degree in Electrical and Electronics Engineering in 1995 from Andhra University, India, M.Tech degree from Indian Institute of Technology, Khargapur, India in 1998 and PhD from Jawaharlal Nehru Technological University, Hyderabad, India in 2006..His fields of interests are Power electronics and drives, energy systems and active filters.

Ch. Sai Babu received the B.E from Andhra University (Electrical & Electronics Engineering), M.Tech in Electrical Machines and Industrial Drives from REC, Warangal and PhD in Reliability Studies of HVDC Converters from JNTU, Hyderabad. He is working as a Professor in Dept. of EEE in JNTUCEK, Kakinada. He has published several papers in National and International Journals and Conferences. His area of interest is Power Electronics and Drives, Power System Reliability, HVDC Converter Reliability, Optimization of Electrical Systems and Real Time Energy Management.