Canadian Journal on Electrical and Electronics Engineering Vol. 2, No. 7, July 2011

Harmonics Reduction of Thyristor Controlled Reactor with Minimal No Load Operating Losses

Abdulkareem Mokif Obais, Dr. Jagadeesh Pasupuleti

Abstract — *In this paper a new approach of thyristor-controlled reactor (TCR) harmonics treatment is presented. The design methodology of this approach is based on suppressing the TCR harmonic current components by inserting a series LC circuit between the ac source and the parallel combination of TCR and filtering circuit. The series LC circuit is tuned at the ac supply fundamental frequency, whereas the filtering circuit is built of a set of significant odd harmonic filters characterized by minimal no load operating losses and no reactive power contribution at the fundamental frequency. The proposed filtering circuit is less sensitive to the adjacent harmonics generating circuits in the power system network, therefore it remains always efficient. A demonstrating system is designed and tested on the computer program PSpice. In this system, the TCR odd harmonics are reduced to one-third the values accepted by IEEE 519-1992.[1]*

Key Words — TCR, Harmonics, static Var, controlled-reactor, reactive power absorption.

I. INTRODUCTION

A thyristor-controlled reactor (TCR) is one of the conventional static Var compensators used in the field of power quality improvement [1]-[4]. It can absorb a continuous reactive power at the fundamental frequency of the power system network, but it releases significant odd harmonics which could cause many undesirable effects, like over currents, extra losses, and noises to telecommunication systems [5]-[7]. Therefore, elimination of harmonic current components associating the TCR performance is handled together with its installation. Tuned passive filters and active filters are usually used to eliminate these harmonics [6]-[11]. Installation of these filters in the location of the TCR circuit offers low-impedance paths for odd harmonic current components, thus resulting in a significant reduction in their components passing to the ac source side. The design of these filters depends on the ac source impedance or the short circuit level at their locations. As high as is the short circuit level, as larger as is the filtering circuit rating. A tuned harmonic filter is of a capacitive nature at the fundamental frequency of the power system network, thus it generates an amount of reactive power and dissipate additional losses depending on its rating. For power factor correction purposes, the reactive power generated by filters, may be handled through the compensation process, but in case of load balancing or voltage control, it may be undesirable and its cancellation adds additional cost and losses. In addition, these filters are sensitive to the adjacent harmonic generating circuits in the power system network therefore, they may be less efficient. The problems associating the filtering circuit like losses, less efficient operation, and undesirable reactive power generation are treated effectively by a new filtering strategy based on the addition of a series LC circuit tuned at the fundamental frequency of the power system network and connected in series with a TCR shunted by a filtering circuit characterized by no reactive power generation and minimal no load operating losses

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II. THE TCR MODELING

The TCR is simply two anti-parallel thyristors connected in series with a reactor as shown in **Fig. 1**.

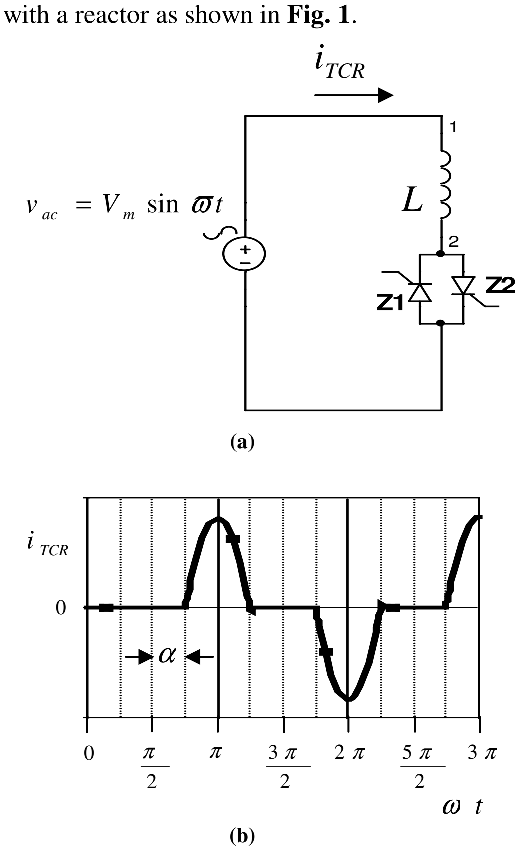


Fig. 1 The TCR (a) configuration, (b) current waveform.

The TCR current (i_{TCR}) waveform is shown in **Fig. 1b**. Its fundamental component (I_1) is given by [6]

$$I_1 = \frac{V_m}{\pi\omega_1 L}\left(\pi - 2\alpha - \sin(2\alpha)\right) = \frac{V_1}{\omega_1 L} \quad (1)$$

Where V_m is the amplitude of the ac source voltage, ω_1 is the ac voltage fundamental angular frequency, L is the TCR reactor self inductance, α is the TCR firing angle, and V_1 is a voltage at the fundamental frequency and is defined by

$$V_1 = \frac{V_m}{\pi}\left(\pi - 2\alpha - \sin(2\alpha)\right) \quad (2)$$

I_1 is controlled in range of $0 \le I_1 \le V_m/\omega_1 L$, as α is adjusted in the range of $0 \le \alpha \le \pi/2$. The kth harmonic component of the TCR current is given by [6]

$$I_k = \frac{V_m}{\omega_1 L}\left(\frac{4}{\pi}\right)\left(\frac{\sin(\alpha)\cos(k\alpha) - k\cos(\alpha)\sin(k\alpha)}{k(k^2-1)}\right)$$

$$or \quad (3)$$

$$I_k = \frac{V_k}{\omega_k L}$$

Where k is a positive odd integer greater than unity and the variables ω_k and V_k are given by

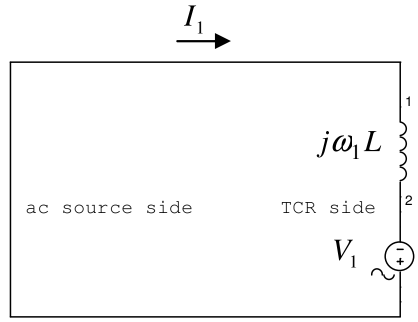
$$\omega_k = k\omega_1 \quad (4)$$

$$V_k = V_m f_k(\alpha) \quad (5)$$

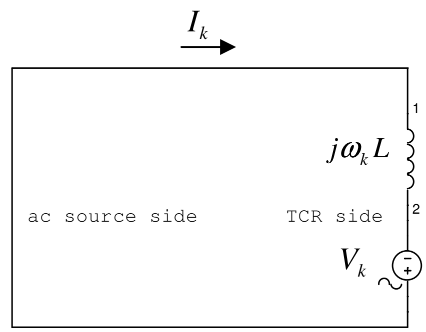
The function $f_k(\alpha)$ is defined as

$$f_k(\alpha) = \frac{4}{\pi}\left(\frac{\sin(\alpha)\cos(k\alpha) - k\cos(\alpha)\sin(k\alpha)}{k^2-1}\right) \quad (6)$$

Equations (2) and (3) can be analogously represented by the circuit models shown in **Fig. 2**. In these models, the ac source impedance is assumed to be very much less than the TCR reactance defined by $\omega_1 L$, or in other words the short circuit level at the TCR location is assumed to be very much greater than the TCR rating which is the maximum fundamental current component that can be handled by the TCR. The internal resistance of the TCR reactor is not included in both circuit models because it is rather negligible compared to its reactance. It is obvious that all the harmonic current components are flowing in the ac source, causing disturbance in the ac voltage profile, additional losses, and undesirable noise to telecommunication systems.



(a)



(b)

Fig. 2 The TCR analogue representation at (a) fundamental, (b) kth harmonic.

III. THE PROPOSED FILTERING TECHNIQUE

The proposed filtering strategy is based on minimizing the odd harmonics associating the TCR operation with no reactive power contribution and minimal no load operating losses. **Fig. 3** shows the proposed filtering technique. The series combinations $L_3r_3C_3$, $L_5r_5C_5$, $L_7r_7C_7$, and $L_kr_kC_k$ are the 3rd, 5th, 7th, and kth harmonic filters respectively. The resistors r, r_2, r_3, r_5, r_7, and r_k are the internal resistances of the reactors L, L_2, L_3, L_5, L_7, and L_k respectively.

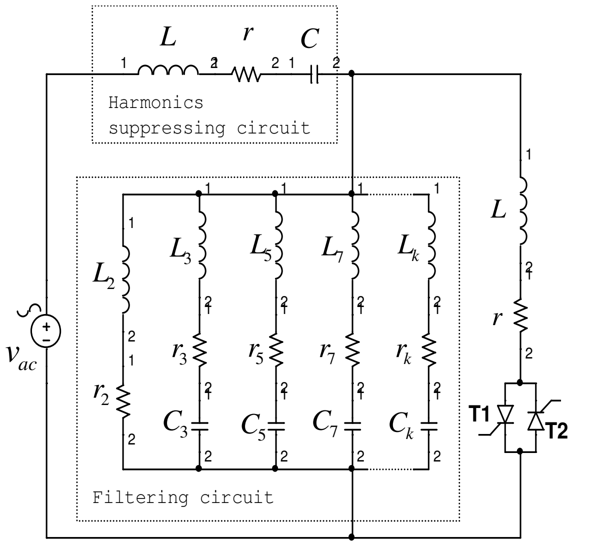


Fig. 3 The proposed filtering technique.

The harmonics suppressing circuit is composed of a capacitor C in series with a reactor L which is identical to that of the TCR. This circuit is assumed to resonate at the fundamental frequency of the ac network. Hence the reactance of L or C at this frequency, can be given by

$$X(\omega_1) = \omega_1 L = \frac{1}{\omega_1 C} = \sqrt{\frac{L}{C}} \tag{7}$$

The insertion of the harmonics suppressing circuit will not affect the magnitude of I_1 and I_k identified by Equations (1) and (3) respectively, if the voltage drop across it is negligible compared to ac source voltage. This condition will be satisfied, if the filtering circuit offers easy path for all harmonics. The impedance of the harmonics suppressing circuit at ω_1 is r, which is rather negligible compared to the TCR reactance. Referring to the circuit model stated in **Fig. 2b**, the proposed filtering circuit of **Fig. 3** can be represented by the circuit model shown in **Fig. 4**. In this model, the k^th harmonic current component flowing in the ac source side (I_{Sk}) is computed as follows:

$$I_{Sk} = I_k \frac{|Z_F(\omega_k)|}{|Z_{HS}(\omega_k) + Z_F(\omega_k)|} \tag{8}$$

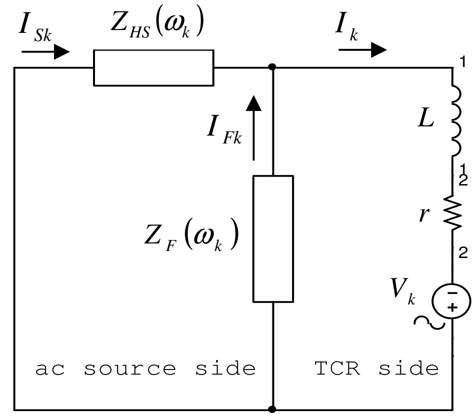


Fig. 4 The k^th harmonic model of the proposed filtering circuit.

Where $Z_S(\omega_k)$ and $Z_F(\omega_k)$ are the impedances at ω_k of the harmonics suppressing and filtering circuits respectively. These impedances are given by

$$Z_{HS}(\omega_k) = r + j\left(\omega_k L - \frac{1}{\omega_k C}\right)$$
$$or \tag{9}$$
$$Z_{HS}(\omega_k) = r - jX(\omega_1)\frac{(k^2-1)}{k}$$

$$Z_F(\omega_k) = \frac{1}{\dfrac{1}{j\omega_k L_2 + r_2} + \sum_k \dfrac{1}{r_k + j\left(\omega_k L_k - \dfrac{1}{\omega_k C_k}\right)}} \tag{10}$$

If the harmonic filters are designed such that they exhibit sharp responses at their resonance frequencies, then $Z_F(\omega_k)$ can be closely approximated to r_k and Equation (8) can be rewritten as follows:

$$\frac{I_{Sk}}{I_k} = \frac{r_k}{|Z_{HS}(\omega_k) + r_k|}$$
$$or \tag{11}$$
$$\frac{I_{Sk}}{I_k} \cong \frac{r_k}{|Z_{HS}(\omega_k)|}, \ldots\ldots |Z_{HS}(\omega_k)| >> r_k$$

Substituting for $Z_{HS}(\omega_k)$ given in Equation (9) into Equation (11) and taking into account $|Z_{HS}(\omega_k)| >> r_k$, results in

$$\frac{I_{Sk}}{I_k} \cong \frac{r_k}{r - jX(\omega_1)\frac{(k^2-1)}{k}} << 1$$
$$or$$
$$r_k \leq 0.1\left(r - jX(\omega_1)\frac{(k^2-1)}{k}\right) \tag{12}$$

The condition in Equation (12) can be reasonably approximated to $r_k \leq 0.1X(\omega_1)/k$. Equation (12) insures that each harmonic filter offers almost a real short circuit to its corresponding harmonic current component. Combining Equations (3), (4), and (11) results in

$$hs\% = \frac{I_{Sk}}{I_{1\max}}\% \cong \frac{r_k}{|Z_F(\omega_k)|} f_k(\alpha) \times 100\% \tag{13}$$

Where $hs\%$ represents the k[th] harmonic current component (as a percentage of the maximum TCR fundamental current I_{1max}) flowing in the ac source side. I_{1max} represents the TCR rating which refers to its fundamental current at α=0 and is given by

$$I_{1\max} = \frac{V_m}{\omega_1 L} = \frac{V_m}{X(\omega_1)} \tag{14}$$

The ac source impedance has negligible effect on this analysis, if the short circuit level ($I_{S.C}$) at the TCR location is very much greater than its rating (I_{1max}).

The magnitude of the current drawn by the filtering circuit at the fundamental frequency is computed as follows:

$$I_F(\omega_1) = \frac{V_m}{Z_F(\omega_1)} \tag{15}$$

The reactor L_2 in the filtering circuit functions as a compensator of the capacitive reactive power generated by harmonic filters at the fundamental frequency of the power system network, thus no reactive power contribution will be handled by the filtering circuit at this frequency. Consequently, the filtering circuit impedance at ω_1 must be real or in other words its imaginary part must be equated to zero.

$$\text{Im}(Z_F(\omega_1)) = 0 \tag{16}$$

In the proposed filtering technique, $I_F(\omega_1)$ must be very small compared to I_{1max} in order to minimize the no load operating losses. The ratio of $I_F(\omega_1)$ to I_{1max} is denoted by m and is given by

$$m = \frac{I_F(\omega_1)}{I_{1\max}} = \frac{V_m / Z_F(\omega_1)}{V_m / X(\omega_1)} = \frac{X(\omega_1)}{Z_F(\omega_1)} \tag{17}$$

Where m is a fraction indicating the no load operating losses of the filtering circuit. Small values of m mean small no load operating losses.

For sharp frequency responses of harmonic filters, the quality factor Q_k of each harmonic filter in the proposed filtering technique, is preferred to be

$$Q_k = \frac{X(\omega_k)}{r_k} \geq 30 \tag{18}$$

Where $X(\omega_k)$ is the reactance of L_k or C_k at the resonance frequency ω_k and is given by

$$X(\omega_k) = \omega_k L_k = \frac{1}{\omega_k C_k} = \sqrt{\frac{L_k}{C_k}} \tag{19}$$

IV. A DEMONSTRATING SYSTEM DESIGN

A distribution power system of a phase voltage of 240 volts (r.m.s) and a frequency of 50Hz is chosen as the ac supply for the proposed system. To start the design process, the TCR reactor must be specified. Let it has an inductance of 9.115m and an internal resistance of o.22785Ω. The ratio (r/L) for this reactor is 0.025Ω/mH. Consequently, 1000μF and 3.02Ω stand for C_1 and $X(\omega_1)$ respectively. The filtering circuit is designed to treat the 3[rd], 5[th], 7[th], and 9[th] harmonics. For simplicity and fast design process, the harmonic filters are assumed to have the same $X(\omega_k)$ and Q_k. This implies that $X_{o3}=X_{o5}=X_{o7}=X_{o9}$ and $r_3=r_5=r_7=r_9$. To show the effectiveness of the proposed technique, $r_k/X(\omega_1)$ is equated to 0.125 and Q_k to 40. Consequently, computations lead to $r_3=r_5=r_7=r_9=0.375\Omega$, $L_3=15mH$, $L_5=9mH$, $L_7=6.43mH$, $L_9=5mH$, C_3=67.5μF, $C_5=40.5\mu F$, $C_7=28.92\mu F$, and $C_9=22.49\mu F$. For easy computation and reasonable cost, the wire gauge of the reactor L_2 is assumed one-half that of the TCR reactor. Considering the latter assumption and applying Equation (16) results in $L_2=55mH$, and $r_2=2.75\Omega$. Considering the electronic parts parameters and regarding supporting literatures [12], the proposed system was designed on PSpice as shown in **Fig. 5**.

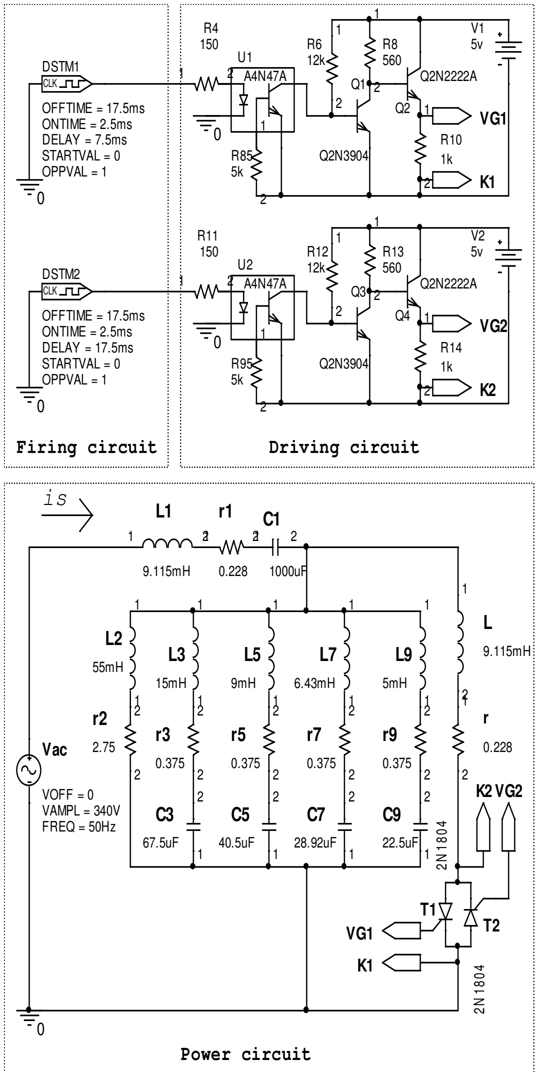


Fig. 5 The PSpice implementation of the proposed filtering technique.

The firing circuit consists of two digital sources for adjusting the TCR firing angle. The driving circuit is designed such that the required conduction angles of thyristors and electrical insulations are guaranteed.

V. RESULTS AND DISCUSSION

The impedances of the filtering and harmonics suppressing circuits at any frequency are denoted by $Z_F(f)$ and $Z_{HS}(f)$ respectively. The two impedances were measured on PSpice at a frequency range of (50 to 800) Hz. **Fig. 6** reflects those measurements. Referring to Equation (8) and examining **Fig. 6**, the treated significant odd harmonics are expected to be highly reduced. In addition, higher order harmonics like 11 and forth are expected to be significantly decreased.

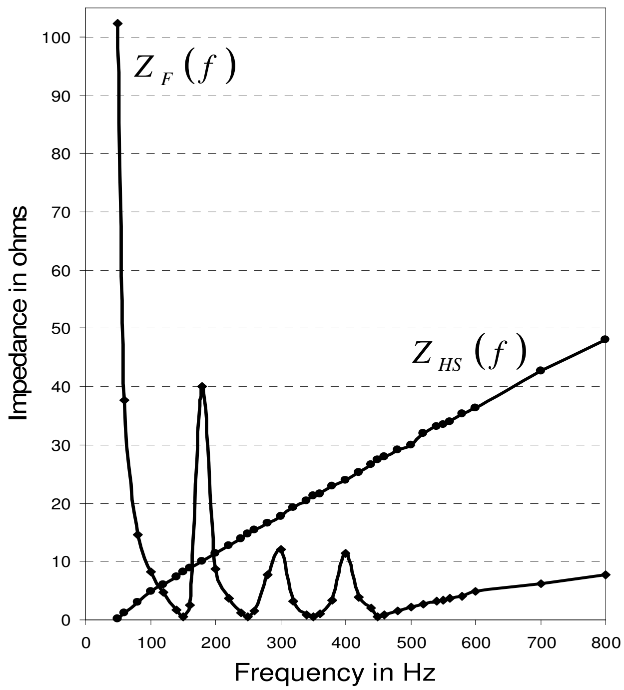


Fig. 6 The frequency responses of filtering and harmonics suppressing circuits.

The circuit of **Fig. 5** was tested on PSpice. The ac source current was measured with and without filtering for revealing the effectiveness of the proposed filtering strategy. The source current without filtering is the same current flowing in the TCR and can be accessed by omitting all power circuit elements in **Fig. 5**, except the ac source and the TCR circuitry. **Fig. 7** to **Fig. 14** show results of tests proceeded at $\alpha=0^o$, 30^o, 45^o, and 60^o. It is obvious that for the same firing angle, the fundamental components are almost equal without and with filtering. In addition, the treated odd harmonic current components flowing in the ac source side were reduced drastically with filtering and higher order harmonic current components were also significantly decreased.

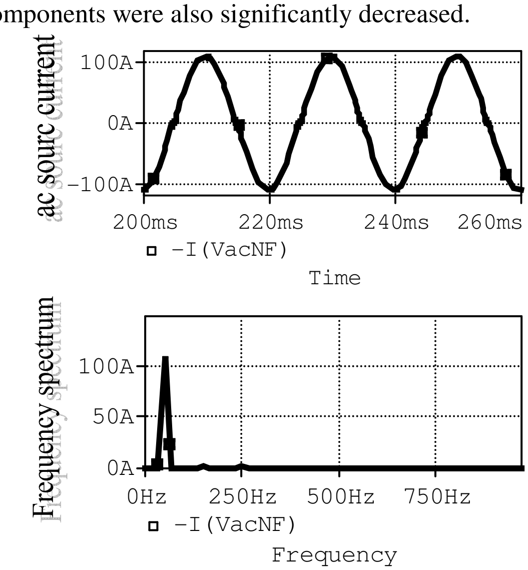


Fig. 7 The ac source current and its frequency spectrum without filtering at α=0°.

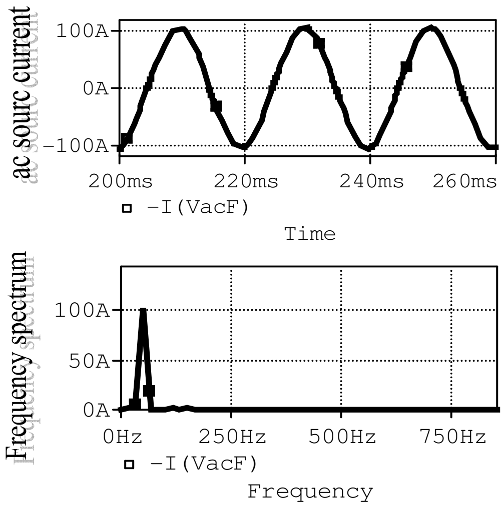


Fig. 8 The ac source current and its frequency spectrum with filtering at α=0°.

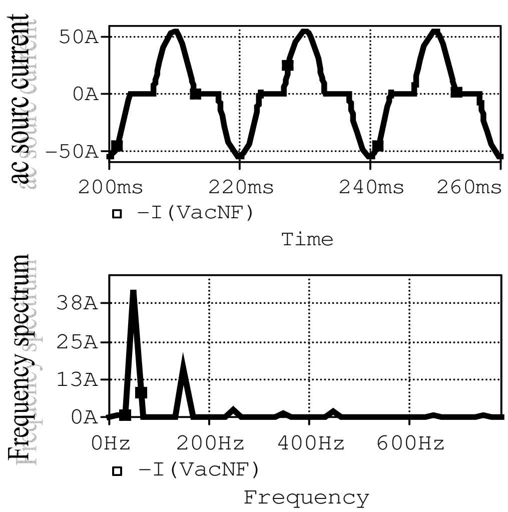


Fig. 9 The ac source current and its frequency spectrum without filtering at α=30°.

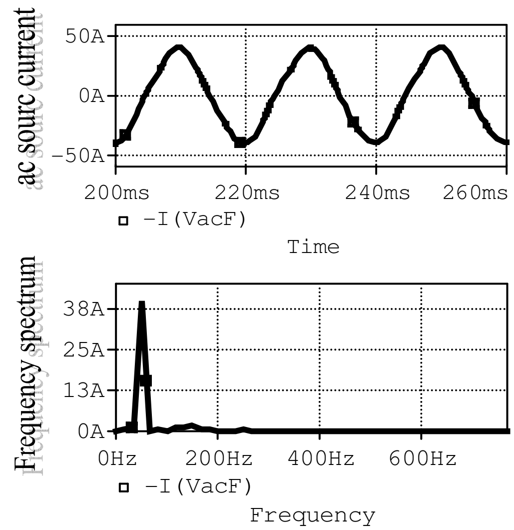


Fig. 10 The ac source current and its frequency spectrum with filtering at α=30°.

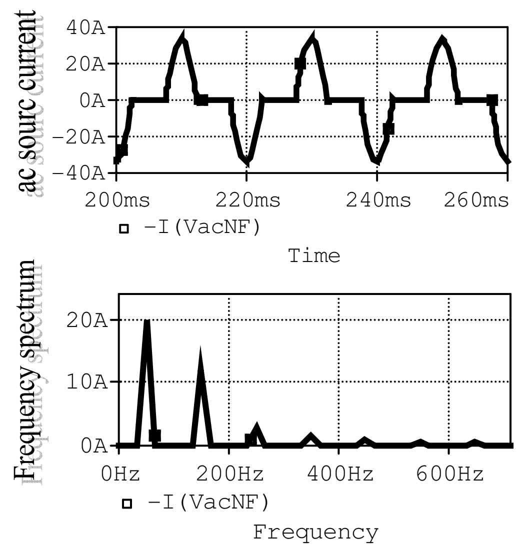


Fig. 11 The ac source current and its frequency spectrum without filtering at α=45°.

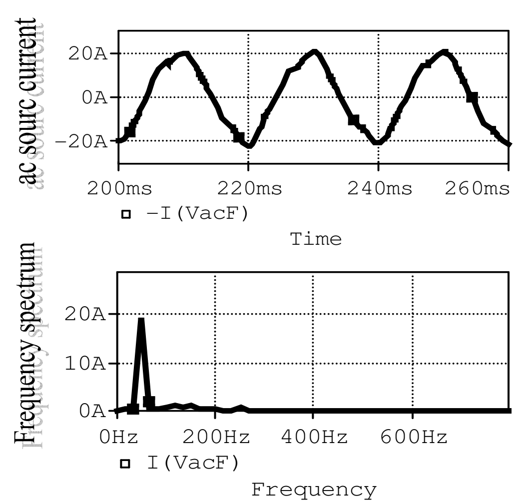


Fig. 12 The ac source current and its frequency spectrum with filtering at α=45°.

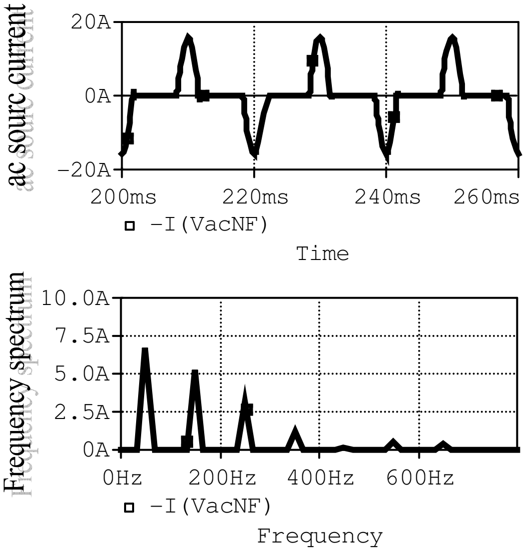


Fig. 13 The ac source current and its frequency spectrum without filtering at α=60°.

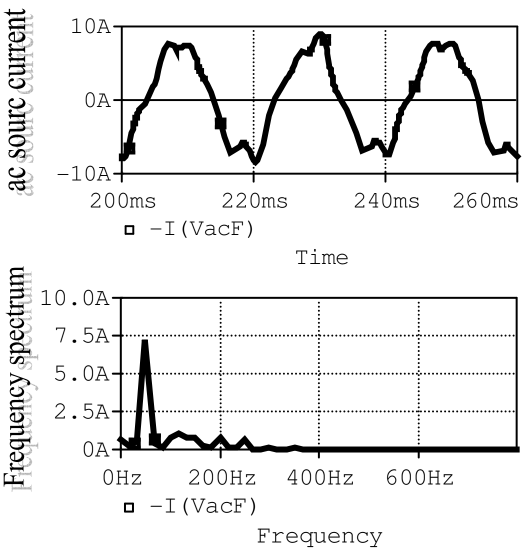


Fig. 14 The ac source current and its frequency spectrum with filtering at α=60°.

Many tests were proceeded for measuring the fundamental and harmonic current components of the ac source current with and without filtering during the variation of α in the range of 0° to 90°. **Fig. 15** and **Fig. 16** reflect the results of those tests. In **Fig. 15**, the fundamental current with filtering is deviated upward by about 3A at α=90o. This current deviation represents the no load current of the filtering circuit specified by Equation (15). It is obvious that the significant harmonic contents with filtering are reduced to approximately one tenth those without filtering. According to IEEE 519-1992 and for $I_{S.C}/I_{1max}<20$, the acceptable values of *h*% defined in equation (13) must be less than 4% for harmonics of order less than 11. The third harmonic for example is reduced to one-third the magnitude accepted by IEEE 519-1992.

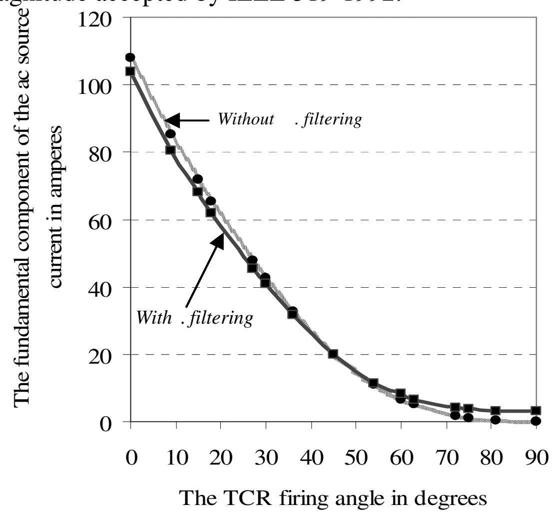
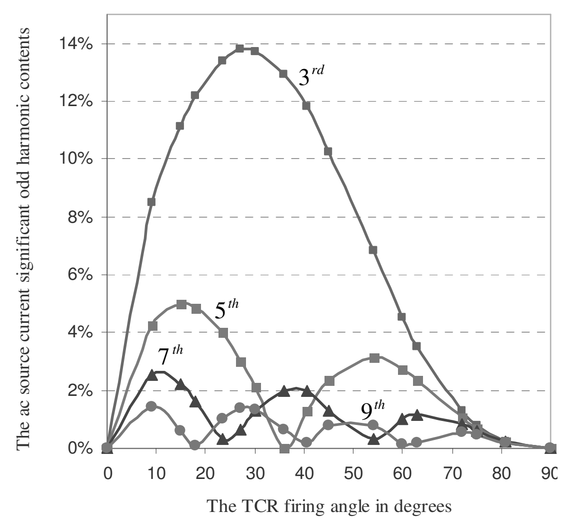
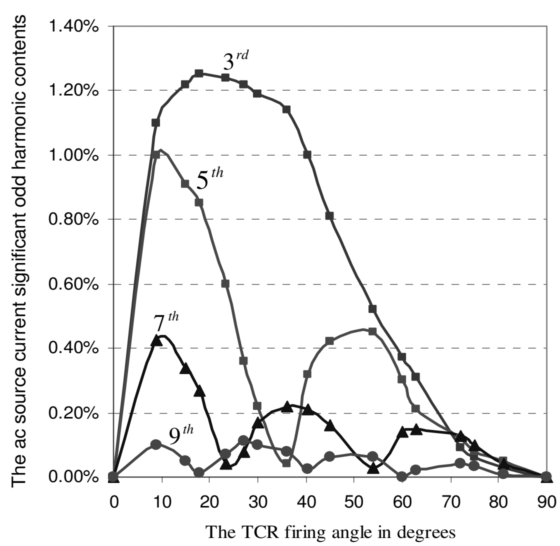


Fig. 15 The ac source current fundamental versus α, (a) with filtering, (b) without filtering.



(a)



(b)

Fig. 16 Significant odd harmonics as percentages of the TCR maximum fundamental, (a) without filtering, (b) with filtering.

The voltage across the TCR with filtering was measured at different firing angles as shown in **Fig. 17**. The figure indicates that all the voltage waveforms are similar and having the same zero crossing and peak points assuring that the TCR firing angle could not be affected by the proposed filtering strategy.

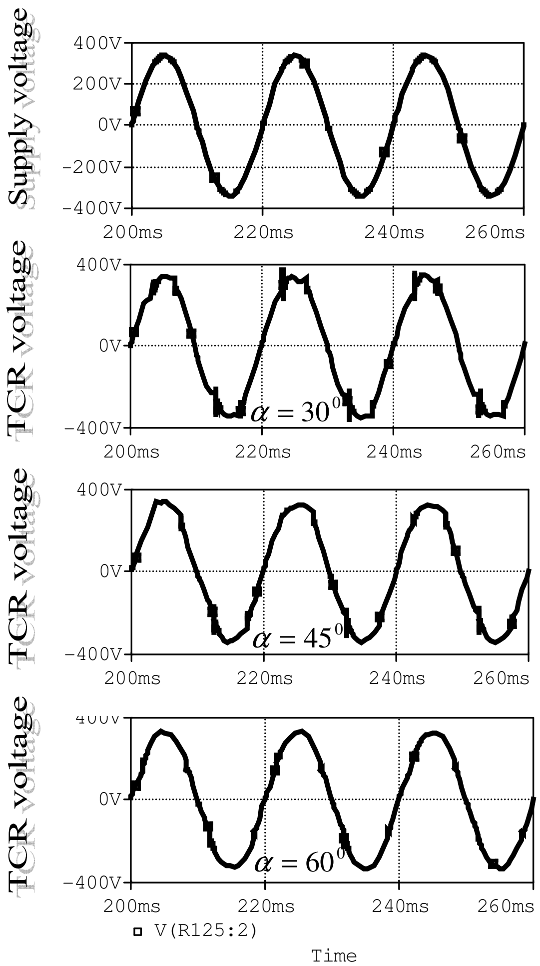


Fig. 17 The TCR voltage at different firing angles.

VI. CONCLUSION

The proposed filtering strategy can be utilized in all reactive power compensation techniques employing TCR, but it is highly productive in techniques requiring only reactive power absorption. There is a high flexibility available in the design methodology of the proposed strategy. Harmonics can be reduced to levels below the limits accepted by IEEE 519-1992, with minimal no load operating losses and without reactive power contribution. For delta-connected TCRs in three-phase systems, this strategy becomes less expensive and more efficient since the third harmonic and its multipliers are no longer being treated. Harmonic filters in this technique are not sensitive to adjacent harmonic generating circuitries in the power system network, thus they remain as efficient as they were firstly designed.

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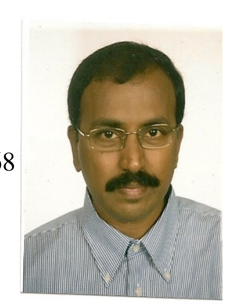

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