Effects of the system and TCR parameters on the harmonic currents of the thyristor controlled reactor

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The growing use of static switching circuits in modern power systems gives a reason for increasing need to analyze and understand these circuits and their interactions with the power system. One of the most important components used in power systems is the Static VAR Compensator (SVC). A compensator contains a Thyristor Controlled Reactor (TCR) which has a switching circuit and produces harmonic currents. The model of TCR contains the independent frequency component, resistor, and dependent frequency component, inductor. In this paper the behavior of the TCR as a harmonic source is dealt with taking into account the effects of some circuit parameters. These parameters are system impedance and the coil resistance of the TCR which affect the harmonic currents of the TCR

أدى الازديــاد المطــرد في استخدام مكونات تحوى دوائر تشغيل ذات قاطع استاتيكى فى نظم القوى الكهربية الحديثة إلى الحاجة لتحلــيل دقــيق لهذه الدوائر لكي تعطى فهماً لأدائها و تأثيراتها على نظم القوى الكهربية المتصلة بها. أحد أهم هذه المكونات هو معوضــات القــدرة الغــير فعالة الإستاتيكية. هذه المعوضات تحوى ملف محكوم بالثايرستورات يؤدى تشغيلها إلى تشوه موجتي الجهــد و التــيار و هذا التشوه يترجم إلى توافقيات. يتم تمثيل الملف المحكوم بالثايرستورات بعناصر لا تتغير مع تغير التردد و هي المقاومة و أخرى تتغير مع التردد و هي المفاعلة الحثية. هذا البحث يتناول بالدراسة الملف المحكوم بالثايرستورات و تمثيله كمصــدر لتيارات التوافقيات فى نظم القوى الكهربية. و قد تم الأخذ فى الاعتبار بعض المعاملات التى كانت تهمل فى الدراسات الســابقة و هى قيم وزاويا معاوقة نظام القوى الكهربية الموصل له هذا الملف وقيم مقاومة هذا الملف. وقد اوضحت هذه الدراسة مدى تأثير هذه المعاملات على قيم تيارات التوافقيات الناتجة.

Keywords: Power system harmonics, Static VAR Compensators, Thyristor controlled reactors, Power system quality

1. Introduction

The main purpose of transmission and distribution networks is to transmit active power. In addition to the active power, most electric devices need reactive power which reduces the capacity of the transmission and distribution networks and results in considerable power loss and undesirable voltage drop [1]. Static VAR compensators, which act as controllable VAR sources with fast response, are widely used in power systems to compensate the varying loads and stabilize their voltage. Fixed capacitor-thyristor controlled reactor (FC-TCR) is one of the basic schemes of static VAR compensators. Thyristor controlled reactor is one of the sources of harmonics in the power systems. Review of the previous modeling and simulation techniques of the TCR circuit concluded that the following assumptions are usually considered [2-5]:

- The TCR coil is taken as a pure inductance.
- The input voltage of the TCR is pure sinusoidal waveform.
- The effect of the system impedance on the harmonics of the TCR is usually ignored.

These assumptions are not always true in the practical operation of the power system networks. Effects of the system and TCR parameters should be considered. The change of the voltage at the static VAR compensator bus, caused by the harmonic current injected into the AC system, is not considered. Therefore, the assumption that the voltage at the static VAR compensator bus is sinusoidal is not true.

In this paper, effects of the system impedance and the internal resistance of the TCR on the harmonic currents and the total harmonic distortion (THD) of the TCR are investigated. Modeling of the thyristor controlled reactor is investigated by using the Fourier matrix equations, which are used to calculate the harmonic currents of the thyristor controlled reactor, and adapted for studying the system with a TCR.

2. Modeling of the TCR switching circuit using Fourier matrix technique

Expressions for the current through and the voltage across the TCR shown in fig. 1 using the Fourier matrix technique [3] can be developed. The current in the reactor is defined by integrating the voltage across the reactor, V_R, represented by its terminal voltage, V_T, multiplied by the switching function H(t). The switching function, H(t), is shown in fig. 2. It has a value of one when a thyristor is on and a value of zero when the thyristors are off. The switching function is represented by the complex Fourier series as:

$$H(t) = \sum_{n=-\infty}^{\infty} k_n(\sigma_1, \phi_1, \sigma_2, \phi_2) e^{jn\omega t} . \qquad (1)$$

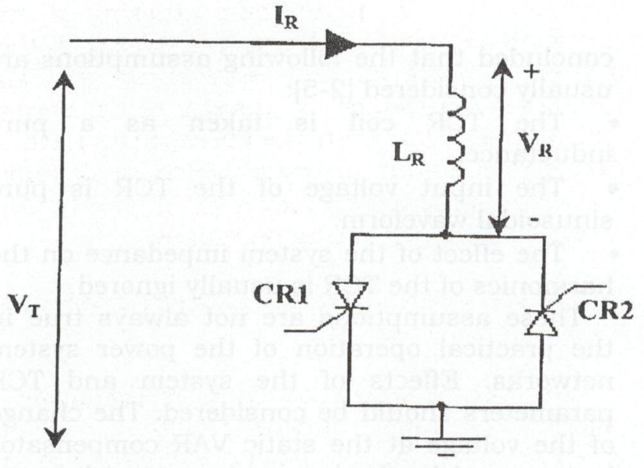

Fig. 1. Thyristor controlled reactor.

The magnitude of the n^{th} Fourier coefficient of the switching function, k_n, is given by the Fourier analysis as follows:

$$k_n = \frac{1}{2\pi} \int_{t_1}^{t_1+2\pi} H(t) e^{-jn\omega t} d\omega t . \qquad (2)$$

Fig. 2 shows the dependency of the Fourier coefficient, k_n, on the conduction angles σ_1 and σ_2 and their centers of conduction periods, ϕ_1 and ϕ_2. The DC and the n^{th} harmonic components of the switching function are defined as follows:

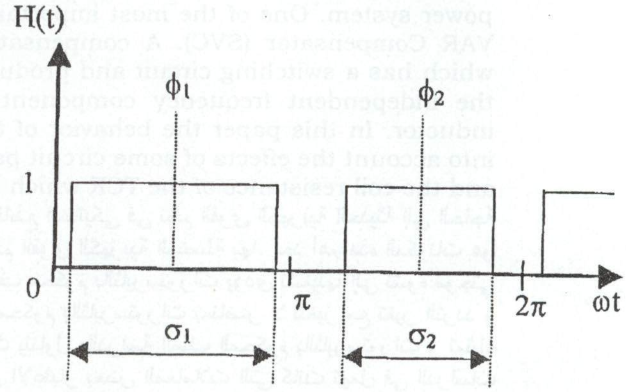

Fig. 2. Switching function.

$$h_o = \frac{(\sigma_1 + \sigma_2)}{2\pi} , \qquad (3)$$

$$h_n = \frac{1}{n\pi} \left[e^{-jn\phi_1} \sin(n\frac{\sigma_1}{2}) + e^{-jn\phi_2} \sin(n\frac{\sigma_2}{2}) \right] . \qquad (4)$$

Where;

h_o is the DC component of the switching function, and

h_n is the n^{th} harmonic component of the switching function.

If the firing angles of the two inverse parallel thyristors of the TCR are symmetrical, from one half to the next, the DC and harmonic components of the switching function become:

$$h_o = \frac{\sigma}{\pi} , \qquad (5)$$

$$h_n = \frac{1}{n\pi} e^{-jn\frac{\pi}{2}} (1 + e^{-jn\pi}) \sin(n\frac{\sigma}{2}) . \qquad (6)$$

The terminal voltage is represented by the complex Fourier series as:

$$v_T(t) = \sum_{m=-\infty}^{\infty} V_{Tm}\, e^{jm\omega t} . \tag{7}$$

The voltage across the reactor is defined as the product of the terminal voltage, $\mathbf{V_T}$, and the switching function, **H**.

$$\begin{aligned} \mathbf{v}_R(t) &= \mathbf{v}_T(t)\ \mathbf{H}(t) \\ &= \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} V_{Tm}\, k_n\, e^{j(m+n)\omega} . \end{aligned} \tag{8}$$

Eq. (8) can be expressed in matrix form as shown in Eq. (9). It is made up of an infinite dimensional switching function matrix **H**, multiplied by a vector of magnitudes of the harmonic voltage across the terminals, $\mathbf{V_T}$.

$$\begin{bmatrix} \cdot \\ \cdot \\ V_{R-2} \\ V_{R-1} \\ V_{R0} \\ V_{R1} \\ V_{R2} \\ \cdot \\ \cdot \end{bmatrix} = \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & h_0 & h_{-1} & h_{-2} & h_{-3} & h_{-4} & \cdot & \cdot \\ \cdot & \cdot & h_1 & h_0 & h_{-1} & h_{-2} & h_{-3} & \cdot & \cdot \\ \cdot & \cdot & h_2 & h_1 & h_0 & h_{-1} & h_{-2} & \cdot & \cdot \\ \cdot & \cdot & h_3 & h_2 & h_1 & h_0 & h_{-1} & \cdot & \cdot \\ \cdot & \cdot & h_4 & h_3 & h_2 & h_1 & h_0 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \cdot \\ \cdot \\ V_{T-2} \\ V_{T-1} \\ V_{T0} \\ V_{T1} \\ V_{T2} \\ \cdot \\ \cdot \end{bmatrix} . \tag{9}$$

The coupling between harmonics is shown in eq. (9). For example, a single frequency of the terminal voltage is produced by the whole spectrum of voltages across the reactor. All the harmonics of the terminal voltage contribute to a single harmonic of the reactor voltage.

The reactor current, $\mathbf{I_R}$, is defined by the product of the voltage across the reactor matrix, $\mathbf{V_R}$, and the harmonic admittance matrix of the reactor, $\mathbf{Y_R}$, as:

$$\mathbf{I}_R = \mathbf{Y}_R \mathbf{V}_R = \mathbf{Y}_R \mathbf{H}\, \mathbf{V}_T . \tag{10}$$

3. System equations

The power system, to which the TCR is connected, is represented by a harmonic Thevenin equivalent as seen from the TCR bus connected to this system to the external system. If the TCR is not connected, the resulting linear system has a harmonic Z_{bus} matrix. The equivalent system impedance is the diagonal element of the Z_{bus} matrix corresponds to the TCR bus. The equivalent Thevenin circuit of the power system containing a bus with a TCR is shown in fig. 3.

The terminal voltage, $\mathbf{V_T}$, and the reactor current, $\mathbf{I_R}$, of the TCR are defined as follows:

$$\mathbf{V}_T = \mathbf{E}_S - \mathbf{Z}_S \mathbf{I}_R , \tag{11}$$

$$\mathbf{I}_R = \mathbf{Y}_R \mathbf{H} \mathbf{V}_T = \mathbf{Y}_{TCR} \mathbf{V}_T . \tag{12}$$

The equivalent input voltage, $[\mathbf{E_s}]$, is:

$$\mathbf{E}_S = \mathbf{U} + \mathbf{Z}_S \mathbf{Y}_{TCR} \mathbf{V}_T . \tag{13}$$

Where;

$\mathbf{Z_S}$: The harmonic impedance matrix of the equivalent power system,

$\mathbf{Y_{TCR}}$: The harmonic admittance matrix of the TCR, and

U is the unity matrix.

If the system impedance is represented by a pure reactor, the switching function matrix, **H**, has ϕs which are the zero crossing of the fundamental value of the source voltage. If the system impedance is represented as an inductive impedance, a resistance in series with an inductor, then the current will have a decaying exponential term; which shall shift the angle ϕs to an unknown point due to the unknown point of conduction angle.

4. Effects of the lossless system impedance on the TCR harmonics

The circuit shown in fig. 3 is the single-phase Thevenin equivalent circuit of a balanced three-phase power system with a FC-TCR static VAR compensator from the TCR bus (bus K). The harmonic currents of the TCR that injected to the equivalent system impedance will change the voltage at the TCR bus. This in turn will lead to change the harmonic currents.

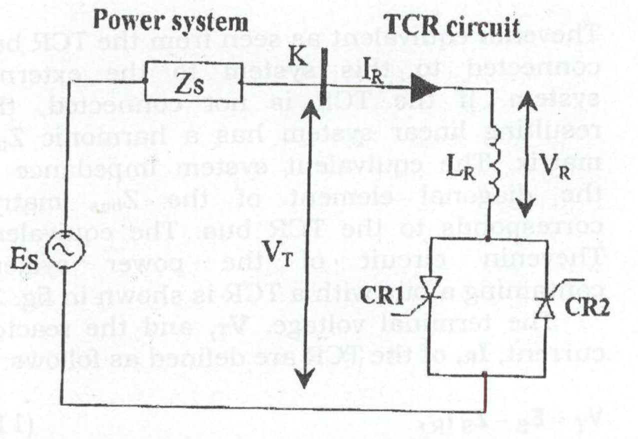

Fig. 3. Thevenin equivalent circuit of the system with TCR.

The controlled reactor and the fixed capacitor bank of the static VAR compensator are assumed to have impedances of 0.566∠90° and 0.265∠-90° pu. respectively. Studying of harmonic currents up to 13th harmonic current, when applied for three values of the equivalent system impedance, and the results are compared with those obtained by neglecting the system impedance. The system impedance is assumed as losses-less impedance (purely reactive impedance) with an angle of 90° and has magnitudes of 0.076 pu, 0.096 pu and 0.126 pu. As the system impedance increased the power system gets weaker.

The TCR was operated over its range of the conduction angle σ, from 0° to 180°. The 5th, 7th, 11th and 13th harmonic currents of the TCR are plotted for each value of the system impedance as shown in figs. 4–7, respectively. The per-unit value of the THD is plotted for each value of the system impedance as shown in fig. 8. There is no change in the value of the switching function angle. It is constant at a value equals to π/2 for each case which is the point of the zero crossing of the applied voltage.

For each case of the system impedance, the magnitude of the harmonic currents and the per-unit value of the THD go up for all values of the conduction angle (σ) as the system gets weaker. Harmonics higher than the 13th harmonic were ignored due to their small amplitudes.

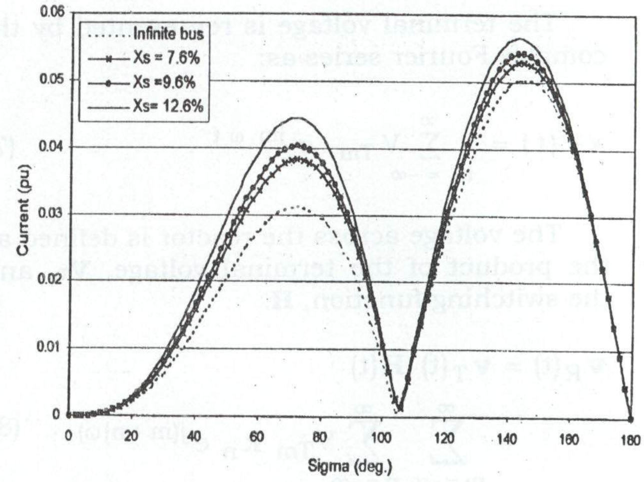

Fig. 4. 5th harmonic current.

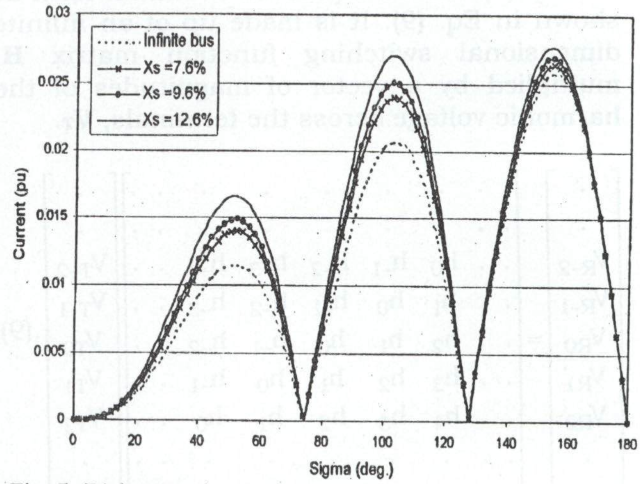

Fig. 5. 7th harmonic current.

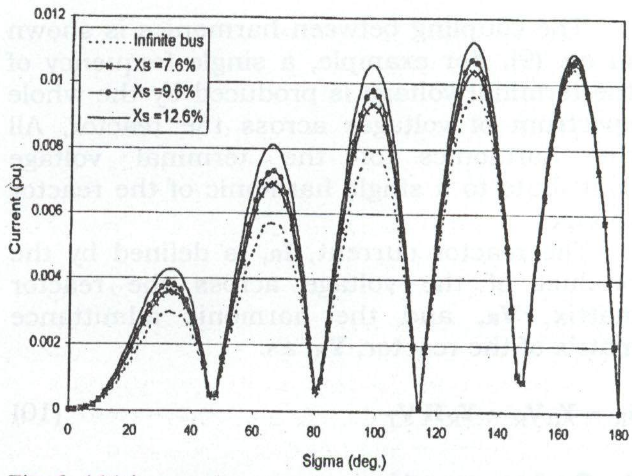

Fig. 6. 11th harmonic current.

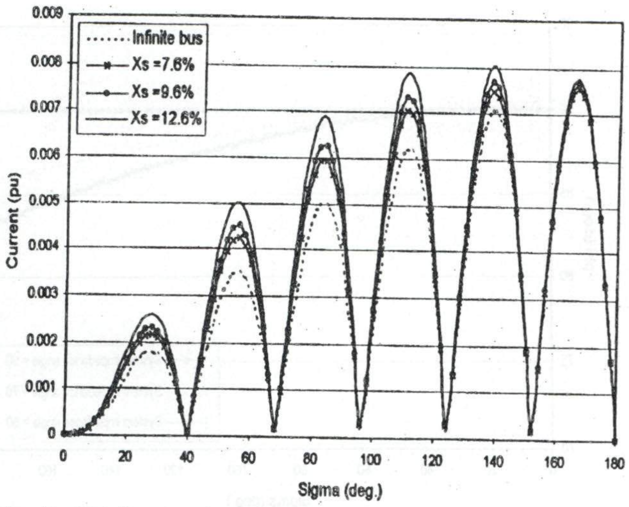

Fig. 7. 13th harmonic current.

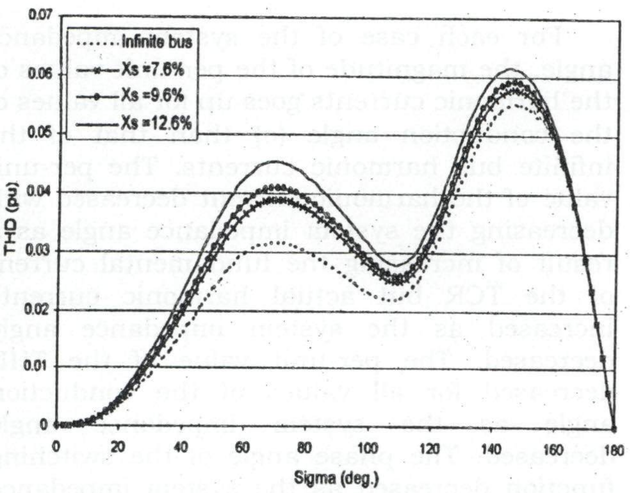

Fig. 8. Total harmonic distortion.

5. Effects of the system impedance angle on the TCR harmonics

Effects of the system impedance angle on the harmonic currents, the total harmonic distortion and the phase angle of the switching function are applied for the same circuit shown in fig. 3.

Studying of the harmonic currents up to 13th harmonic current, when applied with the effect of changing the angle of the system impedance, and the results are compared with those obtained for the case of infinite bus. The system impedance has a magnitude of 0.076 pu. Three values for the resistive part of the system impedance are considered. These values are assumed to change only the system impedance angle. These angles are 90°, 70° and 50°

The TCR was operated over its range of the conduction angle σ, from 0.0° to 180°. The 5th, 7th, 11th and 13th harmonic currents are plotted for different values of the system impedance angle versus the conduction angle as shown in figs. 9 – 12, respectively. The per-unit value of the THD is plotted as shown in fig. 13. The change in the phase angle of the switching function is plotted as shown in fig. 14. Harmonics higher than the 13th harmonic were truncated due to their small amplitudes.

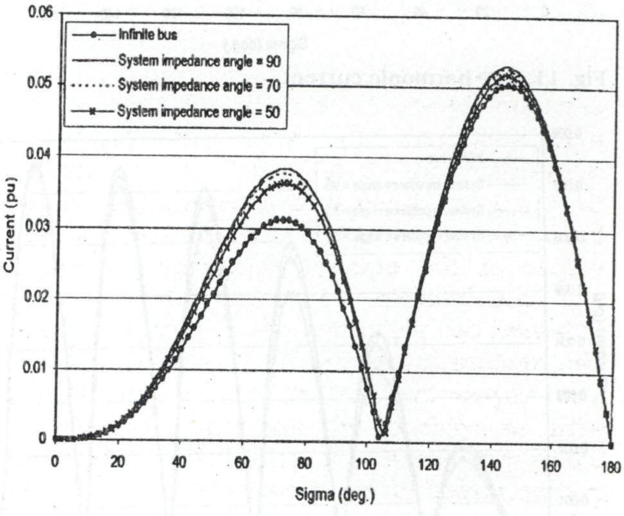

Fig. 9. 5th harmonic current.

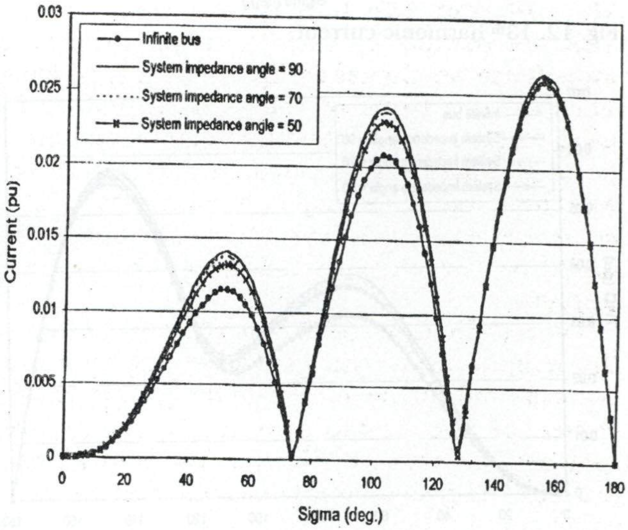

Fig. 10. 7th harmonic current.

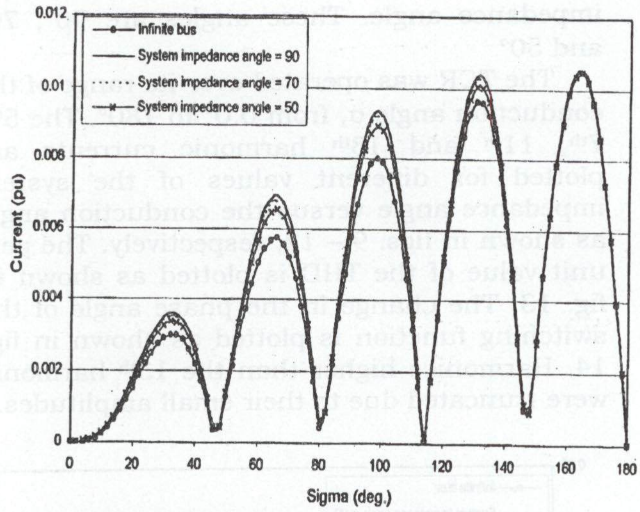

Fig. 11. 11th harmonic current.

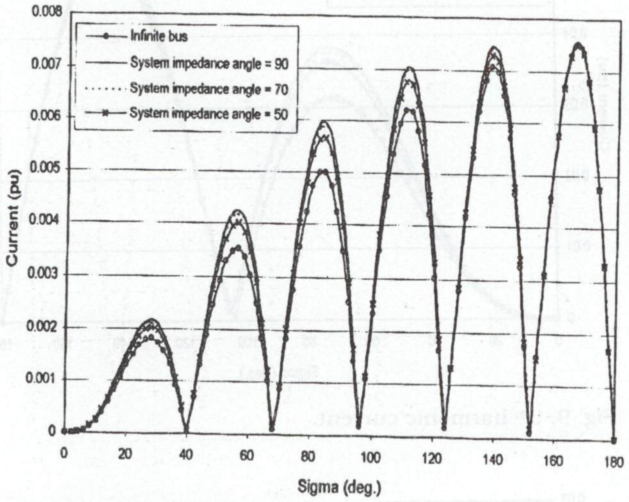

Fig. 12. 13th harmonic current.

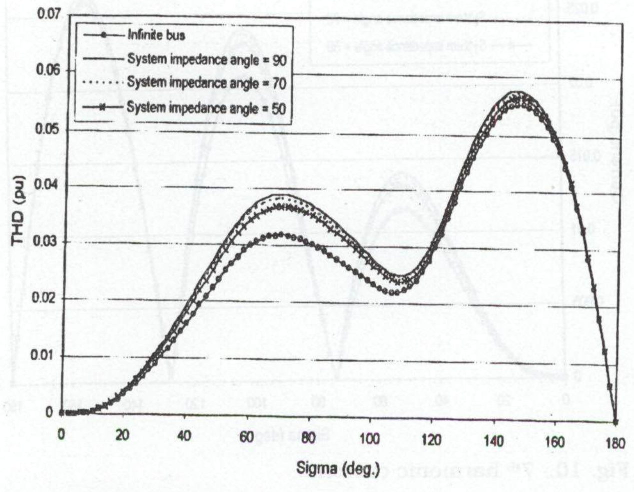

Fig. 13. Total harmonic current.

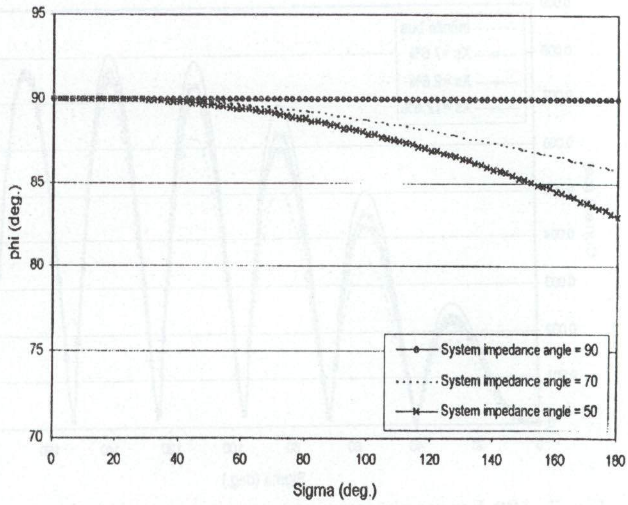

Fig. 14. Phase angle of the switching function.

For each case of the system impedance angle, the magnitude of the per-unit values of the harmonic currents goes up for all values of the conduction angle (σ) than that of the infinite bus harmonic currents. The per-unit value of the harmonic current decreased with decreasing the system impedance angle as a result of increasing the fundamental current of the TCR but actual harmonic currents increased as the system impedance angle decreased. The per-unit value of the THD decreased for all values of the conduction angle as the system impedance angle decreased. The phase angle of the switching function decreased as the system impedance angle decreased. The resistive part of the system impedance makes the current of the TCR more lead, which causes the angle ϕ to decrease.

6. Effects of the TCR impedance angle on the TCR harmonics

Effects of the TCR impedance angle on the harmonic currents, the total harmonic distortion and the phase angle of the switching function are applied for the same circuit shown in fig. 3.

The system impedance and the fixed capacitor of the static VAR compensator are assumed to have impedance of $0.076\angle 90°$ and $0.265\angle -90°$ pu. respectively. Studying of the harmonic currents up to 13th harmonic current, when applied with the effect of changing the internal resistance of the reactor of the TCR, and the results are compared with the assumption that the TCR impedance is losses-less impedance. Different values for the internal resistance of the reactor of the TCR are considered. These values are assumed to change only the impedance angle of the reactor of the TCR. These angles are 90°, 75° and 70°.

The TCR was operated over its range of the conduction angle σ, from 0° to 180°. The 5th, 7th, 11th and 13th harmonic currents of the TCR are plotted for each value of the TCR impedance angle as shown in figs. 15 -18, respectively. The per-unit value of the THD is plotted for each value of the TCR impedance angle as shown in fig. 19. The change in the phase angle of the switching function is plotted as shown in fig. 20. Harmonics higher than the 13th harmonic were ignored due to their small amplitudes.

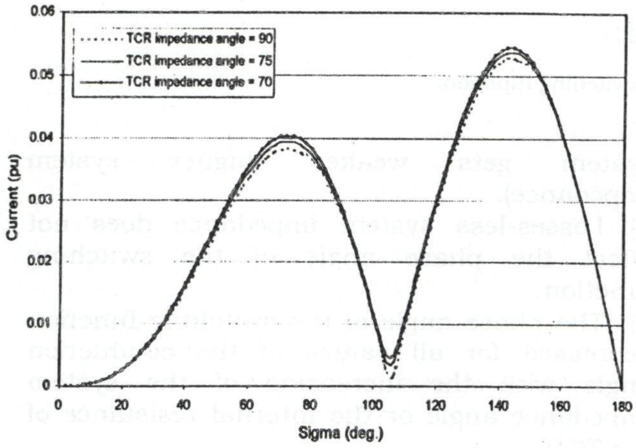

Fig. 15. 5th harmonic current.

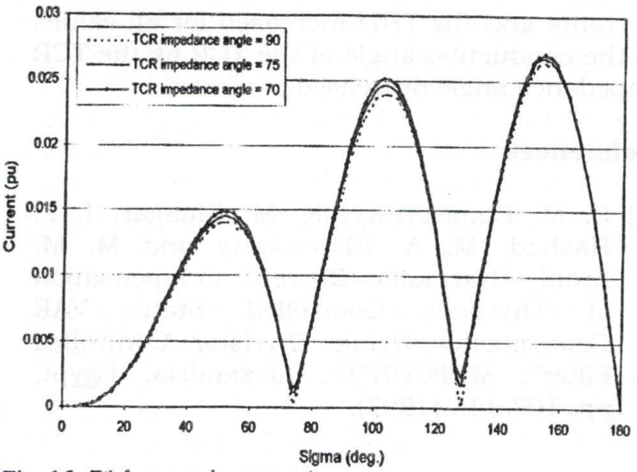

Fig. 16. 7th harmonic current.

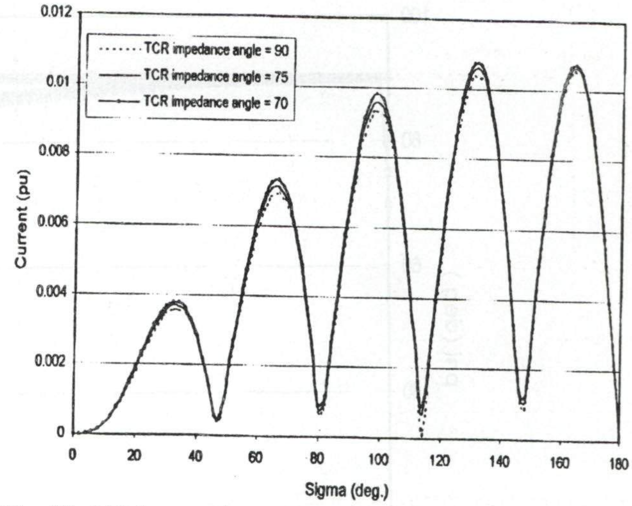

Fig. 17. 11th harmonic current.

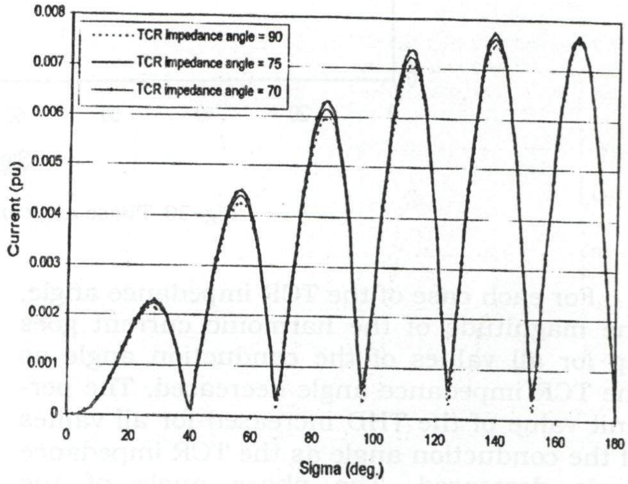

Fig. 18. 13th harmonic current.

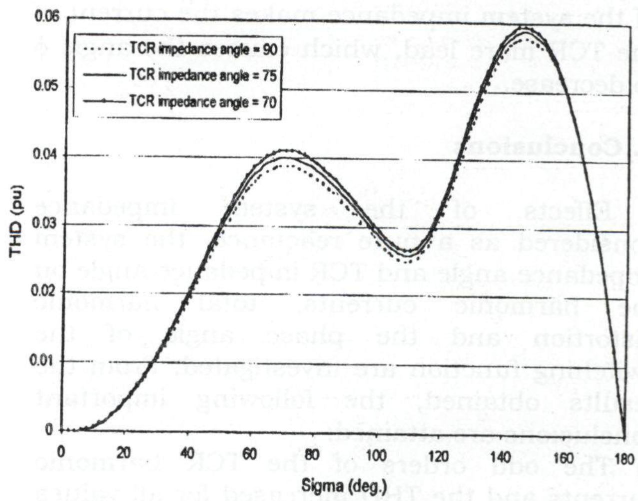

Fig. 19. Total harmonic distortion.

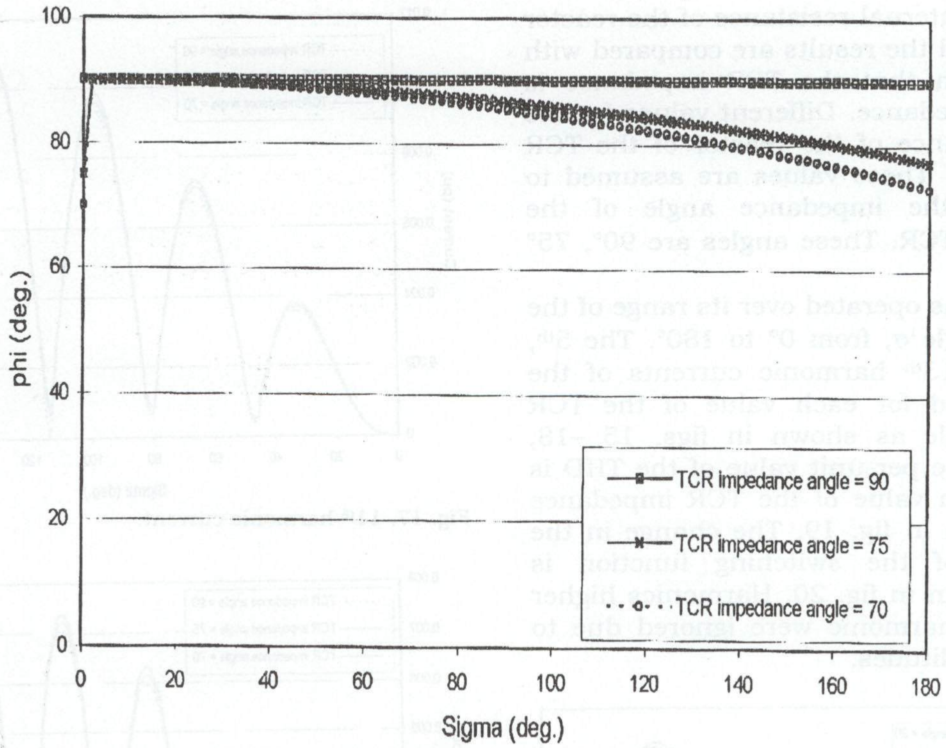

Fig. 20. Phase angle of the switching function.

For each case of the TCR impedance angle, the magnitude of the harmonic current goes up for all values of the conduction angle as the TCR impedance angle decreased. The per-unit value of the THD increased for all values of the conduction angle as the TCR impedance angle decreased. The phase angle of the switching function decreased as the TCR impedance angle decreased. The resistive part of the system impedance makes the current of the TCR more lead, which causes the angle ϕ to decrease.

7. Conclusions

Effects of the system impedance considered as a pure reactance, the system impedance angle and TCR impedance angle on the harmonic currents, total harmonic distortion and the phase angle of the switching function are investigated. From the results obtained, the following important conclusions are attained:

1) The odd orders of the TCR harmonic currents and the THD increased for all values of the conduction angle of the TCR as the system gets weaker (higher system impedance).

2) Losses-less system impedance does not affect the phase angle of the switching function.

3) The phase angle of the switching function decreased for all values of the conduction angle with the increasing of the system impedance angle or the internal resistance of the TCR.

4) The odd orders of the TCR harmonic currents and the THD increased for all values of the conduction angle of the TCR as the TCR impedance angle decreased.

References

[1] S. M. Elmasarawy, K. M. Elnagar, I. F. Hashad, M. A. Elsharkawy and M. M. Awad, "Harmonic Current Compensation of Thyristor Controlled Static VAR Compensator Using Thyristor Controlled Filter", MEPCON'97, Alexandria, Egypt, pp. 107-111 (1997).

[2] J. Timothy and E. Miller, "Reactive Power Control in Electric Systems", Book, John Wiley & Sons, New York (1982).

[3] L. J. Bohmann and R. H. Lasseter, "Harmonic Interaction in Thyristor Controlled Reactor Circuits", IEEE Trans. on Power Delivery, Vol. PWRD-4 (3), pp. 1919-1926 (1989).

[4] A. E. Hammad and R. M. Mathur, "A New Thyristor Controlled VAR Compensator Design", IEEE Canadian Conference on Communications and Power, Montreal (1978).

[5] Shih-Min Hsu, "Using a Static VAR Compensator to Balance a Distribution System", IEEE trans. Industry Applications, Vol. IA-35 (5), pp. 1174-1177 (1999).

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