

ARAŞTIRMA MAKALESİ

HARMONIC EFFECTS AND STABILITY OF THYRISTOR CONTROLLED REACTOR DEPENDING ON CONDUCTION ANGLE

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TRİSTÖR KONTROLLÜ REAKTÖRÜN İLETİM AÇISINA BAĞLI HARMONİK ETKİLERİ VE STABİLİTESİ

ÖZET

Kompanzasyon için kullanılan tristör kontrollü reaktör (TKR) içeren statik VAR sistemleri nonlineer elemanlardır. Güç sistemlerine bağlanan nonlineer elemanlar, akım ve gerilimin dalga şeklini bozarak harmonik bileşenlerinin ortaya çıkmasına yolaçarlar. Bu harmonik bileşenler, sistemde rezonans olaylarına neden olarak sistemi kararsız duruma getirebilirler. Bu makalede TKR'nin hem harmonik üretimi hem sinüsoidal olmayan durumda reaktif güç, sistem kararlılığı gibi çalışma değerleri, değişik işletme şartları için incelenmiştir.

SUMMARY

Static VAR compensators including thyristor controlled reactor (TCR) which are used for compensation are nonlinear elements. Nonlinear elements connected to power systems distort the current and voltage waveforms, thus harmonic components are occurred. These harmonic components cause some resonance events in the system. Due to the resonance events, the system may be instable. In this paper, both harmonic production and operating values (reactive power, system stability etc.) in nonsinusoidal case are examined for various operating conditions.

1. INTRODUCTION

Power system engineers are currently facing challenges to increase the power transfer capability of existing transmission systems. Flexible-AC-Transmission-Systems(FACTS)-controllers offer an economical solution to accommodate that need while maintaining sufficient steady-state and transient stability margins. Due to fast and flexible actions of FACTS devices, many relevant benefits can be achieved such as utilization of transmission capability, efficient power-flow control, transient stability improvement, power oscillation damping, subsynchronous resonances mitigation, and fault current limitation [1].

Recently, utilities have been interested in applying static VAR compensators including TCR technology on distribution systems [2]. In addition, the power factor can

be improved simultaneously by selecting an appropriate amount of capacitive/inductive compensation [3].

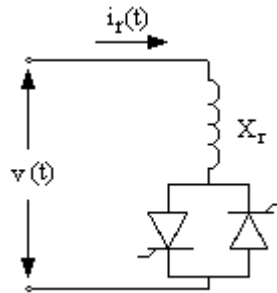


Figure 1. The main elements of a TCR

There are several well known sources of harmonics present in AC power systems. These include AC/DC converters, transformer saturation, arc furnaces, etc. Another source of harmonics which is increasingly being used in power systems, however, is the thyristor controlled reactor (TCR) which is gaining popularity as a method of voltage control [4]. However, as the TCRs contain power electronic components, harmonics and their impacts on the system should be studied [5]. The basic elements of a TCR are a reactor in series with a bi-directional thyristor as shown in Figure 1.

2. THYRISTOR CONTROLLED REACTOR

Thyristor controlled reactors, which have the ability to ensure a continuous and fast reactive power and voltage control can increase the performance of the system from different ways: Such as control of transient over voltages at power frequency, preventing of voltage collapse, increase in transient stability and decrease in the system oscillations. Static VAR compensators consist of thyristor controlled reactors are used for balancing the three phase systems supplying unbalanced loads and for preventing the voltage oscillations caused by short duration loads in transmission and distribution systems.

In order to develop a more accurate in frequency model, the circuit in Figure 2 is analyzed. This represents a fixed capacitor-TCR static VAR compensator connected to an AC system configured as a system reactance, X_s , a voltage source, $v(t)$. The two parallel thyristors are gated symmetrically. They control the time for which the reactor conducts and thus control the fundamental component of the current [6].

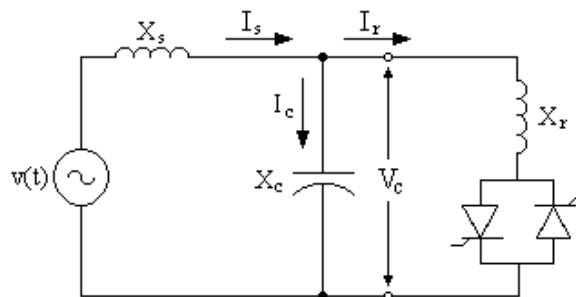


Figure 2. Fixed capacitor-thyristor controlled reactor static VAR compensator.

The thyristors conduct on alternate half-cycles of the supply frequency depending on the firing angle α , which is measured from a zero crossing of voltage. Full conduction is obtained with a firing angle of 90° . The current is essentially reactive and sinusoidal. Partial conduction is obtained with firing angles between 90° and 180° . Firing angles between 0 and 90° are not allowed as they produce asymmetrical currents with a dc component.

Let σ be the conduction angle, related to α by

$$\sigma = 2(\pi - \alpha) \tag{1}$$

Instantaneous current is given by:

$$i_r(t) = \begin{cases} \frac{V_m}{X_r} \left[\cos\left(\frac{\pi - \sigma}{2}\right) - \sin(\omega t) \right], & \frac{\pi - \sigma}{2} \leq \omega t \leq \frac{\pi + \sigma}{2} \\ 0, & \frac{\pi + \sigma}{2} \leq \omega t \leq \frac{3\pi - \sigma}{2} \end{cases} \tag{2}$$

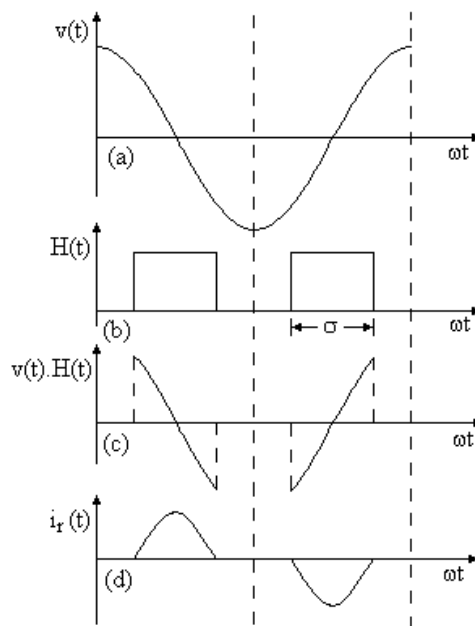


Figure 3. Voltage and current waveforms in a TCR

Fourier analysis of the effective current waveform gives the fundamental component:

$$I_{r1} = \frac{V_m}{\sqrt{2} X_r} \left(\frac{\sigma - \sin \sigma}{\pi} \right) \tag{3}$$

where X_r is the reactance of the reactor at fundamental frequency. The effect of increasing α (i.e., decreasing σ) is to reduce the fundamental component I_1 [7].

Referring to Figure 3, the voltage across the terminals is assumed to be a perfect sinusoidal waveform (Figure 3a). The existence function (Figure 3b) is twice the frequency of the voltage and it is centered on the zero crossing of the voltage. Its width is the angle σ , the angle through which the current in a thyristor conducts. Multiplying the source voltage by the existence function picks up parts of the voltage curve. These parts are integrated to obtain the current through the controlled reactor (Figures 3c and 3d) [6].

The existence function H can be expressed as follow,

$$H(t) = \frac{\sigma}{\pi} + \sum_{h=1}^{\infty} \frac{2}{h\pi} \cos(h\pi) \sin(h\sigma) \cos(2h\omega t) \quad (4)$$

By considering the harmonic effects of static VAR compensator the equivalent circuit can be given as Figure 4 [6].

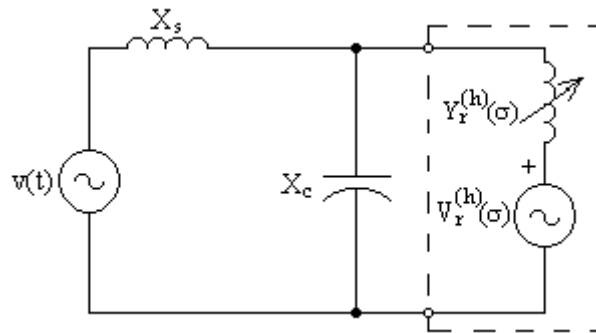


Figure 4. Variable voltage source and admittance model for a TCR.

The reactor admittance depending on thyristor conduction angle can be defined as follows:

$$Y_r^{(h)} = \frac{\sigma - \frac{\sin(h\sigma)}{h}}{hX_r\pi} \quad (5)$$

In the circuit, harmonics components of the current and voltage respectively can be written as below,

$$V_r^{(h)} = \sqrt{2} \cdot V_m \cdot \cos\left(\frac{h-1}{2} \pi\right) \frac{1}{\sigma - \frac{\sin(h\sigma)}{h}} \times \left[\frac{\sin\left(\frac{h+1}{2} \sigma\right)}{h+1} - \frac{\sin\left(\frac{h-1}{2} \sigma\right)}{h-1} \right] \quad (6)$$

$$I_r^{(h)} = V_r^{(h)} \cdot Y_r^{(h)} \quad (7)$$

where the current and the voltage consist of only odd harmonics, and the amplitudes are the functions of the conduction angle [6].

TCRs cause various harmonics problems by acting a nonlinear load. Harmonics occur because of the phase control in a TCR. The voltage of the reactor include various harmonics and fundamental component of the reactor current depend on chosen firing angle (α) or conduction angle (σ).

For the condition of balanced loading TCR produces odd harmonics. In a three phase system where the TCR's are Δ -connected there will be no triplet harmonics injected into the power system [8]. However, TCR circuits should not be operated on the points related to resonance conditions doing effective harmonic production.

3. STABILITY AND HARMONICS

It is necessary to pay attention to energy system stability in the planning, management, and control of electrical power system for a more reliable and quality energy [9]. Stability in an energy system is an ability turning to the first operating condition after a distortion effect [10]. In voltage stability, the amplitude values of the load bus voltages of the system should be kept in a determined limit values in both steady-state and transient conditions.

If there is an uncontrollable and more and more decrease in voltage due to the increase in load demand or a change in the system condition, it occurs voltage instability in the system. The main reason for instability is insufficient condition of power system corresponding to the demand of reactive power. In order to prevent the insufficient condition, it is an advantage to use the static VAR compensator including TCR [11].

Because of using power electronics to perform static VAR compensation cause instability in the power system on some operating conditions. When we do analysis in the matter of stability, the conditions causing instability are seen to be on resonance conditions.

The high harmonic currents occurred in the system in the special conditions can cause compensation capacitors to resonance with other components' inductance in the circuits. The analysis of the system should be done by determining the working condition causing instability.

Depending upon the AC system impedance, the harmonic current injected into the system might distort the bus voltage. This distortion might prove embarrassing as it might be possible to lose control of conduction angle of the TCR [4]. The distortions are defined as total harmonic distortion (THD) for current,

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \quad (8)$$

Resonance condition for h^{th} harmonic component is given by [12]:

$$\frac{X_{sh} \cdot X_{rh}}{X_{sh} + X_{rh}} = X_{ch} \quad (9)$$

where X_{ch} , X_{sh} and X_{rh} are h^{th} harmonic component of capacitor reactance, n^{th} harmonic one of the system reactance and n^{th} harmonic one of TCR reactance, respectively. In the power systems with TCR, general block diagram for resonance analysis is given in Figure 5.

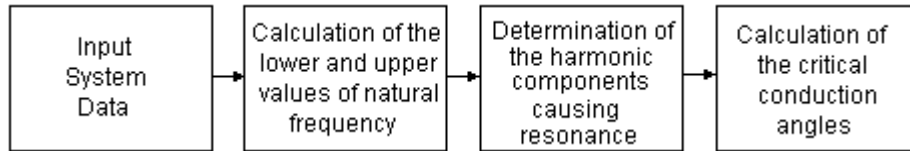


Figure 5. General block diagram for calculation the critical conduction angles causing resonance

4. NUMERICAL APPLICATION

In order to determine the operating conditions of TCR, a numerical analysis is done using figure 3 sample system. The values in the application as per-unit has been taken; voltage $V_c = 1.0$ pu, reactance of TCR $X_r=0.6$ pu, fixed-capacitor reactance $X_c = 2.0$ pu, system reactance $X_s = 0.082$ pu and fundamental frequency 50 Hz (Base power is 1 MVA and base voltage is 1kV). The results from our software as follows:

For the conduction angle (σ) is between 30° and 38° , system will be in resonance at 5^{th} harmonic component. So, 80° , 120° , 160° is chosen for the analysis.

Harmonic current component values of TCR is given in Table 1.

Table 1. Harmonic current component values

Harmonic order (h)	$I_r^{(h)}(80^\circ)$ (pu)	$I_r^{(h)}(120^\circ)$ (pu)	$I_r^{(h)}(160^\circ)$ (pu)
5	0.0345	0.0325	0.0458
7	0.0069	0.0116	0.0287

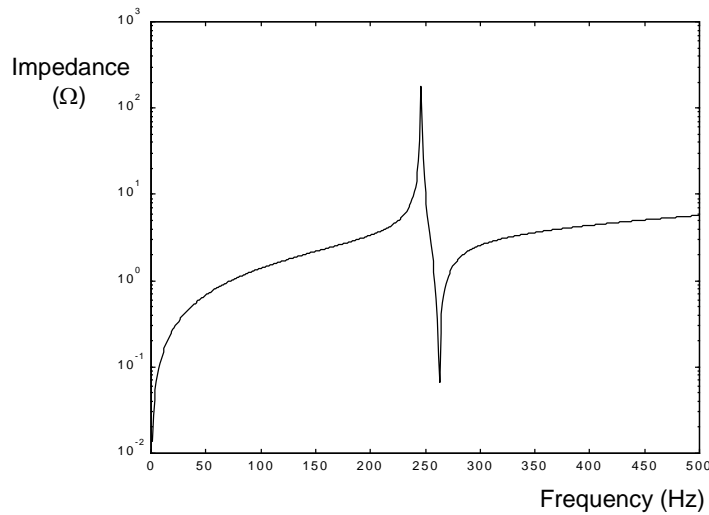


Figure 6. Impedance as function of frequency

To verify the results of the previous analysis, the stability analysis was performed by using MATLAB-Simulink program. The frequency analysis of the circuit shown in Figure 4 was done for 0-500 Hz range. The Bode diagram obtained from this analysis is shown in Figure 6. As shown in Figure 4, there is a resonance event in the system because of the fifth harmonic component (the critical frequencies are between 243-265 Hz range).

The changes of the current, correspond to fundamental and harmonic components for all conduction angles, are shown in Figure 7 and 8, respectively.

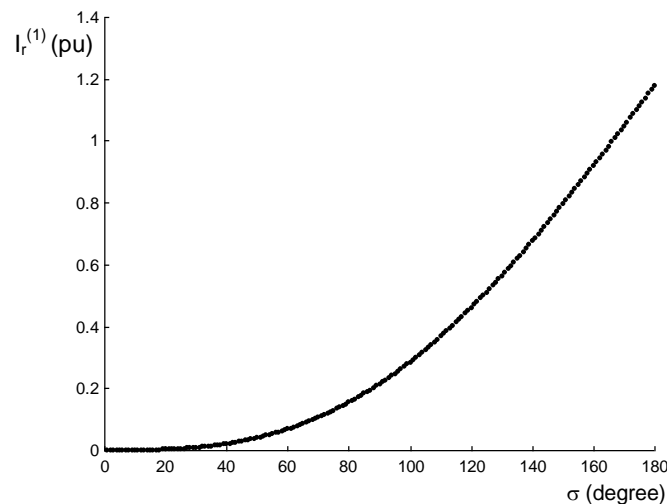


Figure 7. Fundamental current component versus conduction angle (σ)

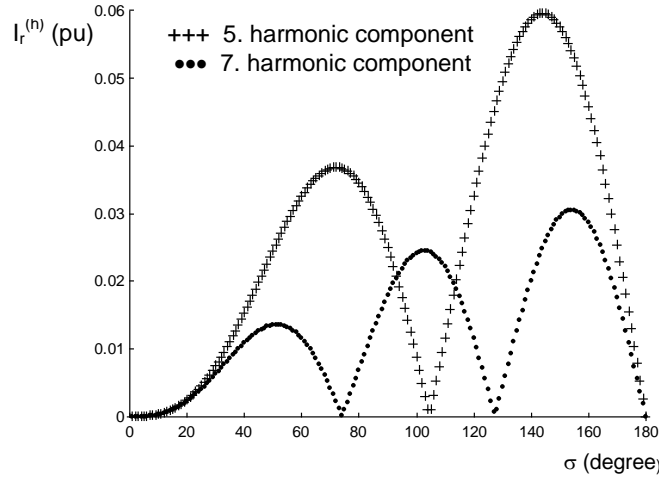


Figure 8. Harmonic current components versus conduction angle (σ).

The current values of fundamental component and the total harmonic distortion belonging to the current for 80°, 120°, 160° in the system are given in Table 2.

Table 2. The current values of fundamental component and the total harmonic distortion values belonging to the current in the system

σ , conduction angle (degree)	$I_r^{(1)}$ (pu)	% THD _{I_r}
80	0.1544	22.78
120	0.4608	7.4863
160	0.9193	5.8749

The change of the total current harmonic distortion for all conduction angles are given in Figure 9.

Equivalent susceptance is calculated as in eq. (10) by using capacitor reactance of FC-TCR.

$$B^{(h)}(\sigma) = Y_r^{(h)}(\sigma) - \frac{1}{X_c^{(h)}} \quad (10)$$

Reactive power changes as follows,

$$Q(\sigma) = B^{(h)} \cdot \left(\frac{V_c}{\sqrt{2}}\right)^2 \quad (11)$$

The presence of 5th and 7th harmonics in the circuit, the variation of reactive power for all conduction angles is shown in Figure 10.

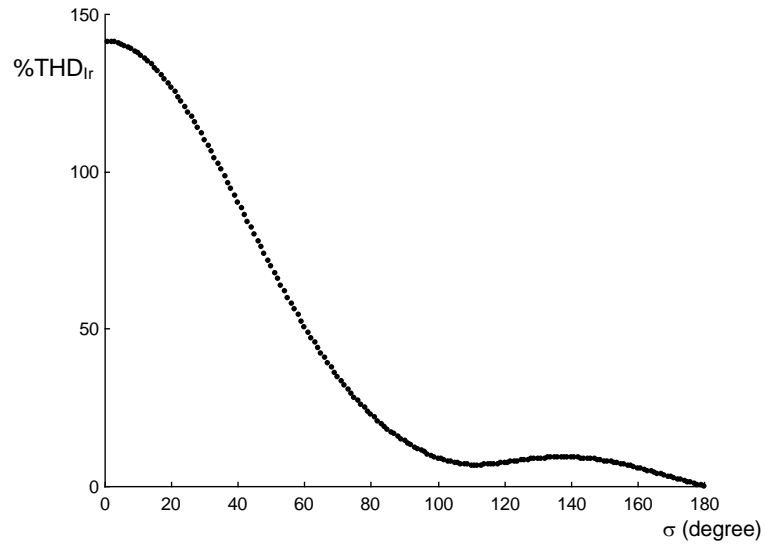


Figure 9. THD_{I_r} versus conduction angle (σ).

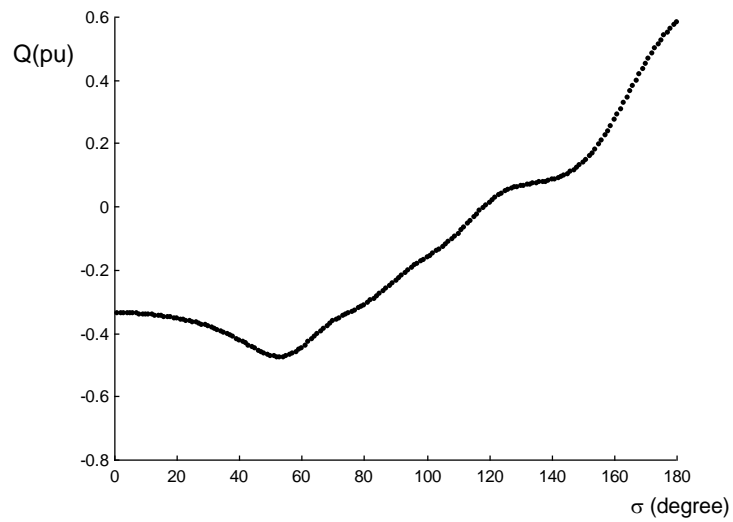


Figure 10. The variations of reactive power for all conduction angles

In this particular example, the system is operated as inductive when conduction angles are between 0° and 120°, except for these conditions, the system is operated as capacitive.

5. CONCLUSIONS

The following conclusions can be derived from this study for the system with static compensator including TCR:

The analysis results show that there are significant harmonic distortions inside the compensator system. The waveform distortions in the network are low in properly designed the static compensator systems. In this study, the conduction angles must be chosen higher than 100° for the minimum total harmonic distortion.

The RMS current is important for operating value of static VAR compensator. The RMS current calculation includes not only the fundamental component of the RMS current, but also the harmonic components.

When harmonic components are not considered, it is no possible to do compensation accurately. It is required to be changed the conduction angle for perfect reactive power.

If the harmonic components cause resonance events in the system, the system will be instable. The determination of conduction angles which cause instable operation is very important for steady-state case. This case must be considered while the systems are designed and operated.

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