NEW METHODS FOR HARMONIC REDUCTION IN T. C. R. BY SEQUENCE CONTROL OF TRANSFORMER TAPS

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Abstract Thyristor controlled static compensators consist of two basic schemes, TCR and TSC. Owing to the discontinuous current in TCR, current harmonics are generated in the supply system. This paper introduces two methods for the reduction of these harmonics. On the basis of the coordination or uncoordination of turn ratios with harmonic reduction levels, each method is described in two alternative schemes. By using either one of these methods, the magnitude of harmonics may be reduced and their undesirable effects in power systems minimized.

چکیده تولید ویا جذب قدرت راکتیو بصورت پیوسته و قابل‌کنترل از مشخصه‌های کار کمپانزاتورهای استاتیکی کنترل‌شونده تریستوری می‌باشد. برای برآورد مشخصه کار کنترل پیوسته فوق‌الذکر، کمپانزاتورهای استاتیکی باید متشکل از دو سیستم .T.C.R و .T.S.C (یا .S.C) باشند. به لحاظ ناپیوستگی جریان راکتور در سیستم هارمونیکهای جریان در شبکه تغذیه تولید شده، که بنوبه خود باعث پایین آمدن کیفیت کار شبکه می‌گردد. این مقاله دو روش جدید برای کاهش این هارمونیکها ارائه می‌دهد. درهریک از دو روش ارائه‌شده ترانسفورماتور بکارگرفته‌شده برای سیستم .T.C.R، با نسبت تبدیل متغیر می‌باشد. لذا براساس هماهنگی ویا عدم هماهنگی نسبت تبدیل پله‌های ترانسفورماتور با سطح کاهش هارمونیکها، هریک از روشها به دو حالت متفاوت موردبررسی قرار گرفته است. با بکارگیری هریک از این روشها و با انتخاب مناسب نسبت تبدیل پله‌ها، می‌توان دامنه هارمونیکها را در شبکه کاهش داده و اثرات سوء آنها را به حداقل ممکن رسانید.

INTRODUCTION

The importance of reactive power control has increased along with power system expansion. Absorption or generation of reactive power in a continuous and controllable manner is one of the operating characteristics of synchronous motors and static compensators. Because of their fast response, high efficiency and low maintenance, static compensators are preferable [1].

In order to meet the above mentioned characteristics, static compensators should consist of two basic schemes, TCR and TSC (or SC) [1, 4].

When phase angle control is used in a TCR system a continuous change in the reactive power consumed by the reactor is obtained. But, in spite of this advantage, current harmonics will be injected into the supply system which will decrease network quality [1, 3].

In symmetrical control of firing angles of both thyristors relevant to one phase, all odd order harmonics are generated: 3rd, 5th, 7th, 9th, 11th, 13th and so on. However, in balanced control of firing angles the zero sequence components (3rd, 9th, etc.) will be circulated between the reactors in delta connection or between delta winding of transformer in star connection of TCR.

Methods generally used by designers for reducing (or eliminating) the remaining harmonics, consist of filtration or circuit modification.

One of the methods uses two thyristor-controlled reactors, each of them designed for half of the rated power. One of the reactors is phase angle controlled, while the other will be either fully conducting or completely disconnected from the network. This method will reduce amplitudes of all harmonics [1, 3].

Another method is 12-pulse connection. This means that two similar delta connected TCR (two six pulse connections) are used, one connected to the star, and the other to the delta connected secondary winding of the feeding transformer. In this method only the 5th and 7th harmonics are eliminated while the magnitudes of the 11th and 13th harmonics remain unchanged as in a large single reactor [1].

Even though these harmonics are eliminated, other harmonics present will cause network quality to be at an unacceptable level. So in order to reduce or eliminate them, appropriate methods must be adopted. For this reason, the reduction of all harmonics was the main aim of this research. Thus, it is supposed that TCR is supplied from a transformer with a tapped secondary (while in the conventional methods it is supplied from a fixed secondary) [2], and on this basis, two alternative methods are considered:

1- Sequence control of transformer taps equipped with on load tapchanger

2- Sequence control of transformer taps without tapchanger

By using "sequence control of transformer taps" the magnitude of harmonics may be reduced in network and their undesirable effects minimized. Under such conditions, system operation quality will be high.

THEORY

Employing back-to-back connected thyristors as a control element (Figure 1a) causes absorbed Var to be a function of the firing angle as shown in Figure 2a.

For firing angles larger than 90°, reactor current would be discontinuous (Figure 1b), so in addition to the fundamental current it consists of other harmonics (Figure 2b).

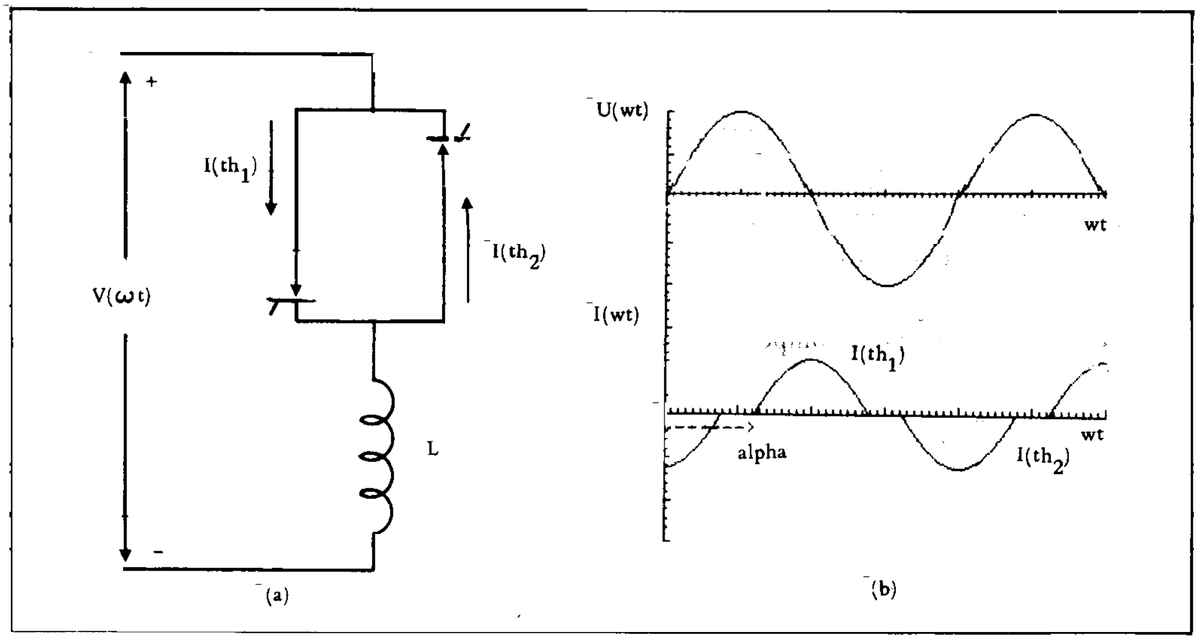

Figure 1: Thyristor – controlled reactor a-Line diagram (conventional method) b-Supply voltage and TCR current waveforms.

In a single phase system, and in case of symmetrical firing angle, these harmonics contain all odd orders and as shown in Figure 2b, 3rd order harmonic has the highest magnitude (13.78%) [1].

In a three phase system and for delta connected TCR, harmonics of ($6K \pm 1$) order would only be injected into the supply. In this case 5th order harmonic has the highest magnitude (5.05%) [1].

In order to improve the power system operation, remaining harmonics must be eliminated by the use of appropriate filters. In bulk power systems with high rating compensators, filtration of these harmonics due to their high power is not a practical scheme.

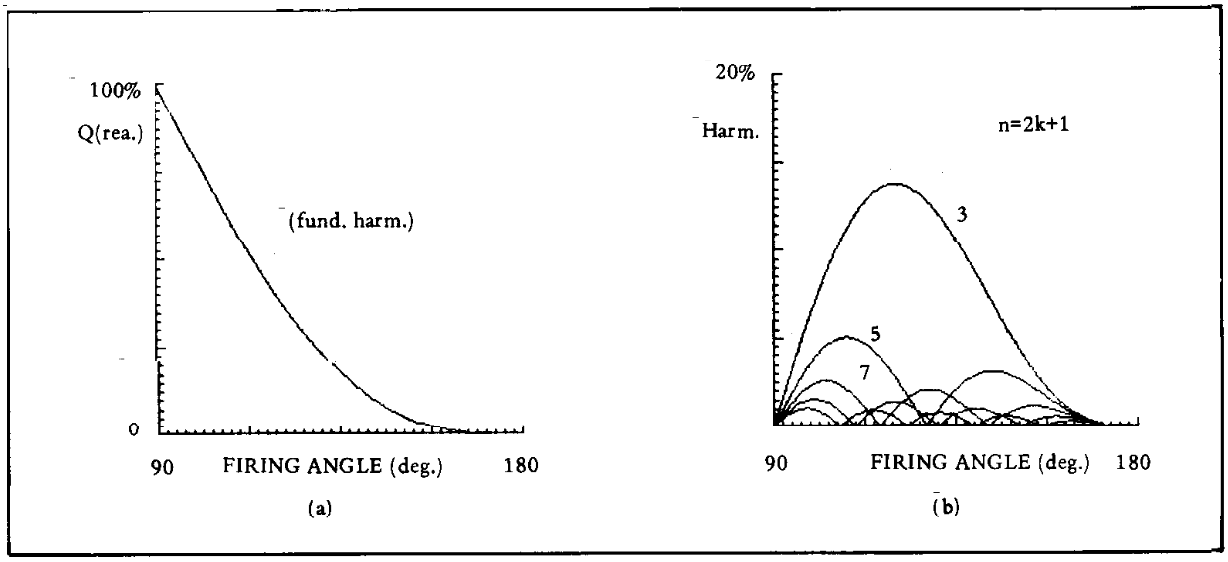

Figure 2: Variation of reactive power (a) and Harmonics (b) for conventional method.

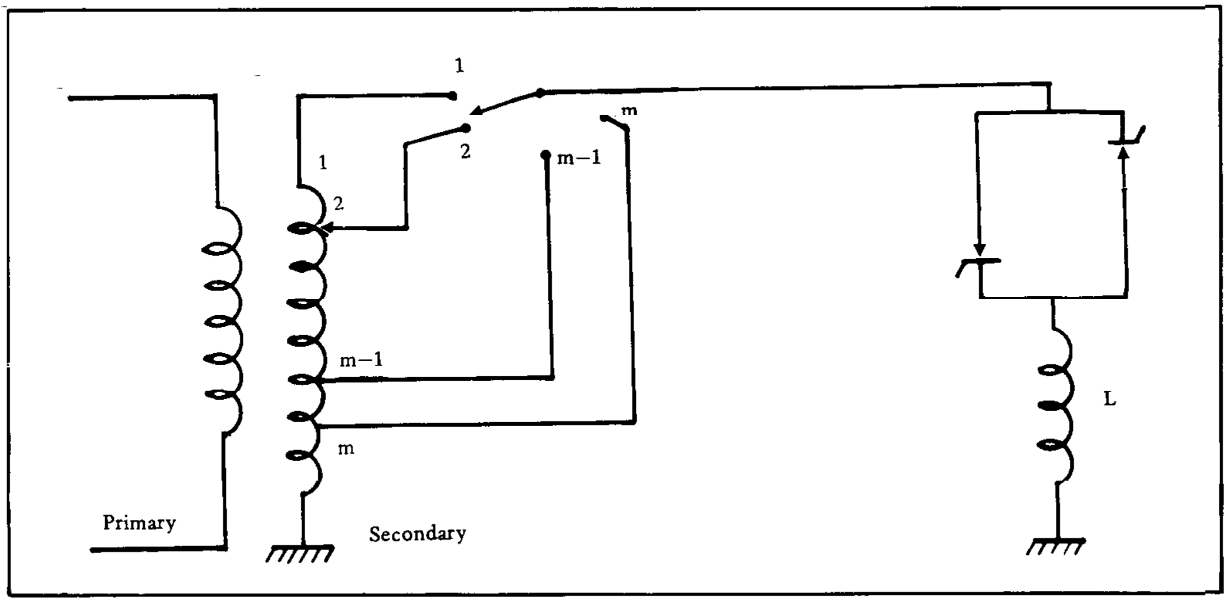

Figure 3: Schematic diagram for sequence control of transformer taps equipped with O.L.T.

Therefore, reduction of their amplitudes is necessary.

This paper presents two methods for this purpose. Using each of them in static Var compensators improves the power system operation.

To examine and evaluate the presented methods the following numerical examples have been used for computational analysis.

Example 1-1: Harmonic reduction up to 50% of 3rd harmonic

Example 1-2: Harmonic reduction up to 100% of 5th harmonic

Example 2-1: Using transformer with three taps and following turn ratios: t1=1, t2=0.67, t3=0.33

Example 2-2: Using transformer with two taps and following turn ratios: t1=1, t2=0.7

Method 1. Using Transformer Equipped With On Load Tapchanger

Figure 3 depicts a transformer with m taps on its secondary winding and turn ratios as: t1, t2, t3, ..., tm connected to a TCR system where t1 > t2 > ... > tm. It is clear that when TCR is supplied from one of the secondary taps, and the firing angle α lies in the range $90^\circ < \alpha < 180^\circ$, harmonics with different magnitudes are injected into network.

The expression for phase current when resolved into harmonics by fourier analysis [2] is:

$$i(t) = a_1 \sin(\omega t - \frac{\pi}{2}) - \sum_{k=1}^{\infty} a_n \sin(\omega t - \frac{\pi}{2}) : n$$

$$2K + 1$$

where

$$a_1 = \frac{1}{\pi} \cdot \frac{Vm}{L\omega} [\sin 2\alpha + 2(\pi - \alpha)]$$

$$a_n = \frac{4}{\pi} \cdot \frac{Vm}{L\omega} \quad \frac{\sin(n+1)\alpha}{2(n+1)} + \frac{\sin(n-1)\alpha}{2(n-1)}$$

$$\frac{1}{n} \cos\alpha \cdot \sin\alpha$$

In the above relations α is the firing angle, Vm is the secondary peak voltage and a_1, a_n are fundamental and nth order harmonic magnitudes respectively.

For harmonic reduction up to a desired limit (e.g. up to x% of nth order harmonic)

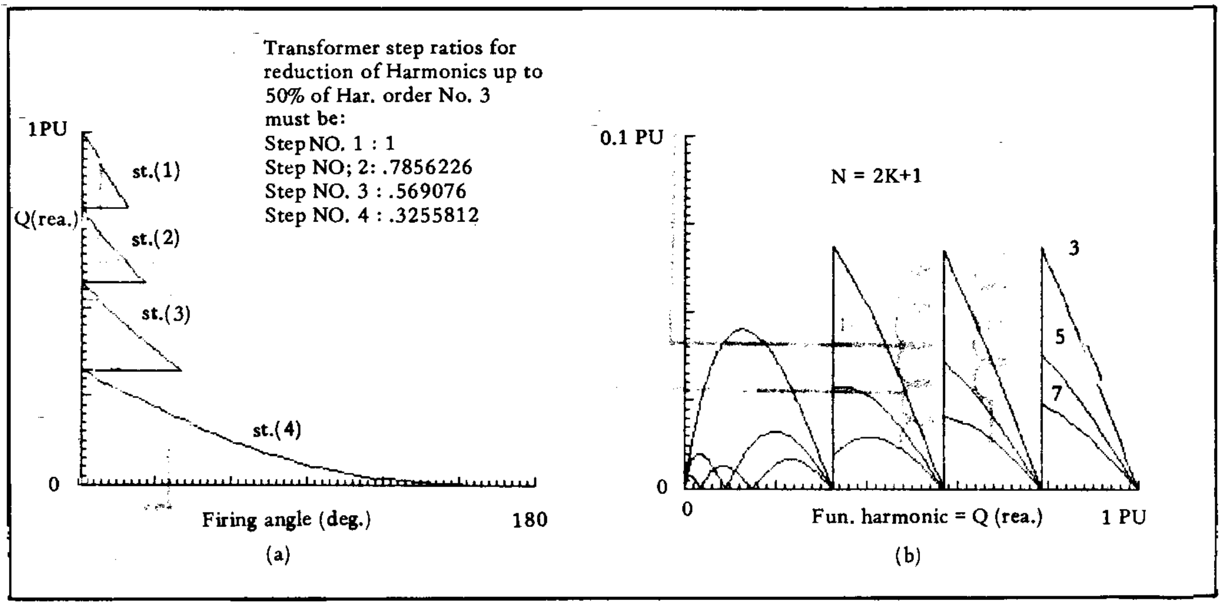

Figure 4: Variation of fundamental current (a) and harmonics (b) for example 1−1

the following is done:

Suppose TCR is supplied from ith tap (with ti ratio). At the firing angle such as α_i' (for which the magnitude of the highest harmonic reaches the desired limit) the operating tap is transferred to the next tap which has a turn ratio equal to $t_i x\ [\sin 2\varphi_i' + 2(\pi - \alpha_i')]/\pi$. In this case, at a new firing angle (which is equal to 90°) not only fundamental current is unchanged but also harmonic magnitudes are diminished to zero.

Suppose again a transformer with m taps. With regard to coordination or uncoordination of turn ratios with harmonic reduction levels, two following alternative schemes must be considered.

Scheme 1. Transformer Taps Have Been Coordianted With Harmonic Reduction Level

In this case the firing angle (α_k) should be

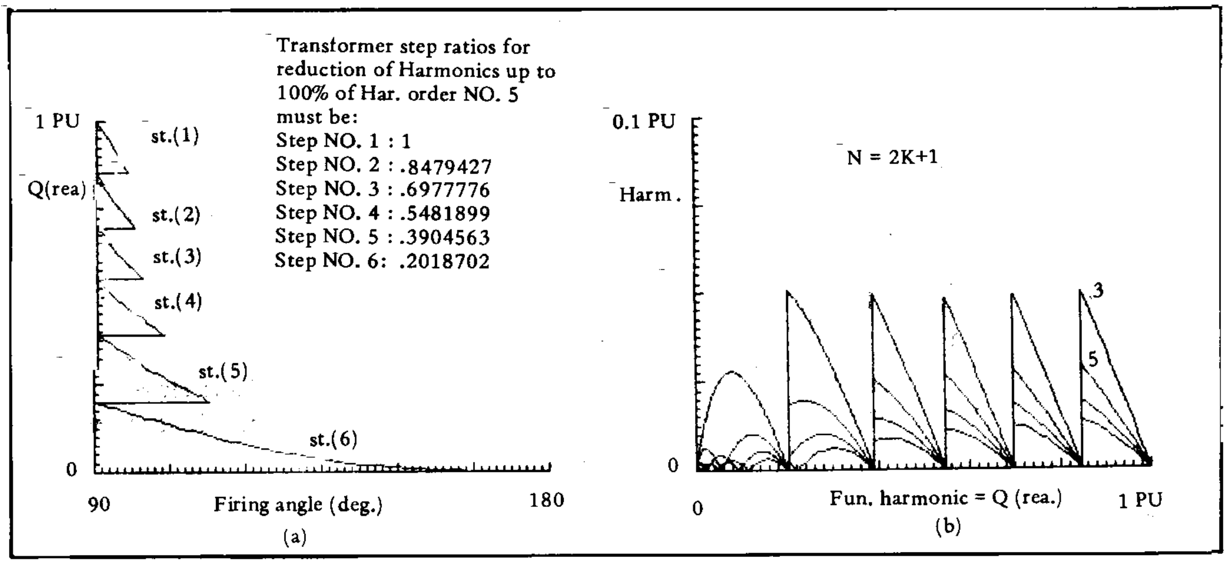

Figure 5: Variation of fundamental current (a) and harmonics (b) for example 1–2

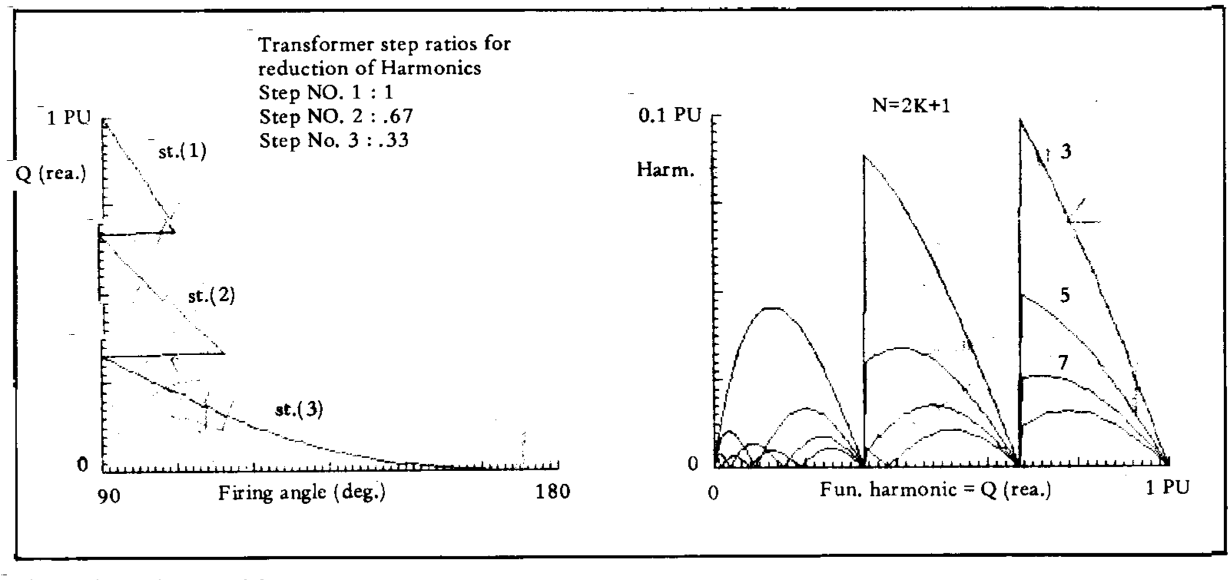

Figure 6: Variation of fundamental current (a) and harmonics (b) for example 2–1

set to meet the following relations:

for first tap $\frac{\pi}{2} \leqslant \alpha_1 \leqslant \alpha_1'$

for second tap $\frac{\pi}{2} \leqslant \alpha_2 \leqslant \alpha_2'$

for mth tap $\frac{\pi}{2} \leqslant \alpha_m \leqslant \alpha_m' = \pi$

Therefore, transformer tap ratios should be selected as:

for first tap $t_1 = \frac{V_{21}}{V_1} = \frac{\text{first tap secondary voltage}}{\text{primary voltage}}$

for second tap $t_2 = \frac{V_{22}}{V_1} = \frac{1}{\pi} [\sin 2\alpha_1' + 2(\pi - \alpha_1')) \times t_1$

for mth tap $t_m = \frac{V_{2m}}{V_1} = \frac{1}{\pi} [\sin 2\alpha_{m-1}' + 2(\pi - \alpha_{m-1}')] \times t_{m-1}$

In the above expressions α_k' is the angle for which the magnitude of the highest harmonic reaches the desired level. Figures 4 and 5 show the evaluation of this scheme by the numerical examples 1–1 and 1–2 respectively. In these Figures variation of the first few dominant harmonics and the fundamental current have been shown. It is evident from Figures 4a and 5a that in order to reduce the harmonics up to 50% of the 3rd harmonic, transformer tap ratios must be selected as:

$t1=1$, $t2 \cong 0.786$ $t3 \cong 0.57$, $t4 \cong 0.33$

and for reduction up to 100% of the 5th harmonic they must be selected as:

$t1=1$, $t2 \cong 0.848$, $t3 \cong 0.698$, $t4 \cong 0.548$, $t5 \cong 0.390$, $t6 \cong 0.202$

Scheme 2. Transformer Taps Have Not Been Coordinated With Harmonic Reduction Level

Suppose the operating tap is ith. Hence, at firing angle equal to α_i', obtained from the following relation, the operating tap must be

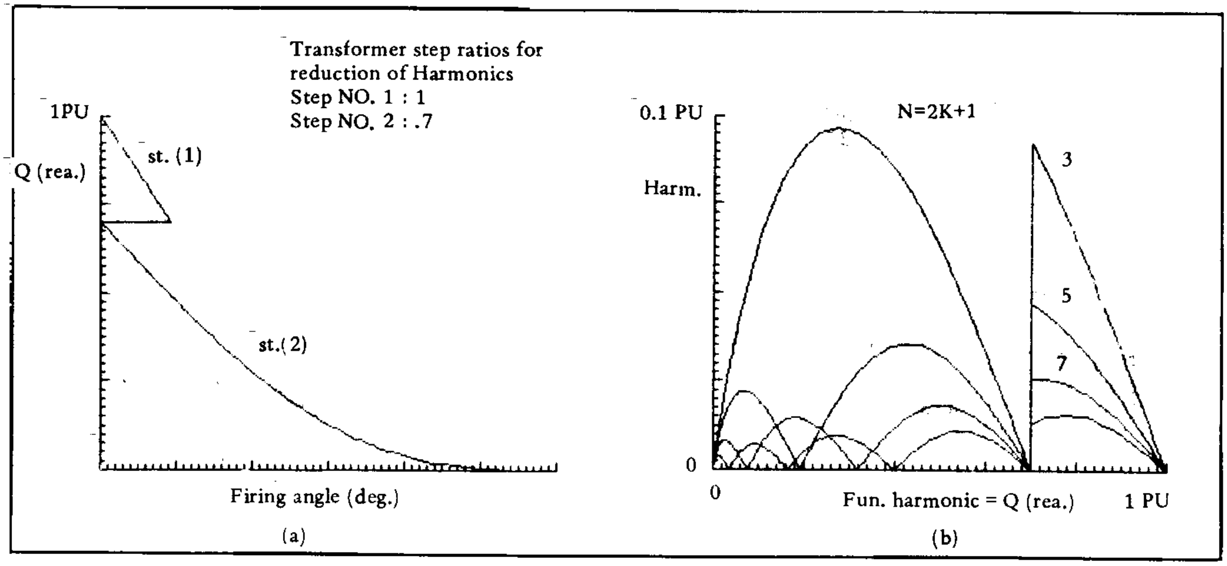

Figure 7: Variation of fundamental current (a) and harmonics (b) for example 2–2

transferred to adjacent tap, jth (j=i+1

$$t_j = \frac{1}{\pi}\left[\sin 2\alpha_i + 2(\pi - \alpha_i)\right] \times t_i$$

Figures 6 and 7 show the evaluation of this scheme by numerical examples 2-1 and 2-2 respectively.

In the cases shown in the Figures, harmonic reduction levels at different taps are not equal. As considered in scheme one, when the permissible final level of harmonics is reduced to a lower value, then the number of required taps increase . In scheme two of this method, since harmonic reduction levels in different taps are not equal, this reduction would not be proportional to increasing the

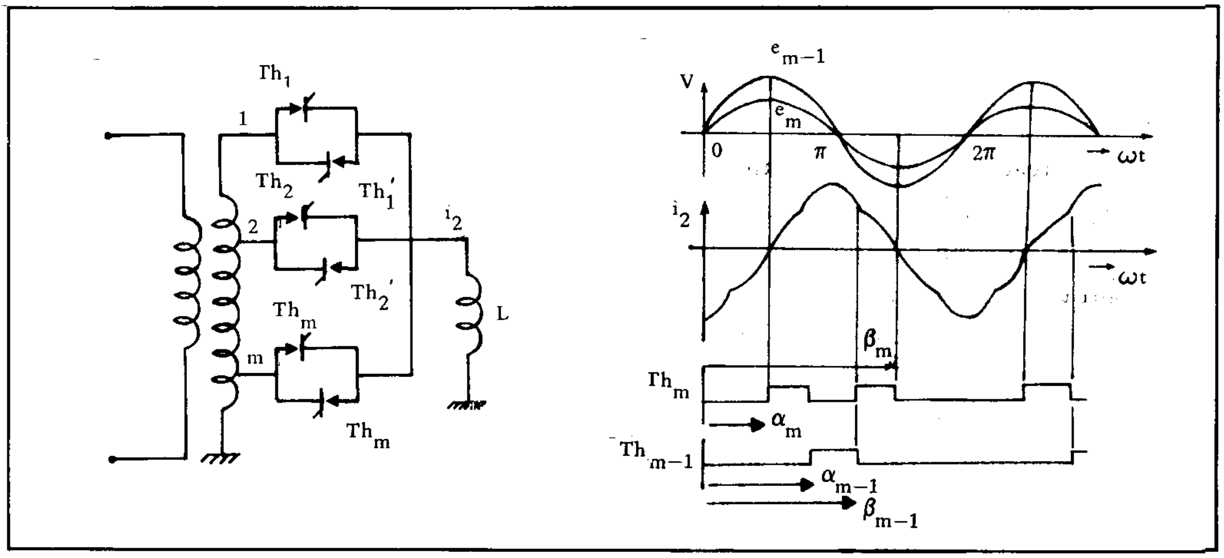

Figure 8: (a): Schematic diagram for sequence control of transformer taps without O.L.T.
(b): Tap voltages, reactor current and gate pulse waveforms

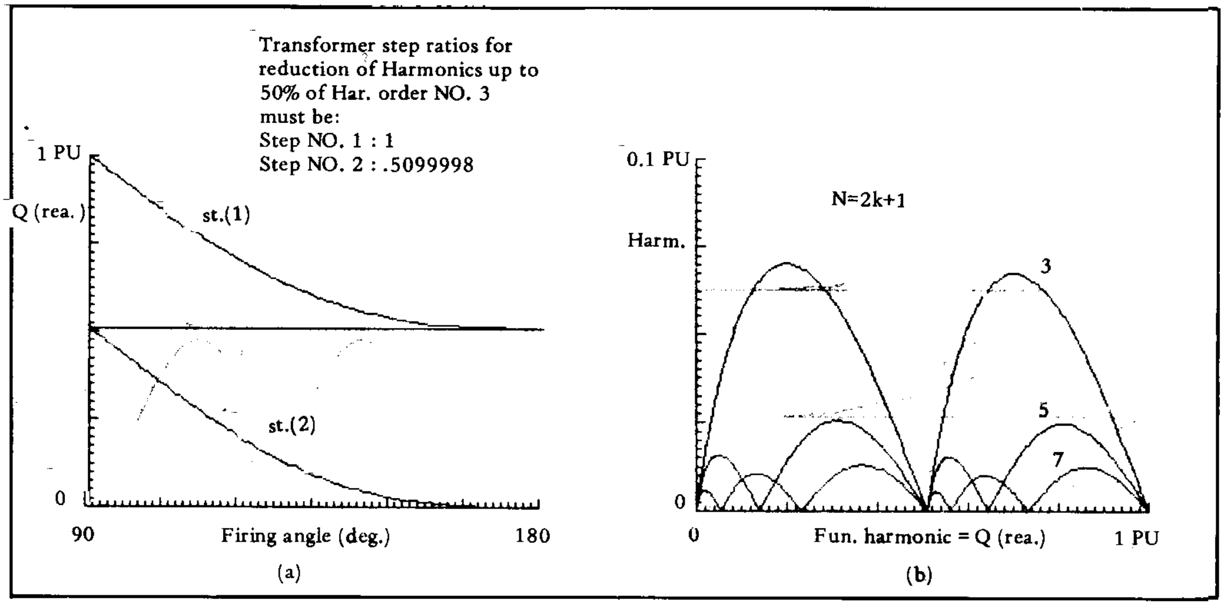

Figure 9: Variation of fundamental current (a) and harmonics (b) for example 1–1

taps. In other words, it is evident from Figures 6 and 7 that the choice of tap ratio values has a greater effect on the magnitude of harmonics than the number of taps.

Method 2. Using Transformer Without On Load Tapchanger

In this method the transformer of the reactor is not equipped with an on load tapchanger. But as shown in Figure 8a, in each tap, thyristor pairs peculiar to that tap conduct reactive current.

For any reactive power in the range $0 =< Q <= tm/t1$, the reactor current will flow through mth tap by triggering gates of the relevant thyristors [2].

As the reactive power increases from tm/t1 the additional value must be supplied from the next tap. The operating principle is explained by reference to Figure 8b where e_m and e_{m-1} are the voltages of mth and (m−1)th taps. In the positive half cycle of voltage the reactor is connected to tap m by triggering th_m at delay angle $\alpha_m = \frac{\pi}{2}$. At the delay angle α_{m-1}, e_{m-1} is more positive than e_m. Thus thyristor th_{m-1} of tap (m−1) is triggered which turns off th_m. The reactive current flows through tap (m−1). At angle β_{m-1} thyristor th_m is forward biased to th_{m-1} by voltage $|e_{m-1} - e_m|$. Consequently triggering of th_m at β_m results in transferring the reactive current from tap m−1 to tap m by turning off th_{m-1}.

In the negative half cycle of current, thyristors th'_m and th'_{m-1} are operated similarly. Therefore, in each period two taps at the most and in any instance one tap only is conducting the reactor current (Figure 8b) [2].

When two adjacent taps i and j are operating the reactor current equations can be written and resolved to harmonics by fourier analysis as below:

$$i(t) = a_1 \sin(\omega t - \frac{\pi}{2}) \quad \sum_{\substack{n=2k+1 \\ k=1}} a_n \sin(\omega t - \frac{\pi}{}$$

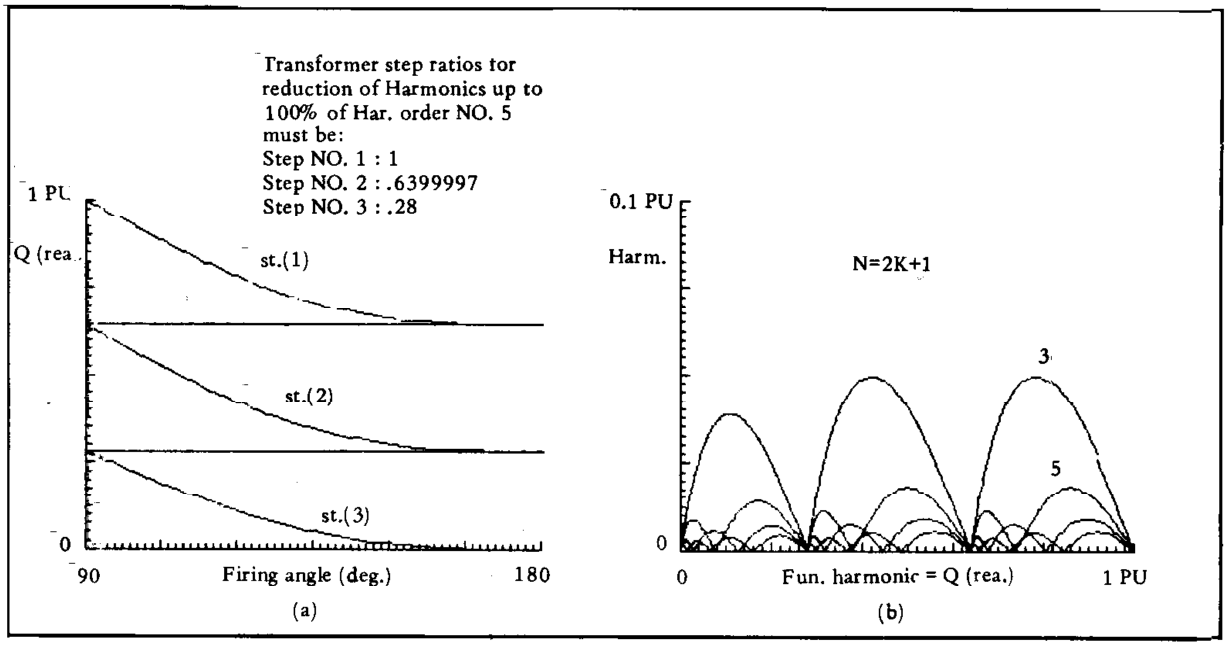

Figure 10: Variation of fundamental current (a) and harmonics (b) for example 1 2

$$a_{1n} = \frac{V_{smi}}{\pi . t_1 . L\omega} [(t_i - t_j) \sin 2\alpha_i + 2(t_i - t_j)(\pi - \alpha_i) + \pi t_j]$$

$$a_{in} = \frac{4 . V_{sm_1}}{\pi . t_1 . L\omega} (t_i - t_j) \quad \frac{\sin (n+1)\alpha_i}{2(n+1)} + \frac{\sin (n-1)\alpha_i}{2(n-1)} - \frac{1}{} \cos\alpha_i . \sin n\alpha_i]$$

where a_1: amplitude of fundamental current
an: amplitude of nth order harmonic
t_i: turn ratio of ith tap
t_j: turn ratio of jth tap (j=i+1)
v_{sm_1} first tap secondary voltage peak

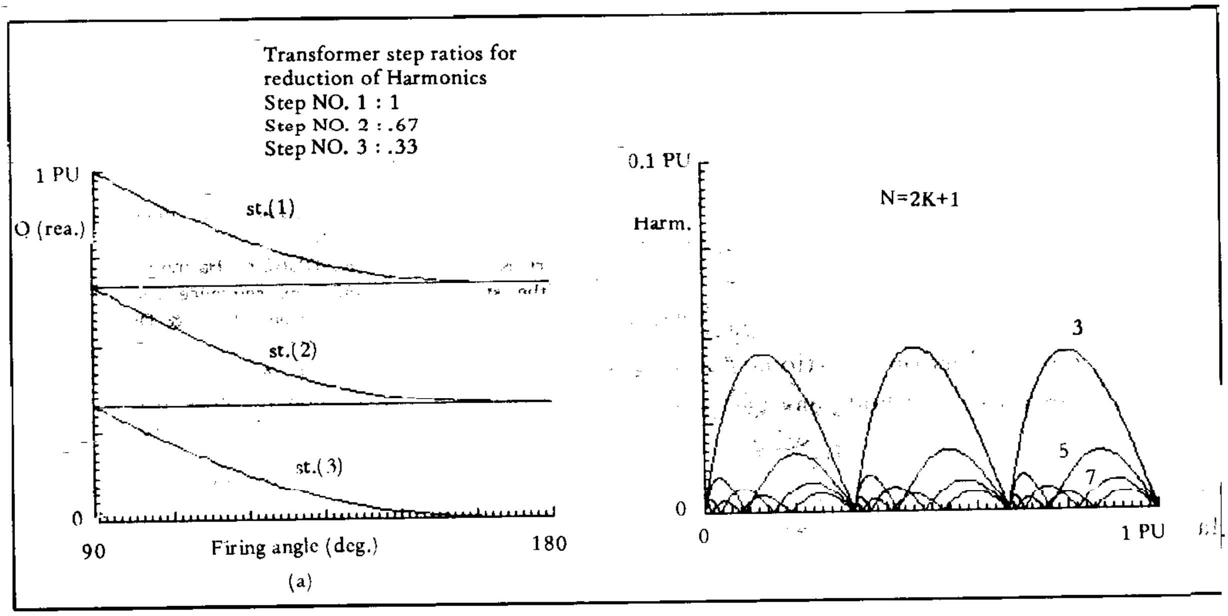

Figure 11: Variation of fundamental current (a) and harmonics (b) for example 2–1

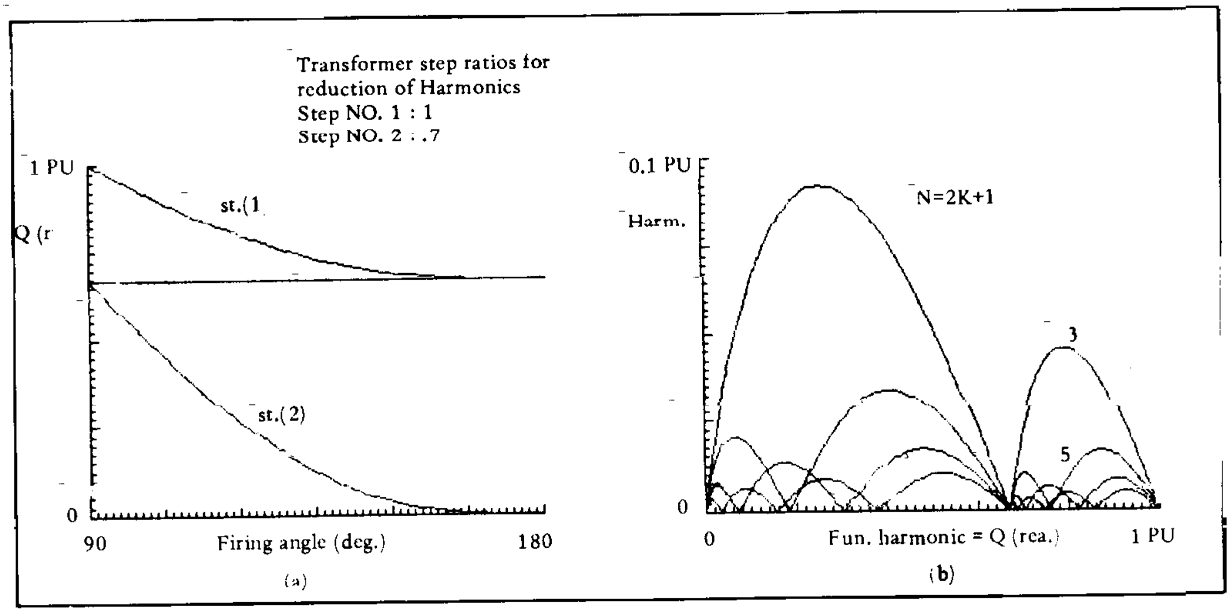

Figure 12: Variation of fundamental current (a) and harmonics (b) for example 2–2

In this method also, on the basis of coordination or uncoordination of turn ratios with harmonic reduction level, computational analysis results by two alternative schemes 1 and 2 covering numerical examples, are shown in Figures 9, 10, 11, 12.

CONCLUSION

The method that is used generally by power engineers and system planners for harmonic elimination, besides the 6-pulse and 12-pulse systems, is the employment of lateral equipment for filtration. For bulk power networks using this equipment is not practical or economical Under such conditions therefore, overall harmonic reduction is a rational method.

In this paper two methods have been presented for this purpose. Computational analysis of numerical examples represents the fact that using each of the methods and a proper selection of turn ratios, may reduce harmonic magnitudes to a lower level. At the same time, the second method, i.e. "using a transformer without tapchanger" yields a higher performance.

In both methods reduction of losses resulting in increased system efficiency is considered as an extra advantage.

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