High Performance Reactive Control for Unbalanced Three Phase Load

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Abstract: In this paper we consider the problem of balancing a three-phase load and how to optimize the TCR operation. For an unbalanced load change a VAT technique is developed by the authors to determine the three compensating susceptance values and then the unsymmetrical firing angles of TCR, which are necessary for a balanced load operation. An objective function (THD) is determined to measure the discontinuity of the TCR operation. For an unbalanced load change, the availability of TSC and the control of TCR produce different values of reactive volt-amperes, in which all produce the balanced operation but with different amounts of harmonics. The paper introduces and develops an iterative algorithm to obtain the optimum firing angle values of TCR, and this is based on minimum generation of harmonics. The results show that a modulated THD is achieved, and this approach guarantees the high performance reactive control for unbalanced three phase load.

Keywords: Reactive Power Compensation; Volt-Ampere Control; Thyristor Control; Harmonic Control

Denotation

VAT Volt Ampere Technique
IVAT Iterative Volt Ampere Technique
α Firing angle of the TCR.
σ Conduction angle of the TCR.
SCR Silicon Controlled Rectifier.
TCR Thyristor- Controlled Reactor.
TSC Thyristor- Switched Capacitor.
V_m Amplitude voltage across TCR.
k Constant.
X Full-thyristor reactance.
V_a, V_b, V_c Phase voltages at compensator node.
Z_{ab}, Z_{bc}, Z_{ca} Impedances of the 3-phase load.
VAR Volt-Ampere Reactor.
I_{ar}, I_{br}, I_{cr} Line currents at 3-phase load.
B_{ab}, B_{bc}, B_{ca} Susceptances of 3-phase TCR.
B_a Changeable susceptance of the TCR compensator.
I_{sd} Magnitude of the continuous current of TCR at maximum conduction angle, π- rad.
I_n n^{th} harmonic current.
SVC Static VAR Compensator
THD Total Harmonic Distortion
Tol Tolerance

1. Introduction

To operate an a.c transmission system in a stable mode and conform to the standard of voltage deviation from normal values, an external control on reactive power flow is required, as mentioned
by Miller [1] and Trujillo et al. [2]. The power transfer capability can be increased by maintaining low impedance in the path between the generation and load. This can be realized by the application of reactive compensation [3, 4]. Unbalanced operation of a three-phase system causes undesirable effects such as negative phase sequence currents. For an unbalanced load, the reactive compensator is employed for two purposes; to balance the load voltage and to maintain constant three-phase voltages at the compensator node [1, 5]. Balanced operation with improved power transfer capability is possible using appropriate unbalanced three-phase reactive compensation. Czarnecki [6] presented the theory of Currents’ Physical Components (CPC) and its application for compensation in three-phase circuits. He has showed that the unbalanced current contributes to the supply current RMS value and apparent power increase and consequently, the power factor decline in the same way as the reactive power. Thus, reduction of reactive and unbalance currents contributes to power factor improvement. He proposed a shunt reactive compensator to reduce these two currents. An active filter controller is connected to an industrial load with unbalance supply voltage to maintain the balanced sinusoidal supply current in phase with the source voltage to have unity power factor [7].

The most important static reactive power devices are the Thyristor-Controlled Reactor (TCR) and Thyristor-Switched Capacitor (TSC) [8, 9, 10]. TCR can modulate its effective fundamental reactance as a function of the thyristor firing angle, and thus absorbs a variable reactive power from the electrical system. The range of operation can be increased, in both lagging and leading VARs regions, by adding a TSC in parallel with the TCR [11, 12]. To achieve a transient-free switching of the capacitors, the TSC has no range of firing angles. Instead it has only two operating states [13]. The thyristors are either "on" to give a full conducting condition or "off" to give a non-conducting condition. Therefore, the main capacitor is split into a number of smaller steps such that to switch them in and out individually by means of the anti-parallel thyristors. An a.c load voltage regulator was established with the static VAR compensator; composed of the fixed excitation capacitor in parallel with the TSC [14]. Voltage regulation scheme of the three-phase Self-Excited Induction Generator (SEIG) on the basis of the static VAR compensator was designed by Ahmed & Nakaoka [15] and Kayikci & Milanovic [16].

The control of the effective reactance of the TCR as a function of the firing angle causes a discontinuity in TCR operation and generates harmonics [17]. Czarnecki [18] showed that a strong distortion of the supply current occurs as the effect of amplification of current harmonics generated by thyristors’ switching, and it is at its maximum when $\alpha = 110^\circ$. For a balanced three-phase system, only odd harmonics are generated by the TCR compensator. By using a balanced delta-connection, it is possible to eliminate the flow of the triple harmonics into the system [19, 20]. Unbalanced reactive compensation giving a resultant balanced load causes unsymmetrical reactances for the three-phase compensator. As a result of that, the harmonics generated by the compensator are unsymmetrical and it is not possible to remove the triple harmonics from the delta-connected of the TCR compensator. A static VAR compensator uses a programmed Pulse Width Modulation (PWM) voltage wave shaping switching patterns of less harmonic components of the reactive current was proposed by Tahri1 & Draou [21].

In this paper, the unbalance change in the three-phase load is managed by the authors in terms of direct measurements of voltages and currents of the load. With the availability of TSC and the control of TCR, different values of reactive volt-amperes were determined for the same unbalanced load change, in which all give the balanced operation. This yields to different sets of thyristor firing angles and then different amount of harmonics. An iterative method is applied to obtain the optimum set of thyristor firing angles that are applied to the system, based on minimum generation of harmonics.

The paper is organized as follows: in Section 2, the thyristor–controlled reactor and its harmonics are discussed in more details. The traditional methods for unbalanced load are discussed in Section 3, this is followed by a discussion of the proposed technique in Section 4. Section 5 discusses the
simulated results and shows the performance of the new proposed method versus the traditional method. Finally, conclusions are given in Section 6.

2. Thyristor-controlled reactor

The most important feature of the shunt reactive compensator is its ability to give continual adjustment of reactive power according to the change in the power system. The TSC has only two operating states; the thyristor is either "on" to give a full conduction or "off" to give a non-conducting condition and harmonics are not generated. A TCR is a linear reactor connected to the system in series with a thyristor-pair connected in reverse parallel, which can modulate the effective fundamental reactance as a function of the firing angle of the thyristor-pair, and thus provides a variable reactive volt-ampere to the system, as shown in Fig.1 (a). The firing angle ($\alpha$) of the TCR is measured from the zero-crossing of the voltage across the TCR to the point when the gate of the thyristor is triggered. The thyristor-current is always lagging, therefore there is only reactive power that could be absorbed and the voltage is nearly constant within the control range of the effective reactance of the TCR. The range of operation can be increased, in both lagging and leading VARs regions, by adding a TSC in parallel with the TCR.

For a sinusoidal voltage across the TCR as shown in Fig1.(a), the Equation of the discontinuous thyristor current $i_r(t)$ is represented by using Equation (1) from Miller [1]:

$$i_r(t) = \frac{V_m}{X} (-\cos \omega t) + k$$

Where: $k = \frac{V_m}{X} \cos \alpha$ then;

$$i_r(t) = \frac{V_m}{X} \left[ \frac{\cos(\pi - \alpha) - \cos \omega t}{\pi - \alpha} \right] + \frac{\cos \alpha - \cos \omega t}{\alpha} \left\{ \cos \alpha + \cos \omega t \right\}^{2\pi - \alpha}$$

The TCR voltage and current waveforms at ($\alpha = \pi / 2$ rad) and ($\alpha = 2.24$ rad) are shown in Fig.1.(b). For a full thyristor-conduction angle ($\alpha = \pi / 2$ rad), the thyristor current is continuous and there is no generation of harmonics by the TCR. If the conduction angle is less than full conduction angle, a discontinuous operation for the thyristor current is occurred.

2.1 TCR-harmonic currents

The control of the thyristor firing angle modifies the effective reactance of the TCR as a function of the firing angle ($\alpha$). This control causes a discontinuity in TCR operation and generates harmonics. The cosine-sine series of the TCR current is derived in Appendix (A), leading to Equation (3):
The harmonic profile of the TCR as a function of firing angle ($\alpha$) is shown in Fig.2. At low and medium range of firing angles, the harmonics are high due to the large amount of reactive power absorbed by the TCR.

3. Compensation of unbalanced load

Most a.c. systems are three-phase designed for balanced operation. Unbalanced operation gives rise to components in a wrong phase sequence such as; negative sequence components and zero sequence components. The reactive compensation is used to balance the load and maintain a constant three-phase voltage at compensated node. The most important reactive power devices are the TCR and TSC. They are connected in parallel at compensated node, to give a continual adjustment of reactive power according to the load change, as shown in Fig.3. The compensating susceptance values which are necessary for a balance operation can be determined by using the traditional methods which will be covered in the following subsections.

3.1. Symmetrical components method (SCM)

The negative sequence components of the load current are the measure of the unbalanced load. In this type of compensation, the three susceptance values necessary for a balanced load are determined in terms of the negative sequence components of the load current as demonstrated by Satapathy and Okelly [22]. For delta connected reactive compensator, the line currents flowing into the compensating reactors are given by:

$$
\begin{align*}
\tilde{I}_a &= \tilde{V}_{ab}(-jB_{ab}) - \tilde{V}_{ca}(-jB_{ca}) \\
\tilde{I}_b &= \tilde{V}_{bc}(-jB_{bc}) - \tilde{V}_{ab}(-jB_{ab}) \\
\tilde{I}_c &= \tilde{V}_{ca}(-jB_{ca}) - \tilde{V}_{bc}(-jB_{bc})
\end{align*}
$$

(4)

The negative sequence component of the compensator line current ($\tilde{I}_2$) is given by:

$$
\tilde{I}_2 = \frac{1}{3}(\tilde{I}_a + a^2 \tilde{I}_b + a\tilde{I}_c)
$$

(5)

Where: $a = 0.5 + j \frac{\sqrt{3}}{2}$

Equations (4) and (5) are handled by Satapathy and Okelly [22], to obtain the susceptance values of a delta connected compensator, required for a balanced load:
\[ B_{ab} = \text{Re}\left[ \frac{2a^2}{\sqrt{3} V_{ab}} \right] \]
\[ B_{bc} = \text{Re}\left[ \frac{2a}{\sqrt{3} V_{ab}} \right] \]
\[ B_{ca} = -(B_{ab} + B_{bc}) \]  

### 3.2. Power quantities method (PQM)

In this type of compensation methodology, the compensating susceptance values are determined in terms of power quantities. The complex power of the three-phase compensator is given by Equation (7):

\[ \vec{S}_{RA} = V_a^* \vec{I}_a \]
\[ \vec{S}_{RB} = V_b^* \vec{I}_b \]
\[ \vec{S}_{RC} = V_c^* \vec{I}_c \]  

The equations above are handled by Thukaram and Ramakrihna [23], and the three reactive power equations at compensated node are derived and given by Equation (8). These equations are required to meet the unbalanced reactive power demand by the load.

\[ Q_{RA} = \left[ V_a V_a^* - V_a V_b^* \cos(\delta_a - \delta_b) \right] B_{ab} \]
\[ + \left[ V_a V_a^* - V_a V_c^* \cos(\delta_a - \delta_c) \right] B_{ca} \]
\[ Q_{RB} = \left[ V_b V_b^* - V_b V_a^* \cos(\delta_b - \delta_a) \right] B_{ab} \]
\[ + \left[ V_b V_b^* - V_b V_c^* \cos(\delta_b - \delta_c) \right] B_{bc} \]
\[ Q_{RC} = \left[ V_c V_c^* - V_c V_b^* \cos(\delta_c - \delta_b) \right] B_{bc} \]
\[ + \left[ V_c V_c^* - V_c V_a^* \cos(\delta_c - \delta_a) \right] B_{ca} \]  

Where: \( V_a, V_b, V_c \) are the magnitudes of the 3-phase voltages at compensated node.
\( \delta_a, \delta_b, \delta_c \) are the angles of \( \vec{V}_a, \vec{V}_b, \) and \( \vec{V}_c \) respectively.

### 4. Volt-ampere technique (VAT)

For a practical control of unbalanced change in three-phase load, equations relating the compensating susceptance values to direct measurable voltages and currents are preferred. The authors have developed the VAT technique to determine the three compensating susceptance values which are necessary for a balanced load, in terms of voltages and currents at compensated node. The equations derived by the authors are used to determine the unsymmetrical firing angles of TCR, which are required for a balanced load operation. As shown in Fig.4, the line current \( \vec{I}_a \) of the TCR equals:

\[ \vec{I}_a = \vec{I}_{ab} + \vec{I}_{ac} \]
Equation (9) has inductive currents only, and therefore;

\[ I_{ab} = \text{Im}(\vec{I}_{ab}) = \text{Im}(\vec{I}_{ar}) + \text{Im}(\vec{I}_{ac}) \]  

(10)

\[ \vec{I}_{ab} = (\vec{V}_a - \vec{V}_b) \times -jB_{ab} \]

\[ I_{ab} \cos \phi + jI_{ab} \sin \phi = \left[ (V_a \cos \phi_a + jV_a \sin \phi_a) \right. \]

\[ \left. - (V_b \cos \phi_b + jV_b \sin \phi_b) \right] \times -jB_{ab} \]

Where:

\( \phi \) is the phase angle of \( I_{ab} \).
\( \phi_a, \phi_b \) and \( \phi_c \) are the phase angles of \( V_a, V_b \) and \( V_c \) respectively.

\[ I_{ab} \cos \phi + jI_{ab} \sin \phi = \left[ (V_a \sin \phi_a - V_b \sin \phi_b) \right. \]

\[ \left. -j(V_a \cos \phi_a - V_b \cos \phi_b) \right] \times B_{ab} \]  

(11)

By equating the imaginary parts of Equation (11), then we get:

\[ I_{ab} \sin \phi = \text{Im}(\vec{I}_{ab}) = (-V_a \cos \phi_a + V_b \cos \phi_b) \times B_{ab} \]  

(12)

Similarly,

\[ \text{Im}(\vec{I}_{ac}) = (-V_a \cos \phi_a + V_c \cos \phi_c) \times B_{ca} \]  

(13)

By substituting (12) and (13) into (10), we get:

\[ I_{ar} = (-V_a \cos \phi_a + V_b \cos \phi_b) \times B_{ab} \]

\[ + (-V_a \cos \phi_a + V_c \cos \phi_c) \times B_{ca} \]  

(14)

Similarly, the other two TCR currents, \((I_{br})\) and \((I_{cr})\) can be calculated and therefore, the TCR matrix current is given by:

\[
\begin{bmatrix}
I_{ar} \\
I_{br} \\
I_{cr}
\end{bmatrix} =
\begin{bmatrix}
B_{ab} & -V_a \cos \phi_a + V_b \cos \phi_b & 0 \\
B_{bc} & -V_b \cos \phi_b + V_c \cos \phi_c & 0 \\
B_{ca} & 0 & -V_c \cos \phi_c + V_a \cos \phi_a
\end{bmatrix}
\]

(15)

The three-voltages at the compensated node are assumed to be balanced and each has a unity magnitude. For an unbalanced change in the load, the three line currents for the compensator are determined and substituted in Equation (15), to find the three susceptance values of the reactive compensator which are necessary for a balance three-phase voltage load. After the determination of the three unsymmetrical susceptance values from previous section, the thyristor firing angles of the 3-phase reactive compensator can be obtained from the solution of Equation (16) borrowed from Miller (1982):
\[ B_\alpha = \frac{2(\pi - \alpha) - \sin 2(\pi - \alpha)}{\pi X} \]  

(16)

Different sets of thyristor firing angles were defined for the same balanced load condition. The different sets of firing angles were obtained by an addition or subtraction of a certain amount of the reactive power for three branches of the reactive compensator. The balanced operation of the system has been kept on by adding or subtracting the same amount of volt-ampere for three branches of the delta-connected TCR compensator. The TSC is connected in parallel with TCR compensator to equilibrate the reactive power change at reactive compensator. All these sets of firing angles give the balance operation; but with different amount of harmonics generated by the reactive compensator. Therefore, an optimum set of firing angles based on minimum generation of harmonics can be selected and then can be applied to the system.

4.1. Iterative volt-ampere technique (IVAT)

It is clear that increasing or decreasing the volt-amperes for the reactive compensator will decrease or increase its fundamental reactance. This is achieved by changing the firing angles of TCR, in which leading to variable amounts of harmonics, and then to different amounts of losses in the system. The amount of harmonics generated by the thyristor at TCR compensator depends on its conduction angle (\( \sigma \)). For a full thyristor-conduction angle equals (\( \pi \) rad), the magnitude of the thyristor current is maximum with no discontinuity and therefore there is no generation of harmonics by the TCR. If the conduction angle of the thyristor is less than full conduction angle, a discontinuous operation is occurred and the harmonic currents are generated.

For an unbalanced load change, the three susceptance values of the reactive compensator can be determined by using Equation (15) and the corresponding thyristor firing angles for the three-phase TCR compensator are obtained from Equation (16). By adding or subtracting the same amount of the volt-ampere (\( \Delta Q \)) new values of reactive power for the compensator are obtained. This yields to new values of susceptance, and then to new set of thyristor firing angles. By keep changing the amount of the addition or subtraction of (\( \Delta Q \)) different sets of thyristor-firing angles will be obtained. These different sets of firing angles will generate different amount of harmonics. The optimum set of firing angles based on minimum generation of harmonics can be chosen by using the iterative algorithm and then applied to the system to guarantee improvements [24, 25]. To measure the amount of harmonics generated by the thyristor, a THD is given below [16]:

\[ THD = \left( \sum_{n=3,5,7} I_n^2 \right)^{1/2} \]  

(17)

and;

\[ I_n (\alpha) = \frac{V_m}{\pi X} \sum_{n=1}^{\infty} \left[ \frac{\cos(\pi - \alpha)}{n} \left( \frac{\sin n \alpha}{n} \right) \right]^{\pi - \alpha} - \frac{1}{2} \left[ \sin(1 - n) \alpha + \sin(1 + n) \alpha \right]^{\pi - \alpha} \]

\[ + \left[ \frac{\cos(\pi + \alpha)}{n} \left( \frac{\sin n \alpha}{n} \right) \right]^{\pi + \alpha} - \frac{1}{2} \left[ \sin(1 - n) \alpha + \sin(1 + n) \alpha \right]^{\pi + \alpha} \]  

(18)
Depending on the initial firing angle \( \alpha_i \) of the TCR that was determined from Equation (16), the expected new firing angle for minimum THD is given below:

\[
\alpha_{\text{new}} = \alpha_i - \frac{I_n(\alpha)}{I_n'(\alpha)}
\]

(20)

\[
Tol = \frac{I_n(\alpha)}{I_n'(\alpha)}
\]

(21)

Where: Tol must be very small or zero.

The calculation of \( \alpha_{\text{new}} \) is repeated until approaching the required Tol value that gives the optimum firing angle value of a minimum THD. The iterative algorithm for calculation of optimum firing angles is given in Fig.5.

5. Standard supply bus and simulated results

The standard IEEE-519 supply system [26] is used in this case study to investigate the behavior of reactive compensator for an unbalanced load change, as shown in Fig.6. The delta-connected three-phase load of 5.1 MW and 4.965 MVar is connected to a supply bus of voltage 4.16kV. A 57.68 kVar Static VAR Compensator (SVC) is connected in parallel with the load. The base value for the line current is 690A.

For unbalanced load change of average value of 0.01p.u rejection current, different sets of TCR firing angles required for a balanced operation are obtained, using the proposed method (IVAT). All these sets of firing angles give the balance operation for the load, but with different amount of harmonics generated by the 3-phase TCR compensator. The THD\% is determined in terms of the fundamental current of TCR. Fig.7 shows the THD\% caused by the TCR at these different sets of firing angles. It can be seen that the optimum set of firing angles for minimum generation of harmonics is set.4 of firing angles:

\( \alpha_{ab} = 150.81^0, \alpha_{bc} = 170.27^0, \alpha_{ca} = 170.27^0. \)

Two tests of 3-phase load change were performed to examine the performance of the proposed method (IVAT) versus the traditional method (PQM); one with different rejections of load current and the other with different injections of load current. Both techniques succeed in balancing the load, but each generates different amount of harmonics. The THD\% of the TCR compensator is shown in Figs. 8 and 9, for both IVAT and PQM. For the same balanced load condition, the IVAT continues to add or subtracts the same amount of the reactive power (\( \Delta Q \)) for three brunches of the delta-connected TCR compensator. The process is performed until getting the optimum operation of minimum THD\%. It can be noticed that a minimum THD\% is obtained with IVAT. This is due to the ability of IVAT to produce the optimum set of thyristor firing angles, based on minimum generation of harmonics. In Fig.8, the unbalanced rejection of current by the three-phase TCR causing more reactive power to be absorbed by the TCR compensator. This causes more discontinuity in compensator current and then large amount of harmonics. The injection of the load current needs a rejection of TRC current. This decreases the discontinuity and generates small amounts harmonics, as shown in Fig.9. At higher range of load injection, the TCR reject all its current and the residual reactive power has to be supplied by the TSC. The operating of TSC has no discontinuity, therefore; no more harmonics to be added by the reactive compensator and therefore gives nearly constant THD\%. 

8
6. Conclusions

A three-phase TCR combined with a TSC is developed to deal with the unbalanced load change. This unbalanced change requires unsymmetrical TCR reactor, and more harmonics to be generated in the system. In this paper, the compensating susceptance values were determined in terms of load voltage and currents. In the presence of TSC, the amount of reactive power for the TCR compensator was modulated using an iterative algorithm to get an optimum condition based on minimum generation of harmonics. The simulation results for THD show that the proposed method IVAT outperforms the traditional PQM and gives an optimum operation for the TCR compensator.

Appendix (A):

The cosine-sine equation of the thyristor current $i_r(t)$, which is shown in Fig.1 can be represented by Equation (A-1) below (Lander, 1981):

$$i_r(t) = a_0 + \sum_{n=1}^{\infty} \left( a_n \cos n \omega t + b_n \sin n \omega t \right)$$  \hspace{1cm} (A-1)

Where:

$$a_0 = \frac{1}{T} \int_{0}^{2\pi} i_r(t) d\omega t \hspace{1cm} (A-2-a)$$

$$a_n = \frac{2}{T} \int_{0}^{2\pi} i_r(t) \cos n \omega t d\omega t \hspace{1cm} (A-2-b)$$

$$b_n = \frac{2}{T} \int_{0}^{2\pi} i_r(t) \sin n \omega t d\omega t \hspace{1cm} (A-2-c)$$

By substituting $i_r(t)$ in Equation (2), for the intervals; $(0, \pi - \alpha)$, $(\alpha, 2\pi - \alpha)$ and $(\pi + \alpha, 2\pi)$ respectively $a_0$ and $b_n$ equal zero and;

$$a_n = \frac{2}{2\pi X} \frac{V_m}{\pi} \left[ \int_{0}^{\pi - \alpha} \left( \cos (\pi - \alpha) - \cos \omega t \right) \cos n \omega t d\omega t \right]$$

$$a_n = \frac{2}{2\pi X} \frac{V_m}{\pi} \left[ \int_{\alpha}^{2\pi - \alpha} \left( \cos \omega t - \cos \omega t \right) \cos n \omega t d\omega t \right]$$

$$a_n = \frac{2}{2\pi X} \frac{V_m}{\pi} \left[ \int_{\pi + \alpha}^{2\pi} \left( \cos (\pi + \alpha) - \cos \omega t \right) \cos n \omega t d\omega t \right]$$

By substituting $a_0$, $a_n$ and $b_n$ in Equation (A.1):
\[
i_r(t) = \frac{V}{\pi X} \sum_{n=1}^{\infty} \left[ \left( \cos(\pi - \alpha) \right) \left( \frac{\sin n \omega t}{n} \right) \right]^{2\pi-\alpha} - \frac{1}{2} \left[ \frac{\sin(1-n)\alpha t}{1-n} + \frac{\sin(1+n)\alpha t}{1+n} \right]^{2\pi-\alpha} \times \cos n \omega t \quad (A.4)
\]

References:

1. Miller, T. J. E. Reactive power control in electric systems; John Wiley and Sons, 1982.


Fig 1: (a). Thyristor-controlled reactor, (b). Voltage and current waveforms for TCR.

Fig 2 Harmonic profile of TCR.
Fig 3  Compensation of unbalanced load.

Unbalanced 3-ph load $Z_{ab} # Z_{bc} # Z_{ca}$ by adding a modulated reactive compensator, to get a balanced 3-phase load voltages

Resultant of a balanced three-phase load voltages

Unsymmetrical 3-phase TCR

Unsymmetrical 3-phase TSC

Fig 4  Three-phase TCR compensator.

Unbalanced 3-ph load $Z_{ab} # Z_{bc} # Z_{ca}$
Fig 5  State diagram for calculation of optimum firing angles.

Start

System initialization:
Unity magnitude of 3-φ compensated-node voltages is assumed

Determination of 3-φ compensator currents:
I_{ar}, I_{br}, I_{cr} for an unbalanced load change

Calculation of 3- susceptance values and their firing angles for balanced operation:
B_{ab}, B_{bc}, B_{ca}
α_{ab}, α_{bc}, α_{ca}

THD and Tol calculations:
THD = \sqrt{\sum I^2_n}
Tol = ln(α)/|I_n(α)|

is

[ln(α)/|I_n(α)|] < Tol

YES

\[ \alpha_{new} = \alpha_{old} - \frac{ln(α)/|I_n(α)|}{I''(n(α))} \]

\[ I''(n(α)) = \frac{d(ln(α))/dα}{dα} \]

NO

Apply the calculated \( \alpha_{ab}, \alpha_{bc}, \alpha_{ca} \) to the system as optimum values

Stop
Fig 6  Single line diagram of supply system.

![Single line diagram of supply system.](image)

Fig 7  THD for 3-ph TCR at 0.01p.u rejection of average load current.

![THD for 3-ph TCR at 0.01p.u rejection of average load current.](image)
Fig 8  THD with different rejections of load current.

Fig 9  THD with different injections of load current.