Reactive power control for Unbalanced Load

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Abstract: An unbalanced three-phase load may be transformed into balanced load by the implementation of the reactive compensator. The balanced operation of the three-phase load requires an unbalanced reactive compensator, by that more amount of harmonics are generated. A three- phase reactive compensator includes thyristor- controlled reactors and switched capacitors is developed in this paper to evaluate the optimum values of reactive volt- amperes generated by the compensator. The calculations of reactive volt- amperes are based on the fact that the addition or subtraction of the same volt-amperes for three brunches of unbalanced TCR does not change the balanced operation of the load, but can modulate the amount of harmonics generated by the reactive compensator. This balanced-change in volt-amperes of TCR can be equalized by the three-phase thyristor-switched capacitor (TSC). Different sets of firing angles for thyistors are determined. All sets of firing angles balance the load and generate different amount of harmonics. Optimum values of firing angles required for a balance load and minimum generation of harmonics were defined.

Keywords: Reactive power compensation, Power systems, Reactive power control, Static VAR compensation, Thyristor control.

Denotation

TCR	thyristor- controlled reactor.
TSC	thyristor-switched capacitor.
V_a, V_b, v_c	phasors of phase voltages at compensator node.
I_{ar}, I_{br}, I_{cr}	phasors of the line currents at 3-phase TCR.
B_{ab}, B_{bc}, B_{ca}	susceptances of 3-phase TCR.
α	firing angle of the TCR.
X	full thyristor reactance.
B_α	changeable susceptance of the TCR compensator.
Q_{abr},Q_{bcr},Q_{car}	reactive powers of 3-phase TCR
I_n	nth harmonic current.
σ	conduction angle of the TCR.

1 Introduction

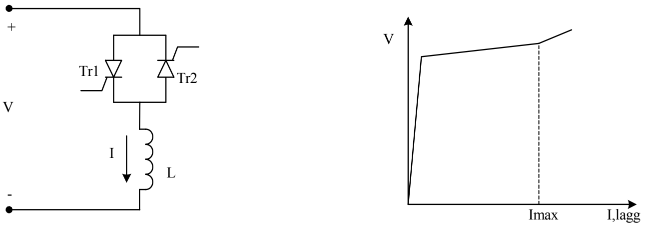
Three- phase a.c systems are designed for a balanced operation. Unbalanced operation gives rise to negative sequence voltages and currents. These components can have undesirable effects such as additional losses and harmonics. Thyristor-controlled reactors are used in power system for voltage regulation thereby, increasing system stability and power transfer capability [1,2]. The most important static reactive power devices are the thyristor – controlled reactor (TCR) and the thyristor- switched capacitor (TSC) [3,4,5]. A combination of both thyristor- controlled reactors and thyristor- switched capacitors increases the operating range [6,7]. Unbalanced reactive compensation to give a resultant balanced load is well known [8]. However, using TCRs, the harmonic currents generated by each phase of compensator are unequal causing additional losses. Eliminating the negative-phase sequence components gives a balance operation. Tam and Lasseter [9] have suggested a conventional twelve pulse arrangement to eliminate some order of harmonics generated by the static volt- ampere reactive (VAR) control system.

In this paper, a set of equations were derived to determine the reactive volt-amperes generated by the compensator to meet unbalanced-varying demand by the load. Optimum firing angle values of a reactive compensator to balance the load and minimize the harmonics generated by the compensator were defined. The optimum reactive compensation is based on minimum generation of harmonics.

2 Reactive Compensator

The most important feature of the shunt reactive compensator is its ability to give continual adjustment of reactive power according to the changes in the power system. The thyristor-switched capacitor compensator (TSC) has only two operating states ,i .e; the thyristor is either (on) to give a full conduction or (off) to give a non-conducting condition , and harmonics are not generated.

A thyristor- controlled reactor compensator (TCR), Fig.1, is a linear reactor connected to the system in series with a thyristor- pair connected in reverse parallel, which modulate the effective fundamental reactance as a function of the firing angle of the thyristor– pair, and thus provide a variable reactive volt-ampere to the system. The firing angle (α) 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 could be absorbed and the voltage is nearly constant within the control range of the effective reactance of the thyristor-controlled reactor; Fig.1-b. The range of operation can be increased, in both lagging and leading VARs regions, by adding a thyristor- switched capacitor in parallel with the thyristor- controlled reactor.



a- TCR Compensator b- Volt/Current characteristics

Fig.1 Thyristor- controlled reactor characteristics

3 Unbalanced Load Compensation

For unbalanced – varying load, the reactive compensator is employed to balance the voltages and also to maintain a constant 3-phase voltage at the compensated node.

For an unbalanced load shown in Fig.2, the three-phase voltages at the compensated node are assumed balanced and given by:

$$\mathbf{V_a} = V_r$$

$$\mathbf{V_b} = a.V_r \qquad (1)$$

$$\mathbf{V_c} = a^2.V_r$$

Where: $a = -0.5+j0.866$ and $a^2 = -0.5-j0.866$

The current flowing into phase-ab of the three-phase TCR is:

$$\mathbf{I_1} = B_{ab}(\mathbf{V_a} - \mathbf{V_b}) \qquad (2)$$

and its real part is:

$$\mathrm{Re}\mathbf{I_1} = B_{ab}(V_r - V_r\mathrm{Cos}(-120^0)) \qquad (3)$$

The current flowing into phase-ac of the three-phase TCR is:

$$\mathbf{I_2} = B_{ca}(\mathbf{V_a} - \mathbf{V_c}) \qquad (4)$$

And its real part is:

$$\mathrm{Re}\mathbf{I_2} = B_{ca}(V_r - V_r\mathrm{Cos}(-120^0)) \qquad (5)$$

$$\mathbf{I_{ar}} = \mathbf{I_1} + \mathbf{I_2} \qquad (6)$$

So, the real part of the line current $\mathbf{I_{ar}}$ of three-phase TCR is:

$$\mathrm{Re}\mathbf{I_{ar}} = 1.5V_r(B_{ab}+B_{ca}) \qquad (7)$$

The real parts of other two line currents at three-phase compensator are derived in the same way, and the three real parts are expressed in the matrix below:

$$\begin{vmatrix} \mathrm{Re}\,\mathbf{I_{ar}} \\ \mathrm{Re}\,\mathbf{I_{br}} \\ \mathrm{Re}\,\mathbf{I_{cr}} \end{vmatrix} = \begin{vmatrix} B_{ab}+B_{ca} \\ B_{ab}+B_{bc} \\ B_{bc}+B_{ca} \end{vmatrix} \begin{vmatrix} 1.5V_r & 0 & 0 \\ 0 & 1.5V_r & 0 \\ 0 & 0 & 1.5V_r \end{vmatrix} \qquad (8)$$

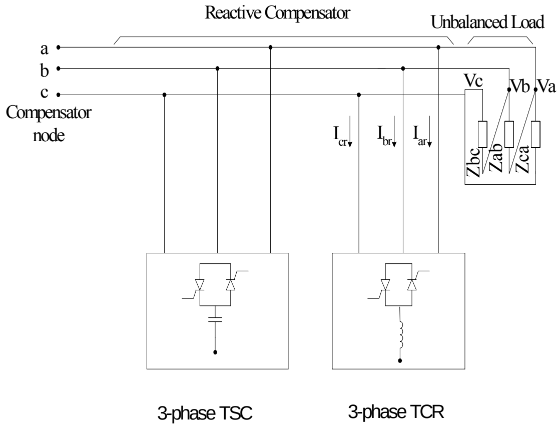


Fig.2 Compensation of unbalanced load

Responding to the unbalanced varying load, the real quantities of three line currents for compensator are determined and substituted in Equation (8) to find the three susceptances of reactive compensator which are required to balance the three voltages at load.

4 Optimum Control for Unbalanced-Varying Load

After the determination of the three unsymmetrical susceptances of the reactive compensator from previous section, the firing angles can be obtained from the solution of the equation below, [1]:

$$B_\alpha = \frac{2(\pi - \alpha) - \mathrm{Sin}2(\pi - \alpha)}{\pi X} \qquad (9)$$

In this work, different sets of thyristor-firing angles were defined for the same unbalanced load condition. The different sets of firing angles were obtained by an addition or subtraction of the same reactive power for three brunches at 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 reactive compensator. The three-phase bank capacitor was connected in parallel with TCR compensator to equilibrate the reactive power change at reactive compensator. All these sets of firing angles give the balanced operation for the load, but with different amount of harmonics that were generated by the reactive compensator. Therefore, optimum set of firing angles based on minimum generation of harmonics can be defined and applied to the system.

4.1 Volt- Ampere Measurements

At certain unbalanced- change of the load, the three susceptances of the reactive compensator can be determined using Equation (8) and the corresponding thyristor- firing angles for the three phase thyristor- controlled reactor are determine from Equation (9).

The reactive power (Q) of the TCR is:

$$Q = VI \sin(\theta) \qquad (10)$$

For the thyristor- controlled reactor, the phase angle is (π/2 rad), so;

$$Q_{abr} = (V_{ab})^2 . B_{ab}$$

$$Q_{bcr} = (V_{bc})^2 . B_{bc} \qquad (11)$$

$$Q_{car} = (V_{ca})^2 . B_{ca}$$

4.2 Different Set of Thyristor- Firing Angles

By adding or subtracting a same amount of the volt- ampere (ΔQ) to the old values of the reactive power given in Equation (11), new values of reactive power at TCR are obtained. This yields to new values of TCR- susceptances, and then to new set of thyristor- firing angles. By changing the amount of an added or subtracted volt- ampere (ΔQ), different sets of thyristor- firing angles are produced. These different sets of firing angles will generate different amount of harmonics.

4.3 Harmonic Measurements

The amount of harmonics generated by the thyristor at TCR depends on its conduction angle (σ rad). To measure the amount of harmonics generated by the thyristor, a harmonic function is derived below. For a full thyristor- conduction angle equals (π rad), the magnitude of the thyristor current is maximum with no discontinuity and there is no generation of harmonics at TCR. If the conduction angle of the thyristor is less than the full conduction angle, a discontinuous operation is occurred and the harmonic currents are generated. The magnitude of the discontinuous compensator current (I_r) at firing angle (α rad) can be calculated based on the magnitude of the continuous compensator current (I_M) of firing angle (π/2 rad) and equals:

$$I_r = 2\, I_M (\pi - \alpha) / \pi \qquad (12)$$

Where:

$\alpha = (2\pi - \sigma)/2$

I_M: magnitude of the continuous current of TCR at maximum conduction angle, π rad.

I_r: magnitude of the fundamental component of discontinuous TCR current.

The harmonic reactance is relative to the inverse of the conduction angle, and the magnitude of n^{th} harmonic current (I_n) equals:

$$I_n = 2\, I_M (\pi - \alpha) / \pi . n \qquad (13)$$

5 Optimum Compensation

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.

The balanced load is taken the normal condition in the system, and the three-phase reactive compensator is also balanced for this condition. For a certain balanced load condition, the line currents of reactive compensator are:

$I_{ar} = I_{br} = I_{cr} = 0.009$ p.u.

and this will produce three-firing angles for the compensator, their values are given below:

$\alpha_{ab} = \alpha_{bc} = \alpha_{ca} = 154.722^0$.

By delta connection of reactive compensator, it is possible to eliminate the flow of the triple harmonics. Therefore, the 5th harmonic current is taken in this work as a measure of harmonics generated by the TCR.

5.1 Results

For unbalanced change of average value of 0.0033 p.u injection current, the different sets of firing angles required for a balanced operation are given in Table.1. 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. Figure.3 shows the 5th harmonic current generated 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.

Different load conditions for unbalanced change are investigated, and their different sets of TCR firing angles for a balanced operation are given in Table.2 and Table.3. Their 5th harmonic currents generated by the three-phase compensator are given in Fig.4 and Fig.5, with minimum generation of harmonics at set.7 and set.1, respectively.

For a balanced change of 0.003 p.u rejection current, Fig.6 shows the 5th harmonic current generated by the three-phase compensator at different sets of firing angles given in Table.4. It can be seen that the optimum set of firing angles for minimum generation of harmonics is set.3.

6 Conclusions

A three- phase compensator model with a switched capacitor was developed to get a balanced operation for an unbalanced demand of reactive power by the load. Unsymmetrical reactances of reactive compensator which are required for a balanced operation cause more harmonics to be generated into the system. The optimum values of firing angles for a balanced operation and minimum harmonics were calculated. Results were obtained for different load conditions.

The determination of different values of the firing angles required for a balanced operation and thereby to choose optimum values of firing angles required for minimum harmonics was based on the fact that the balanced operation of the system can be kept on by adding or subtracting the same value of volt-ampere for three branches of unbalanced reactive compensator. This balanced change in volt-ampere for TCR can be equilibrated from switched capacitors.

Table 1

Different sets of TCR firing angles for an unbalanced change, 0.0033 p.u injection current.

Set.No	Firing Angles(degrees)		
	α_{ab}	α_{bc}	$_{ca}\alpha$
1	130.6602	161.5542	142.0780
2	112.3093	139.3220	122.7581
3	127.0458	156.7402	138.1689
4	142.8384	179.7815	155.3893
5	108.7195	135.3227	119.0625
6	123.2901	152.1022	134.1979
7	101.6095	127.5872	111.7947
8	98.0790	123.8231	108.2088
9	115.9298	143.4335	126.5056
10	119.5876	147.6823	130.3150

Table 2

Different sets of TCR firing angles for an unbalanced change, 0.0047 p.u injection current.

Set.No	Firing Angles(degrees)		
	α_{ab}	α_{bc}	$_{ca}\alpha$
1	127.9161	133.4426	151.3185
2	120.6405	125.9667	142.8384
3	131.9693	137.5955	156.0620
4	116.9708	122.2272	138.7443
5	126.2360	131.6926	149.2391
6	113.3403	118.5383	134.7594
7	144.0314	150.1843	172.0056
8	99.0865	104.1400	119.5876
9	109.7424	114.8918	130.8648
10	124.3573	129.7666	147.0657

Table 3
Different sets of TCR firing angles for an unbalanced change, 0.0047 p.u rejection current.

Set.No	Firing Angles(degrees)		
	α_{ab}	α_{bc}	$_{ca}\ \alpha$
1	169.3413	169.3413	178.6430
2	149.5532	149.5532	156.0620
3	163.8895	163.8895	172.0056
4	133.0802	133.0802	138.7443
5	121.6973	121.6973	127.0458
6	154.0598	154.0598	160.9409
7	158.8108	158.8108	166.1974
8	125.4291	125.4291	130.8648
9	141.0690	141.0690	147.0657
10	145.2358	145.2358	151.4587

Table 4
Different sets of TCR firing angles for a balanced change, 0.003 p.u rejection current.

Set.No	Firing Angles(degrees)		
	α_{ab}	α_{bc}	α_{ca}
1	165.3163	165.3163	165.3163
2	130.3150	130.3150	130.3150
3	171.1320	171.1320	171.1320
4	160.2238	160.2238	160.2238
5	142.2460	142.2460	142.2460
6	155.3893	155.3893	155.3893
7	138.1689	138.1689	138.1689
8	126.5056	126.5056	126.5056
9	146.4525	146.4525	146.4525
10	155.3893	155.3893	155.3893

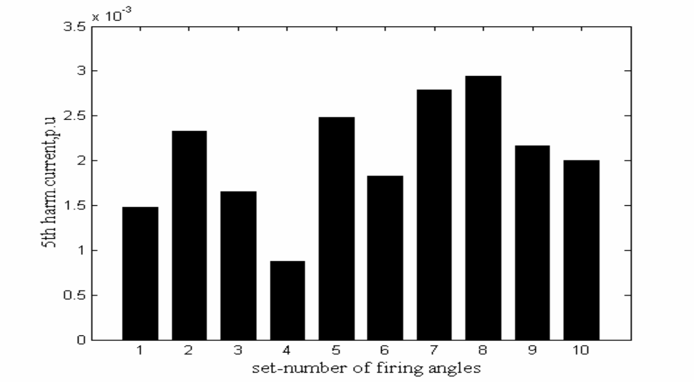


Fig.3. The 5th harmonic current generated by TCR at 0.0033 p.u injection current.

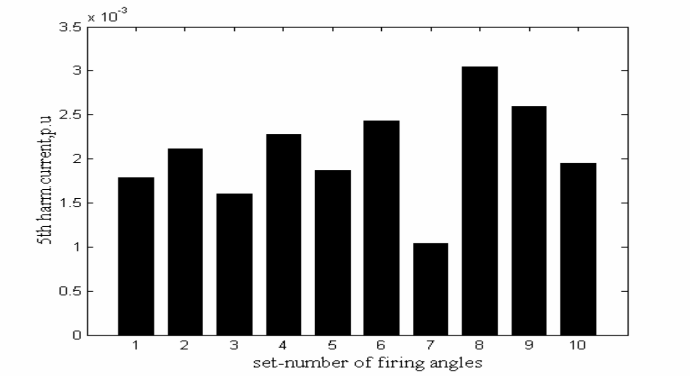


Fig.4. The 5th harmonic current generated by TCR at 0.0047 p.u injection current.

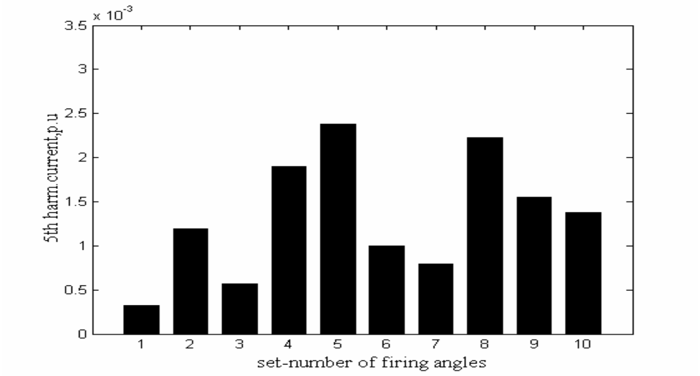


Fig.5. The 5th harmonic current generated by TCR at 0.0047 p.u rejection current.

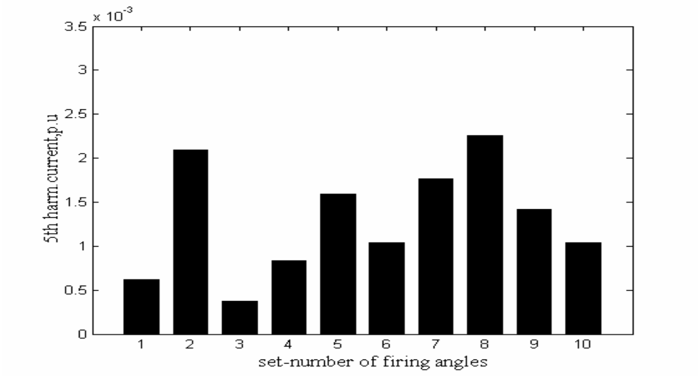


Fig.6. The 5th harmonic current generated by TCR at 0.003 p.u rejection current.

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