Harmonic Minimization in the Operation of Static VAR Compensators for Unbalanced Reactive Power Compensation

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Abstract—Phase-wise unbalanced reactive power compensations are required in distribution systems for dynamic power factor correction and terminal voltage stabilization. Shunt compensators are generally used to reduce or cancel the phase-wise unbalanced reactive power (VAR) demand and to minimize the reactive power drawn from the AC supply lines. Static VAR compensators are preferred over traditional VAR compensators for this purpose. The operation of thyristor-controlled compensators at various conduction angles can be used advantageously to meet the unbalanced reactive power demands in a system. However such an operation introduces harmonic currents in to the AC system. In such cases it becomes necessary either to minimize harmonic generation internally or provide external harmonic filters. In this paper, an approach is presented for operation of VAR compensators for minimization of the effect of the harmonics using the telephone influence factor (TIF) and the Total Harmonic distortion factor (THD) for a typical distribution system.

Index Terms—power quality, thyristor controlled reactor, VAR compensation, and harmonic reduction.

I. INTRODUCTION

THE dynamic behavior of industrial loads such as rolling mills, arc furnaces, traction loads and large fluctuating single-phase loads draw wildly fluctuating amounts of reactive power from the supply systems. These loads cause unbalance on the system and leads to wide fluctuations in the supply voltage and effects like incandescent light flicker, television picture distortion disturbance in electric control circuits and computer equipments, etc., which are undesirable to the consumers. These types of heavy industrial loads are generally concentrated in one plant and fed from one network bus, and therefore, can be handled best by a local compensator connected to the same bus and therefore requires the use of compensator that can be adapted to load changes. Static VAR Compensators (SVC) are preferred over the traditional VAR compensators such as saturable reactors, switched capacitors

or a combination of these due to additional advantages like fast response, high reliability, flexibility and low maintenance cost. Regardless of the type of shunt compensators employed the basic compensation principles are the same, requiring the generation/absorption of controllable reactive power. Several types of Static VAR compensators with different operating features can be realized by using various power conversion concepts and thyristor circuits. The operation of thyristor controlled compensators at various conduction angles can advantageously be used to meet the unbalanced reactive power demands in the system. However, such operation introduces harmonic currents into the A.C. system. In such cases, it becomes necessary to either minimize harmonic generation internally or provide external harmonic filters.

Gyugyi *et al.* [1] examined the theoretical foundation of thyristor-controlled shunt compensation. Further, Gyugyi and Taylor [2] suggested methods for minimizing the harmonics generated internally by the thyristor-controlled reactors (TCR). D. Thukaram *et al.* [3] proposed an algorithm to evaluate optimum combination of phase wise reactive power generations from a SVC to reduce the harmonic injections and achieve a balanced reactive power supply from the system, which results in minimum harmonic contents. James k. Phipps *et al.* [4] have given an introduction of the power system harmonics, basic definitions on computing harmonics, harmonic distortion, and parallel resonance. J. Gutierrez *et al.* [5] have presented an optimization algorithm to minimize the rms and THD values of the line current, controlling the firing angle value of TCR branch.

This paper presents an approach to evaluate an optimum combination of the phase-wise reactive power generations from SVC and balanced reactive power supply from the AC system based on the defined performance indices TIF (telephone influence factor) and THD (Total Harmonic distortion factor). The approach results in minimization of the effect of harmonics in the AC system, thereby reducing the burden on the external harmonic filter. Results of the studies conducted on a typical distribution system with balanced/unbalanced loading conditions and also for a cyclic loading condition with various combinations of SVC compensation.

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II. COMPENSATOR MODELLING

Two types of static VAR compensators, namely the Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) and the Thyristor Switched Capacitor-Thyristor Controlled Reactor (TSC-TCR) are considered for the analysis. The arrangement of a typical static VAR compensator is shown in Fig. 1.

Fig.1. Block schematic of a FC-TCR type SVC for phase-wise compensation

A. Compensator requirements

The compensator essentially functions as a variable reactance (capacitive and inductive impedances). A series of steady state loads at discrete time instants are used to represent time varying loads. With this approximation, the compensator requirement is to generate/absorb unbalanced reactive power which, when combined with the load demand, will represent balanced load to the system. Let the phase-wise load demands are $P_{La} + jQ_{La}$, $P_{Lb} + jQ_{Lb}$ and $P_{Lc} + jQ_{Lc}$ and phase-wise load seen by the source after compensation are $P_{La} + jQ_{Sa}$, $P_{Lb} + jQ_{Sb}$ and $P_{Lc} + jQ_{Sc}$.

Phase-wise complex voltages at the load bus are given by

$$[V_L] = [V_S] - [Z][I_S] \quad (1)$$

Where $[V_L] = [V_{La}, V_{Lb}, V_{Lc}]^T$ is the complex voltage vector at the load bus, $[V_S] = [V_{Sa}, V_{Sb}, V_{Sc}]^T$ is the complex voltage vector at the source bus, and $[Z]$ is the 3-phase line impedance matrix. The vector of currents in the lines between the source bus and the load bus $I_S = [I_{Sa}, I_{Sb}, I_{Sc}]^T$ is obtained from

$$\begin{aligned} I_{Sa} &= (P_{Sa} - jQ_{Sa})/V_{Sa}^* \\ I_{Sb} &= (P_{Sb} - jQ_{Sb})/V_{Sb}^* \\ I_{Sc} &= (P_{Sc} - jQ_{Sc})/V_{Sc}^* \end{aligned} \quad (2)$$

The non-linear complex set of equations given by (1) and (2) can be solved for load bus voltages using a three-phase load flow solution method. The phase-wise reactive power balance equations at the load bus are,

$$[Q_S] + [Q_C] = [Q_R] + [Q_L] \quad (3)$$

For a given reactive power demand $Q_L = [Q_{La}, Q_{Lb}, Q_{Lc}]^T$, setting balanced values for $Q_C = [Q_{Ca}, Q_{Cb}, Q_{Cc}]^T$ of the TSC and $Q_S = [Q_{Sa}, Q_{Sb}, Q_{Sc}]^T$ of the source, the unbalanced reactive power absorbed by the TCR, $Q_R = [Q_{Ra}, Q_{Rb}, Q_{Rc}]^T$ can be obtained from (3). The compensator is considered as variable delta-connected reactances x_{ab} , x_{bc} , and x_{ca} of the TCR, required to absorb the desired reactive powers [6]-[9].

B. Realization of Variable Reactances

The variable reactances of the compensators are achieved by delaying the closure of the thyristor switch by angle α ($0 < \alpha < \pi/2$). The unsymmetrical firing of thyristors can advantageously be used to obtain the unsymmetrical delta connected reactances. Considering only the fundamental component, the unsymmetrical firing angle α_1 corresponding to the delta reactance x_{ab} can be obtained by solving the following equations,

$$x_{ab} = x_{ab}^0 \left/ \left(1 - \frac{2\alpha_1}{\pi} - \frac{\sin(2\alpha_1)}{\pi} \right) \right. \quad (4)$$

Where, x_{ab}^0 is the reactance for full conduction of thyristor. Similar equations can be written for x_{bc} and x_{ca} to obtain the values of α_2 and α_3 .

C. Harmonic Measurement Indices

In harmonic analysis there are several important indices used to describe the effects of harmonics on power systems. This section describes the definitions of those harmonic indices in common use [10], [11].

Telephone Influence Factor (TIF):

Telephone influence factor (TIF) is a measure used to describe the telephone noise originating from harmonic currents and voltages in power systems. TIF is adjusted based on the sensitivity of the telephone system and the human ear to noises at various frequencies. It is defined as

$$TIF_I = \sqrt{\sum_{h=1}^m (W_h * I_h)^2} / I_{rms}^2 \quad (5)$$

Where W_h is a weighting factor for the harmonic and m is the maximum order of the harmonic considered.

In the above definition, only non-triple series of harmonics are considered to find the balanced telephone influence factor. The weightages to be applied for each individual component of different frequencies are as given by the frequency weighting curve. The highest order of the harmonic (m) to be considered is based on the considerations of audio frequency range. The weightage factors for different harmonics depend on the frequency of the harmonic and psophometric weighting.

Total Harmonic Distortion Factor (THD):

The most commonly used harmonic index is

$$THD_I = \sqrt{\sum_{h=2}^m I_h^2} / I_f \quad (6)$$

This is commonly used as the ratio of rms value of the harmonic component to the rms value of the fundamental component and usually expressed in percent. This index is used to measure the deviation of a periodic waveform containing harmonics from a perfect sine wave. For a perfect sine wave at fundamental frequency, the THD is zero.

The fundamental and the harmonics components of the line currents are obtained as a difference of the corresponding branch currents; I_f and I_h are given by given by,

$$I_f = \frac{V_m}{2\pi\omega L} \left[G_f^2 + H_f^2 \right]^{1/2} \sin(\omega t - \phi - \theta_f) \quad (7)$$

$$I_h = \frac{V_m}{2\pi\omega L} \left[G_h^2 + H_h^2 \right]^{1/2} \sin(h\omega t - \phi) - \theta_h \quad (8)$$

Where,

I_f = R.M.S value of fundamental line current

I_h = R.M.S value of harmonic line currents

ω = Fundamental frequency (rad/sec)

L = inductance of each delta connected reactance (henries)

$$G_f = (3\pi - 4\gamma - 2\sin 2\gamma - \sin 2\beta) \quad (9)$$

$$H_f = \sqrt{3}(\pi - 2\beta - \sin 2\beta) \quad (10)$$

$$G_h = \left(\frac{\sin(h+1)\gamma}{(h+1)} - \frac{\sin(h-1)\gamma}{(h-1)} - \frac{2\sin\gamma \cosh\gamma}{h} \right) + \frac{1}{2} \left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta \cosh\beta}{h} \right) \quad (11)$$

$$H_h = \pm \sqrt{3} \left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta \cosh\beta}{h} \right) \quad (12)$$

$$\theta_f = \tan^{-1}(H_f / G_f)$$

$$\theta_h = \tan^{-1}(H_h / G_h) \quad (13)$$

$\phi = 0, \gamma = \alpha_1, \beta = \alpha_3$ for line current i_a

$\phi = 2\pi/3, \gamma = \alpha_2, \beta = \alpha_1$ for line current i_b

$\phi = 4\pi/3, \gamma = \alpha_3, \beta = \alpha_2$ for line current i_c

h = harmonic order, $(6k \pm 1), k = 1, 2, 3, \dots$

+ sign for harmonics of order $(6k + 1)$

- sign for harmonics of order $(6k - 1)$,

For triple harmonics $(3^{\text{rd}}, 9^{\text{th}}, \dots)$

$$G_h = \left(\frac{\sin(h+1)\gamma}{(h+1)} - \frac{\sin(h-1)\gamma}{(h-1)} - \frac{2\sin\gamma \cos h\gamma}{h} \right) + \left(\frac{\sin(h+1)\beta}{(h+1)} - \frac{\sin(h-1)\beta}{(h-1)} - \frac{2\sin\beta \cos h\beta}{h} \right) \quad (14)$$

$$H_h = 0$$

D. Optimum Approach for Unbalanced Load Compensation

This section presents the development of an approach to evaluate an optimum combination of the phase-wise unbalanced reactive power compensations from an SVC based on the performance indices TIF and THD. The approach results in minimization of the effect of harmonics into the A.C system caused by the unsymmetrical firing of thyristors.

Consider a system as shown in Fig. 1, where Bus1 represents the A.C system source node and Bus2 represents the load bus, with a static VAR compensator connected at that bus. The approach is as follows:

Step 1: Read the system load and SVC data.

Step 2: Set $Q_{Sa} = Q_{Sb} = Q_{Sc} = 0.0$.

Step 3: Set $Q_{Ca} = Q_{Cb} = Q_{Cc} =$ close to maximum of $(Q_{La}, Q_{Lb}$ and $Q_{Lc})$.

Step 4: Compute the voltages at the load bus.

Step 5: Compute the phase-wise reactive powers to be absorbed by the TCR and the corresponding delta reactances of the TCR.

Step 6: Check for the design limitations of the delta connected reactances of the TCR. If no limit violation, go to step 9.

Step 7: Compute the angles of the TCR and the performance indices TIF and THD.

Step 8: Check for satisfactory limits on the performance TIF and THD. If no limit violation, go to step 10.

Step 9: Increase the settings of the FC/TSC or increase the setting of reactive power supply from the source. Go to step 4.

Step 10: Print results.

E. System Studies and Results

The system considered is a 220/66 kV substation (source) feeding a cyclic load shown in Fig. 1. Fixed Capacitor - Thyristor Controlled Reactor (FC-TCR) type of Static VAR Compensators is considered in the analyses. The parameters of the line between the source bus and load bus in p.u on 100 MVA base are taken as, $Z_s = 0.00855 + j0.0803$ p.u/km, $Z_m = 0.00123 + j0.06929$ p.u/km. Four case studies are presented with varying load and SVC compensator combinations.

Case 1: Balanced load

Considering the balanced phase-wise loadings of $P_{La} = P_{Lb} = P_{Lc} = 30.0$ MW and $Q_{La} = Q_{Lb} = Q_{Lc} = 20.0$ MVAR. The rated values of SVC are proportional to the maximum values of QC and QR. The compensator values considered in this case are Q_{C-max} is 20.0 MVAR and Q_{R-max} is 25.0 and 30.0 MVAR. The various possible combinations of SVC, the corresponding harmonics and their effects measured by their performance indices are shown in Fig.2, Fig.3 and Fig.4.

Fig.2. The amplitudes of the harmonic currents versus delay (firing) angle for the thyristor-controlled reactor

Fig.3. TIF and THD versus reactive power absorptions from the TCR

Fig.4. TIF and THD versus delay angle for the thyristor-controlled reactor.

TABLE I
OPTIMAL RANGE OF DELAY ANGLE FOR DIFFERENT TCR RATINGS WHEN
BALANCED LOAD PRESENTS
Load = 30.0 - j 20.0 MVA, $Q_{Cmax} = 20.0$ MVAR

Q_{Rmax} (MVAR)	Range of delay angle for minimum harmonic content	Range of reactive power absorption ($Q_{R1} - Q_{R2} - Q_{R3}$) (MVAR)	For Minimum TIF		For Minimum THD	
			Range of QR (MVAR)	Range of delay angle	Range of QR (MVAR)	Range of delay angle
25.0	30.6° - 49.4°	3.5 - 9.8	8.0 - 25.0	0.0° - 35.0°	6.5 - 25.0	0.0° - 39.2°
30.0	30.6° - 49.0°	4.3 - 12.0	9.75 - 30.0	0.0° - 34.8°	5.9 - 30.0	0.0° - 44.4°

Fig. 2 shows the amplitudes of fundamental component, 5th, 7th, and 11th harmonics for different delay angles. Fig.3 and Fig.4 show the performance indices for different reactive power absorptions from the TCR and delay angles. Table I provides the ranges of delay angle, QR for minimum harmonic content. From the above figures and table the following conclusions can be made:

- Fundamental current component changes slowly for the delay angle 0° to 30°; while for other angles it changes very rapidly.
- Harmonic content will be more if the delay angle of the TCR is in between 65° and 90°. i.e. less the absorption of the reactive power will create more harmonics for a given value of TCR.

- Minimum harmonics will appear for the delay angles between 31° and 49°, irrespective of the Q_{Rmax} (TCR) value.
- For optimal design of SVC, the TCR to be chosen in such a way that it should operate for the delay angle ranges from full conduction to around 49°.
- Particular harmonics can be eliminated with a defined delay angle, irrespective of the TCR value. For example, fifth harmonic content alone can be eliminated for a delay angle operation of 37.6° and full conduction. For seventh harmonic elimination, the delay angles are around 26.2°, its integer multiples and full conduction. For 11th harmonic elimination, the delay angles are around 16.3°, its integer multiples and full conduction.

Case 2: Unbalanced Load

In this case, two different unbalanced loadings in each phase 30.0+j20.0, 29.0+j18.0, 28.0+j16.0 and 30.0+j20.0, 28.0+j16.0, 26.0+j12.0 are considered. The compensator values considered in this case are Q_{Cmax} is 20.0 MVAR and Q_{Rmax} is 20.0, 25.0 and 30.0 MVAR for the above two different unbalanced loading conditions. The various possible combinations of SVC to meet the unbalanced load demands, and the corresponding effects of harmonics measured by their performance indices are shown in Fig.5 and Fig.6.

Fig.5. TIF versus reactive power absorptions from the TCR for Q_{Rmax} of 20.0 MVAR

Fig.6. TIF versus reactive power absorptions from the TCR for Q_{Rmax} of 25.0 MVAR and different unbalanced loading

TABLE II
OPTIMAL REACTIVE POWER SUPPLY FROM THE SOURCE FOR MINIMUM
HARMONIC CONTENT FOR DIFFERENT UNBALANCES

Sl.No	Load MVA in Three phases (A, B, C)	Q_{C-max} (MVAR)	Q_{R-max} (MVAR)	Minimum range of Q_S for minimum harmonic content (MVAR)
1	30.0+j20.0 29.0+j18.0 28.0+j16.0	20.0	20.0	4.5 – 5.5
			25.0	14.0 – 16.0
			30.0	17.0 – 19.0
2	30.0+j20.0 28.0+j16.0 26.0+j12.0	20.0	25.0	4.5 – 5.5
			30.0	7.5 – 9.5
			35.0	8.5 – 10.0

Fig. 5 and Fig. 6 shows the variation of TIFs in three phases versus the variation of the reactive power supply from the source for the different Q_{R-max} values. Table II provides the minimum range of the reactive power supply from the source for minimum harmonic content. From the Table II, it is clear that, the minimum range of Q_S for minimum harmonic content is increasing with the increase of Q_{R-max} . From the above results the following conclusion can be made:

- The size of the TCR is chosen such that reactive power drawn from the source is minimum.
- According to the load requirements, designing the SVC will help in improving the system performance with lesser harmonic.

Fig.7. Real power demands of a cyclic load at various intervals

Fig.8. Reactive power demands of a cyclic load at various intervals

TABLE III
COMBINATIONS OF Q_{C-max} AND Q_{R-max}

Q_{C-max} (MVAR)	Q_{R-max} (MVAR)			
25.0	25.0	30.0	35.0	40.0
30.0	30.0	35.0	40.0	45.0
35.0	35.0	40.0	45.0	50.0

Case 3: Balanced Cyclic Load

Consider the variable phase-wise balanced load at different intervals of time as shown in Fig.7 (for P_L) and Fig.8 (for Q_L) and also given in Table IV. To select a suitable Static VAR Compensator (SVC) to meet this cyclic load, different sizes of SVC are analyzed. Using the approach presented in the section D, the analysis are carried out for each combination of the Q_{C-max} and Q_{R-max} presented in Table III. In this section, results are presented for the combinations of $Q_{C-max} = 30.0$ MVAR, $Q_{R-max} = 30.0$ MVAR and $Q_{C-max} = 35.0$ MVAR, $Q_{R-max} = 35.0$ MVAR. Harmonic performance indices TIF and THD versus delay angles are presented in the Fig.9 and Fig.10 for the phase-wise balanced loads 29.2 MW + j29.2 MVAR. For each combination of Q_{C-max} and Q_{R-max} , and different load conditions, Q_S , and delay angles are identified for minimum harmonic generation by the TCR, are presented in Table V. From the Table V, it is clear that Q_S is minimum for the combination $Q_{C-max} = 35.0$ MVAR, $Q_{R-max} = 35.0$ MVAR, keeping the harmonic content minimum for the entire cyclic load.

TABLE IV
CYCLIC BALANCED LOAD AT DIFFERENT INTERVALS OF TIME IN EACH PHASE

Time range (seconds)	Real Load (MW)	Reactive Load (MVAR)
0 - 9	3.4	3.4
10-50	29.2	29.2
50-61	54.0	33.0
62-75	36.0	29.0
75-90	3.4	3.4

Fig.9. TIF and THD versus Delay angle for $Q_{C-max} = 30.0$ MVAR, $Q_{R-max} = 30.0$ MVAR, and balanced load 29.2 MW + j 29.2 MVAR

Fig.10. TIF and THD versus Delay angle for $Q_{C-max} = 35.0$ MVAR, $Q_{R-max} = 35.0$ MVAR, and balanced load 29.2 MW + j 29.2 MVAR

TABLE V
MINIMUM HARMONIC OPERATING RANGE VALUES FOR THE BALANCED CYCLIC LOAD

Q_{C-max} (MVAR)	Q_{R-max} (MVAR)	For Balanced Load presented over a time range of							
		0-9 sec.		10-50 sec.		50-61 sec.		62-75 sec.	
		Q_s (MVAR)	Alpha (α)	Q_s (MVAR)	Alpha (α)	Q_s (MVAR)	Alpha (α)	Q_s (MVAR)	Alpha (α)
25	25	-5.89- 3.40	0.0- 17.69	12.36-29.2	0.0-34.65	16.00-33.0	0.0-35.09	12.0-29.0	0.0-35.08
	30	-4.00- 8.40	0.0-19.90	14.0-34.2	0.0-34.76	17.66-38.0	0.0-35.08	13.66-34.0	0.0-35.07
	35	-1.06-13.40	0.0-20.00	15.79-39.2	0.0-34.60	19.30-43.0	0.0-35.16	15.32-39.0	0.0-35.11
	40	1.83-18.40	0.0-20.16	17.37-44.2	0.0-34.85	20.89-48.0	0.0-35.33	17.05-44.0	0.0-35.05
30	30	-5.99- 3.40	0.0-14.87	8.79-29.2	0.0-35.21	12.69-33.0	0.0-35.01	8.72-29.0	0.0-34.93
	35	-5.99- 8.40	0.0-19.88	10.66-34.2	0.0-34.83	14.33-38.0	0.0-35.09	10.59-34.0	0.0-34.59
	40	-2.92-13.40	0.0-19.83	12.29-39.2	0.0-34.97	15.98-43.0	0.0-35.17	12.29-39.0	0.0-34.65
	45	0.14-18.40	0.0-19.82	14.32-44.2	0.0-34.54	17.67-48.0	0.0-35.21	13.76-44.0	0.0-35.06
35	35	-5.99- 3.40	0.0-12.77	5.57-29.2	0.0-34.99	9.50-33.0	0.0-34.76	5.57-29.0	0.0-34.62
	40	-5.99- 8.40	0.0-17.37	7.25-34.2	0.0-35.03	11.32-38.0	0.0-34.60	7.09-34.0	0.0-34.96
	45	-4.88-13.40	0.0-19.83	9.02-39.2	0.0-34.95	13.04-43.0	0.0-34.66	8.81-39.0	0.0-34.97
	50	-2.05-18.40	0.0-20.08	10.95-44.2	0.0-34.72	14.53-48.0	0.0-35.02	10.48-44.0	0.0-35.07

Case 4: Unbalanced Cyclic Load

Consider the variable phase-wise unbalanced load at different intervals of time as given in Table VI. Using the approach presented in the section D, the analysis is carried out for each combination of the Q_{C-max} and Q_{R-max} , chosen close to reactive load, as presented in Table III. In this case, results are presented for the combinations of $Q_{C-max} = 30.0$ MVAR, $Q_{R-max} = 30.0$ MVAR and $Q_{C-max} = 35.0$ MVAR, $Q_{R-max} = 35.0$ MVAR. Harmonic performance indices TIF versus reactive power drawn from the supply (Q_s) are presented in the Fig.11 and Fig.12 for the un-balanced loads appeared in the time range 10-50 sec. For each combination of Q_{C-max} and Q_{R-max} , and different load conditions, the ranges of Q_s are identified for minimum harmonic generation by the TCR. Results are presented in Table VII.

TABLE VI
CYCLIC BALANCED LOAD AT DIFFERENT INTERVALS OF TIME IN EACH PHASE

Time range (sec)	Phase-A		Phase-B		Phase-C	
	P_L (MW)	Q_L (MVAR)	P_L (MW)	Q_L (MVAR)	P_L (MW)	Q_L (MVAR)
0 - 9	3.4	3.4	2.9	2.9	2.4	2.4
10-50	29.2	29.2	27.2	25.2	25.2	21.2
50-61	54.0	33.0	50.0	30.0	46.0	27.0
62-75	36.0	29.0	34.0	25.0	32.0	21.0
75-90	3.4	3.4	2.9	2.9	2.4	2.4

Fig.11. TIF versus Delay angle for $Q_{C-max} = 30.0$ MVAR and $Q_{R-max} = 30.0$ MVAR for an unbalanced load presented in the time range 10-50 sec

Fig.12. TIF versus Delay angle for $Q_{C-max} = 35.0$ MVAR and $Q_{R-max} = 35.0$ MVAR for an unbalanced load presented in the time range 10-50 sec

TABLE VII
MINIMUM HARMONIC OPERATING RANGE VALUES FOR THE ENTIRE
UNBALANCED CYCLIC LOAD

Q_{C-max} (MVAR)	Q_{R-max} (MVAR)	For Unbalanced Load presented over a time range of			
		0-9 sec.	10-50 sec.	50-61 sec.	62-75 sec.
		Q_s (MVAR)	Q_s (MVAR)	Q_s (MVAR)	Q_s (MVAR)
25	25	-5.99 - 1.9	8.78-9.29	14.02-15.01	8.60- 9.07
	30	-4.00 - 6.9	11.88-13.26	15.36-16.27	11.90-12.78
	35	-1.00 -11.9	12.84-14.09	16.76-18.07	12.68-13.72
	40	2.02 -16.9	14.03-15.34	19.96-21.67	13.88-14.80
30	30	-5.99 - 1.9	6.90 - 8.12	10.28-11.28	6.78 - 7.78
	35	-5.99 - 6.9	7.83 - 8.92	12.04-13.18	7.66- 8.90
	40	-3.07 -11.9	9.13-10.20	15.18-16.38	8.91- 9.94
	45	1.00 -16.9	10.64-13.35	18.59-22.25	10.66-11.86
35	35	-5.99 - 1.9	2.85- 3.98	6.91 - 8.08	2.57- 3.84
	40	-5.99 - 6.9	4.11 - 5.30	12.41-14.31	3.91- 4.98
	45	-4.95 -11.9	5.64 - 8.16	13.55-17.18	5.51- 7.81
	50	-1.85 -16.9	7.29-10.10	17.24-19.84	8.79-11.60

From the Table VII, it is clear that the reactive power supply from the source (Q_s) is minimum for the combination $Q_{C-max} = 35.0$ MVAR, $Q_{R-max} = 35.0$ MVAR, keeping the harmonic content minimum for the entire cyclic load.

From the above analysis for cyclic load (Balanced/Unbalanced) conditions, the following observations can be made,

- By knowing the range of reactive load to be met, the design parameters Q_{C-max} , Q_{R-max} , of the FC-TCR is chosen such that minimum reactive power is drawn from the source, while keeping the harmonics minimum.
- Based on the range of reactive load to be met, designing the SVC accordingly will help in improving the system performance and keeping the harmonic levels low

III. CONCLUSIONS

The operation of thyristor-controlled compensators at various conduction angles can be used advantageously to meet the unbalanced reactive power demands in a system. The compensator operation beyond certain range may increase the harmonic components, and thus the compensator capacitor / reactor size should be selected based on the overall requirement of meeting the loads. The proposed approach can be used to reduce the balanced reactive power drawn from the source under unbalanced loadings while keeping the harmonics injection to the power system low.

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