

LC Compensators Based on Transmission Loss Minimization for Nonlinear Loads

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Abstract—This paper presents a method employing the penalty function search algorithm to determine the LC compensator value for the optimal power factor correction in nonsinusoidal systems. The objective of the proposed method is to minimize the transmission loss while the power factor and efficiency are taken as constraints and utilized in order to solve the multiobjective optimization problem by transforming it into a single objective one. Examples show that the load nonlinearity can have a significant impact on optimal compensator sizes.

Index Terms—Harmonics, power factor, reactive power optimization.

I. INTRODUCTION

THE increasing proliferation of electronic equipment and appliances connected to the power line represents an important, growing challenge to power providers and users alike. These nonlinear loads degrade power quality because they reduce the power factor and introduce harmonic current. The power factor is of great concern to the utilities because low power factor results in harmonic currents, which propagate through the system and produce potentially dangerous harmonic voltages. Amplification of harmonic currents and voltages can have detrimental effects on other elements of the system [1]. On the other hand, if a nonlinear load generates significant harmonic currents locally, tuned filters [2], [3] may be installed to prevent the currents from being injected into the system. However, such filters are resorted only for heavily nonlinear loads because of the high cost. An important side effect of adding a filter is that it creates a sharp parallel resonance point at a frequency below the notch frequency [4]. This resonant frequency must be safely away from any significant harmonic. Filters are commonly tuned slightly lower than the harmonic to be filtered so as to provide a margin of safety in case of any change in system parameters. If they were tuned exactly to the harmonic, changes in either capacitance or inductance with temperature or failure might shift the parallel resonance into the harmonic. This might be worse than without a filter because the resonance is generally very sharp. That is why filters are added to the system starting with the lowest problem harmonic. For example, installing a seventh-harmonic filter usually requires a fifth-harmonic filter to be installed as well. The new parallel resonance with a seventh filter only would be very near the fifth, which is generally disastrous. In [5], both the equivalent

source and load are considered to generate harmonics. The different criteria for the design of the LC compensator: i) maximizing power factor, ii) minimizing transmission loss, and iii) maximizing transmission efficiency, are discussed. While discussing such criteria, the nonlinearity of the load by using direct polytope search method should be taken into account. In [6], the manufacturer's standard values for power shunt capacitors are taken into consideration. These values are considered as constraints in the sense that the solution for the capacitor should be one of the standard values. The different criteria for the design of the LC compensator are discussed by using the golden section search method. Such criteria are discussed to compare the values obtained in [6] with real practical values in the market. Reference [7] formulates the problem of minimizing the transmission losses with expressions for the power factor and efficiency taken as constraints neglecting the harmonic contents of the nonlinear loads. Reference [8] shows the voltage and reactive power ratings of shunt capacitors. The inductive reactive values are almost continuous and there is little limitation on the manufacturer's values.

This paper generalizes the method used in [7], taking into account the nonlinearity of the loads, the frequency-dependent nature of the supply source, compensator values which would create resonant conditions, the effect of the transmission-line impedance on the load voltage, and the manufacturer's standard values for power shunt capacitors. The major attribute of this method is that it, unlike conventional approaches, guarantees convergence to the optimal solution. Finally, the contribution of the newly developed method is demonstrated in examples taken from previous publications.

II. HARMONIC MODELING

References [9]–[12] demonstrate the representation of the power system loads and extended networks. Nonlinear loads are commonly represented by ideal current source at their characteristic frequencies. Characteristic harmonic orders K and the harmonic injection currents I_{LK} of a line-commutated converter, operating under ideal conditions, are [9]

$$K = n * p \pm 1$$

$$I_{LK} = \frac{I_1}{K}$$

respectively, where n is any integer number; p is the pulse number of converter; and I_1 is the fundamental current.

This model is adequate where the voltage harmonic distortion (THD_V) is less than 10% [10].

The source is often represented by an impedance, found from the short-circuit test [11]. Linear loads are modeled as a resis-

Manuscript received January 8, 2003; revised March 21, 2003. Paper no. TPWRD-00009-2003.

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Digital Object Identifier 10.1109/TPWRD.2004.835426

tance in parallel with an inductance, selected to account for the respective active and reactive powers at the fundamental frequency.

Finally, the linear load is represented by admittance

$$Y_{LK} = G_{LK} - jB_{LK}$$

or impedance

$$Z_{LK} = R_{LK} + jX_{LK}$$

which is a function of the order of the applied voltage harmonic frequencies. The configuration of the employed system is given in Fig. 1.

In [12], a new model for the distribution system, including nonlinear loads, is introduced. The model is based on measurements, where current and voltage measurements at two different operating conditions are used to derive an equivalent Norton model for the distribution system

$$Z_{LK} = \frac{V_{LK}^{(1)} - V_{LK}^{(2)}}{I_{LK}^{(1)} - I_{LK}^{(2)}}.$$

To simplify the analysis, only the load model using the respective active and reactive powers at the fundamental frequency is considered while sizing compensators.

III. DERIVATION OF THE OBJECTIVE FUNCTION

Let	
X_C	capacitive reactance of the compensator;
X_L	inductive reactance of the compensator;
R	compensator resistance at the fundamental frequency;
R_{TK}, X_{TK}	resistance and reactance of the source found from the short-circuit test at the fundamental frequency;
R_{LK}, X_{LK}	resistance and reactance of the load selected to account for the respective active and reactive powers at the fundamental frequency.

Then

$$\begin{aligned} Z_{CK} &= R + j \left(KX_L - \frac{X_C}{K} \right) \\ Z_{CLK} &= \frac{(R_{CLK} + jX_{CLK})}{(Z_{LK} + Z_{CK})} \end{aligned} \quad (1)$$

where

$$\begin{aligned} R_{CLK} &= RR_{LK} - X_{LK} \left(KX_L - \frac{X_C}{K} \right) \\ X_{CLK} &= RX_{LK} + R_{LK} \left(KX_L - \frac{X_C}{K} \right) \\ Z_{TLK} &= \frac{(R_{TLK} + jX_{TLK})}{(Z_{TK} + Z_{LK})} \end{aligned}$$

where

$$\begin{aligned} R_{TLK} &= R_{TK}R_{LK} - X_{TK}X_{LK} \\ X_{TLK} &= R_{TK}X_{LK} + X_{LK}R_{LK} \\ Z &= Z_{TK} + Z_{CLK}. \end{aligned}$$

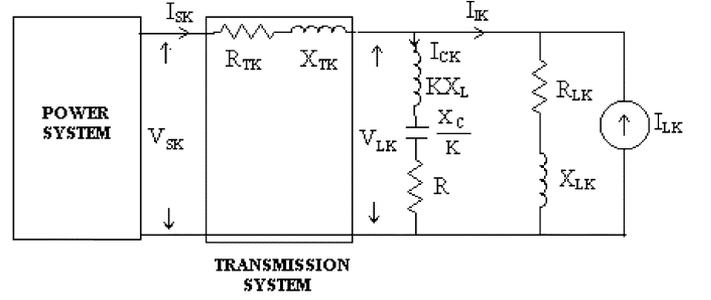


Fig. 1. Power system under study with shunt LC compensator.

Following the previous definitions, the compensated line current (I_{SK}) and the load voltage (V_{LK}) at each harmonic order (K) are given, respectively, by the following equations:

$$I_{SK} = \frac{V_{SK}(AR + jBR) + I_{LK}CR}{A_{IK} + jA_{JK}} \quad (2)$$

$$V_{LK} = \frac{V_{SK}(CR) - I_{LK}(DR + ER)}{A_{IK} + jA_{JK}} \quad (3)$$

where

$$\begin{aligned} AR &= R + R_{LK}; \\ BR &= (X_{LK} + KX_L - X_C/K); \\ CR &= R_{CLK} + jX_{CLK}; \\ DR &= R + j(KX_L - X_C/K); \\ ER &= R_{TLK} + jX_{TLK}; \\ A_{IK} &= R_{TLK} + R(R_{LK} + R_{TK}) - (X_{LK} + X_{TK})(KX_L - X_C/K); \\ A_{JK} &= X_{TLK} + R(R_{LK} + X_{TK}) + (R_{LK} + R_{TK})(KX_L - X_C/K). \end{aligned}$$

The compensated power factor at the load is given as

$$PF = \frac{P_L}{V_L I_S} = \frac{\sum G_{LK} V_{LK}^2}{\sqrt{\sum I_{SK}^2} \sqrt{\sum V_{LK}^2}}. \quad (4)$$

The transmission loss is given as

$$TL = \sum_K I_{SK}^2 R_{TK}. \quad (5)$$

The transmission efficiency is given as

$$\eta = \frac{P_L}{P_S} = \frac{\sum G_{LK} V_{LK}^2}{\sum I_{SK}^2 R_{TK} + \sum G_{LK} V_{LK}^2}. \quad (6)$$

IV. HARMONIC RESONANCE CONSTRAINT

System resonant conditions are the most important factors affecting system harmonic levels. Parallel resonance is high impedance to the flow of harmonic current, while series resonance is low impedance to the flow of harmonic current [13]. In actual electrical systems utilizing power factor correction, both types of resonance or a combination of both may occur if the resonant point happens to be close to one of the frequencies generated by harmonic sources in the system.

For the system configuration given in Fig. 1, the driving point impedance can be determined by the following equation:

$$Z = \frac{(R_{TK} + jX_{TK}) + (R_{CLK} + jX_{CLK})}{(Z_{LK} + Z_{CK})}. \quad (7)$$

Setting the imaginary part of this impedance equal to zero, series resonance, results in the following quadratic equation:

$$A_1 \left(KX_L - \frac{X_C}{K} \right)^2 + A_2 \left(KX_L - \frac{X_C}{K} \right) + A_3 = 0 \quad (8)$$

where A_1 equals $X_{TK} + X_{LK}$; A_2 is equal to $R_{LK}^2 + X_{LK}^2 + 2X_{LK}X_{TK}$; and A_3 equals $R^2X_{LK} + X_{TK}[(R + R_{LK})^2 + X_{TK}^2]$. Solving (8) for finding X_L and X_C

$$KX_L - \frac{X_C}{K} = \frac{-A_2 \pm \sqrt{A_2^2 - 4A_1A_3}}{2A_1}.$$

Hence, using only the set values for shunt capacitors, we can obtain values for the inductive reactance since (8) will then become a one-variable equation in X_L only.

Note that for sufficiently large load resistance and/or load reactance, (8) reduces to

$$KX_L - \frac{X_C}{K} + X_{TK} = 0 \quad (9)$$

which then represents only the series resonance, that represents all possible combinations of X_C and X_L values which result in resonance between the transmission impedance and compensated load. Under these conditions, the power factor will reach a minimum. It is evident that the number of series resonance lines will depend on the number of harmonics present in the transmission source.

V. SKIN EFFECT CONSTRAINT

Skin effect is an alternating current phenomenon where the current in a conductor tends to flow more densely near the outer surface of a conductor than in the center area. Skin effect will be applied in the analysis to account for the impact on the system impedance of the frequency dependence of the resistive component of the load. On utilizing voltages, such as industrial power systems, the equivalent system reactance is often dominant by the service transformer impedance [14]. For lines and cables, an estimated correction factor [15] for skin effect is applied by increasing the resistance with frequency by

$$R = R * \left[1 + \frac{0.646K^2}{192 + 0.518K^2} \right] \text{ for lines} \quad (10)$$

or

$$R = R * [0.187 + 0.532K^{1/2}] \text{ for cables.} \quad (11)$$

For transformers, an estimated correction factor [15] for skin effect is applied by increasing the resistance with frequency by $K^{1.15}$. The exception to this rule is with some transformers. Because of stray eddy current losses, the apparent resistance of large transformers may vary almost proportionately with the frequency [16]. Finally, in most power systems, one can generally assume that the resistance does not change significantly when studying the effects of harmonics less than the ninth [14].

VI. CAPACITOR LOADING CONSTRAINT

One problem that is to be addressed is whether the values obtained from theoretical optimization solution can be obtained

from standard manufactured values. Depending on the voltage, manufacturers have discrete capacitors available. In the presented method, manufacturers standard values for shunt capacitor are taken into consideration. The standard values are considered as constraints in the sense that the capacitor chosen should be one of these values.

VII. PROPOSED SOLUTION OF THE PROBLEM

The power factor PF , the transmission loss TL , and the transmission efficiency η can be expressed as functions of X_C and X_L using (4)–(6). Each value of the reactive power ratings Q_{Ci} of the particular voltage [8] is used to calculate the corresponding value of X_{Ci} . This value is then substituted into the objective function to become one variable equation in X_L , which can be solved by using the penalty function method.

After formulating the objective function and the constraints, the problem addressed in this study becomes

$$\begin{aligned} & \text{Minimize} \quad TL(X_{Ci}, X_L) \\ & \text{Subject to:} \quad 0.9 \leq PF(X_{Ci}, X_L) \leq 1.0 \\ & \quad \quad \quad 0.85 \leq \eta(X_{Ci}, X_L) \leq 1.0 \\ & \quad \quad \quad X_{Ci}, X_L \text{ is not part of the solution of (8).} \end{aligned} \quad (12)$$

Naturally, the solution will satisfy the upper limit of the power factor and efficiency constraints. Power factor in distribution systems may be allowed within certain limits according to the authority, and similarly for the efficiency so the presented method will generalize the limits of the constraints.

This problem can be rewritten in the form

$$\begin{aligned} & \text{Minimize} \quad TL(X_{Ci}, X_L) \\ & \text{Subject to:} \quad g_1(X_{Ci}, X_L) = 0.9 - PF(X_{Ci}, X_L) \leq 0.0 \\ & \quad \quad \quad g_2(X_{Ci}, X_L) = PF(X_{Ci}, X_L) - 1.0 \leq 0.0 \\ & \quad \quad \quad g_3(X_{Ci}, X_L) = 0.85 - \eta(X_{Ci}, X_L) \leq 0.0 \\ & \quad \quad \quad g_4(X_{Ci}, X_L) = \eta(X_{Ci}, X_L) - 1.0 \leq 0.0 \\ & \quad \quad \quad X_{Ci}, X_L \text{ is not part of the solution of (8).} \end{aligned} \quad (13)$$

Note that in order to have the algorithm to guarantee convergence, the objective function has to be a unimodal function [17]. Due to the resonant conditions, there might be local minimums to which the solution will converge. To avoid this problem, the precalculated compensator values for series resonance will be used to subdivide the entire search region into numerous small regions. Within these regions, the local minimums are identified and, hence, the global minimum. Note that the square of the root mean square (rms) value of the line current at a given harmonic order (I_{SK}^2) is a unimodal (convex) function. Consequently, within these regions, the objective function TL is also convex function [18]. As a result, the convergence to an optimal solution is guaranteed.

VIII. SEARCH ALGORITHM

The suggested search algorithm is discussed below.

Step 1: Choose the first value of the standard manufactured reactive power rating of capacitors in kvar **[8]**

$$Q_{Ci} = \{Q_{C1}, Q_{C2} \dots Q_{Cn}\} \quad (14)$$

where n is the number of discrete values available for the particular voltage rating used and i has a starting value of 1.

Step 2: Using only the selected value of Q_{Ci} , calculate X_{Ci} from the following equation:

$$X_{Ci} = \frac{V_{S1}^2}{Q_{Ci}}. \quad (15)$$

Substitute the value of X_{Ci} into **(8)** to become one variable problem in X_L , and solve it to get the precalculated inductor values for series resonance. These values are used to subdivide the entire search region into small regions. Step 3: Let penalty parameter $\mu > 1$, scalar $\beta > 0$, and $J = 1$. Starting with $X_L^{(J)}$ to solve the following problem:

$$\text{Min. } TL(X_{Ci}, X_L) + \sum \mu_m (\max[0, g_m(X_{Ci}, X_L)]).$$

For a certain value of $\mu_m^{(J)}$, the golden search method **[1]** can be applied for obtaining the optimal $X_L^{(J+1)}$. According to the penalty function method, the value of $\mu_m^{(J)}$ is updated using

$$\mu_m^{(J+1)} = \beta \mu_m^{(J)}.$$

Step 4: The previous step is repeated until convergence is achieved using

$$\mu_m^{(J)} (\max[0, g_m(X_{Ci}, X_L^{(J+1)})]) < \epsilon.$$

Step 5: If $i = n$ stop; otherwise, replace i by $(i+1)$ and go to step 2.

Step 6: After stopping, scan through to get the global minimum.

Reference [19] shows that the starting penalty parameter value $\mu^{(0)} = 10$. Values of β are in the range 0.1–0.5 work well for most problems. The algorithm will stop when a feasible point will be reached or when the relative change in the objective function is small (less than $\epsilon = 10^{-6}$).

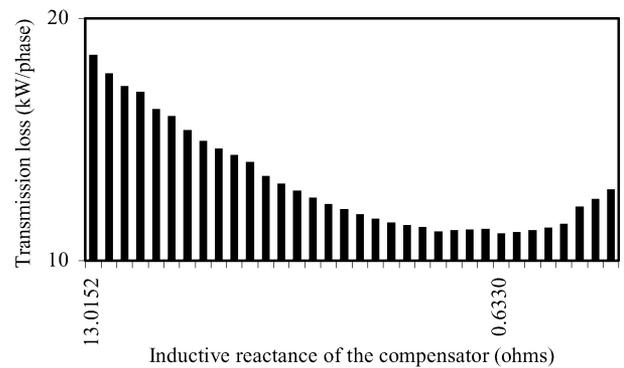
In the optimization process, the resistance of the compensator reactor has been neglected due to its small value with respect to its fundamental reactance (less than 5%) [20].

IX. EXAMPLES AND SIMULATED RESULTS

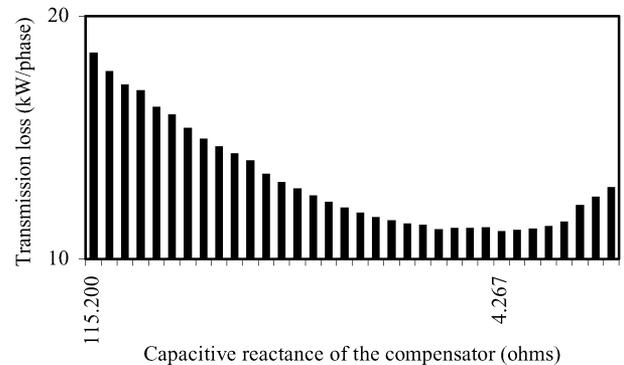
Four cases of an industrial plant were simulated using the optimization method; the numerical data were primarily taken from an example in [13] where the inductive three-phase load is 5100 kW with a displacement factor (dPF) of 0.7165. The

TABLE I
SYSTEM PARAMETERS AND SOURCE HARMONICS

PARAMETERS & HARMONICS	CASE 1	CASE 2	CASE 3	CASE 4
Short Circuit MVA	150	80	80	80
$R_{T1} (\Omega)$	0.01154	0.02163	0.02163	0.02163
$X_{T1} (\Omega)$	0.1154	0.2163	0.2163	0.2163
$R_{L1} (\Omega)$	1.742	1.742	1.742	1.742
$X_{L1} (\Omega)$	1.696	1.696	1.696	1.696
$V_{S1} (kV)$	2.4	2.4	2.4	2.4
$V_{S3} (\%V_{S1})$	0	0	0	3
$V_{S5} (\%V_{S1})$	4	4	5	5
$V_{S7} (\%V_{S1})$	3	3	3	3
$V_{S11} (\%V_{S1})$	0	0	2	2
$V_{S13} (\%V_{S1})$	0	0	1	1
$I_{L3} (A)$	0	0	304	304
$I_{L5} (A)$	33	33	33	33
$I_{L7} (A)$	25	25	25	25
$I_{L9} (A)$	0	0	26	26
$I_{L11} (A)$	8	8	8	8
$I_{L13} (A)$	9	9	9	9
Uncompensated PF (%)	71.58	71.57	68.50	68.54



(a)



(b)

Fig. 2. Global minimum points for case 4 during the search method. (a) TL against X_L . (b) TL against X_C .

60-cycle supply bus voltage is 4.16 kV (line-to-line). The resistance and fundamental reactance values are given in Table I. In this study, it is assumed that the load harmonics are not sufficiently serious to suggest tuned filters, but when combined with source harmonics, the use of a pure capacitive compensator would degrade the power factor and overload equipment. Consequently, an LC compensator is selected.

Fig. 2 shows the improvement in choosing the value of X_L during the search method and how it affects the objective function.

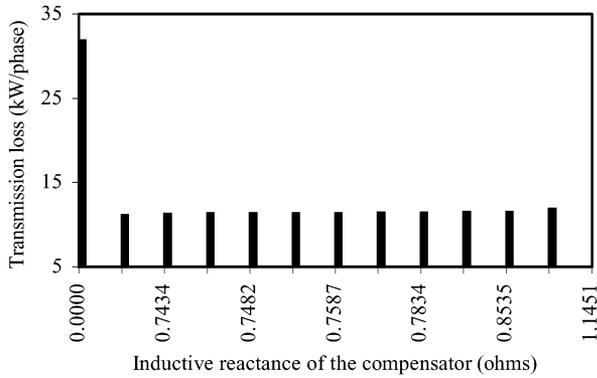


Fig. 3. Global and local minimum points for case 4.

TABLE II
SIMULATED RESULTS FOR THE PRESENTED OPTIMIZATION METHOD

CASE	X_C (Ω)	X_L (Ω)	PF (%)	I_s (A)	η (%)	TL (kW)
1	4.27	0.827	99.65	705.85	99.66	5.75
2	4.27	0.743	99.72	701.40	99.36	10.64
3	4.61	0.654	97.60	711.52	99.34	10.95
4	4.27	0.633	97.52	715.99	99.34	11.09

TABLE III
SIMULATED RESULTS FOR THE OPTIMIZATION METHOD IN [21]

CASE	X_C (Ω)	PF (%)	I_s (A)	η (%)	TL (kW)
1	7.81	85.24	807.64	99.54	7.53
2	3.12	93.84	751.45	99.28	12.21
3	3.02	91.66	770.77	99.25	12.85
4	2.85	87.22	812.64	99.18	14.28

Fig. 3 shows the location of the global minimum point and the local minimum points, which are located in the subdivisions where the resonant conditions exist.

Comparison of the results: Table II shows that a lower short-circuit capacity corresponds to a higher power factor at the same conditions. This is to be expected since with higher transmission impedance, less harmonic current will flow into the compensated load, cases 1 and 2. Also, it is shown that additional harmonic contents result in lower power factor. This is caused by the increase in compensated line current due to the additional harmonics, cases 3 and 4. Comparing these results with Table II for the same system data but with the load being linear, we realized a degraded power factor, a high line current, and, hence, an increase in transmission loss and a decrease in the transmission efficiency. Table III shows the required capacitive reactance, the power factor, the supply current, the efficiency, and the transmission loss for the same system data but with the load being linear.

Finally, in the IEEE Standard 519-1992 [13], the objectives of the nonlinear load harmonic current limits are to limit the maximum individual harmonic voltage to 3% of the fundamental voltage and the total harmonic distortion of the voltage to 5%.

TABLE IV
HARMONIC DISTORTIONS AND DISPLACEMENT FACTOR AFTER COMPENSATION

CASE	THD _I (%)	THD _V (%)	dPF (%)
1	7.32	4.22	99.99
2	6.43	3.93	99.99
3	18.28	5.55	99.34
4	21.68	5.92	99.92

Table IV shows the distortion levels and the displacement factor after compensation when taking harmonic components into account. The resultant values all come out well within standard limits except cases 3 and 4 where the load harmonics may be sufficiently serious to suggest tuned filters. It is shown that in all cases, the proposed method improves the performance of the system under study.

X. CAPACITOR LOADING STANDARDS

ANSI/IEEE Standard 18-1992 [8] specifies the following continuous capacitor ratings:

- 1) 135% of nameplate kvar;
- 2) 110% of rated rms voltage (including harmonics but excluding transients);
- 3) 180% of rated rms current (including fundamental and harmonic current);
- 4) 120% of peak voltage (including harmonics).

The capacitor bank data for case 1 are

bank rating: 4050 kvar;
voltage rating: 4160 V (L-L);
operating voltage: 4160 V (L-L);
supplied compensation: 4050 kvar;
fundamental current rating: 562.08 A;
fundamental frequency: 60 Hz;
capacitive reactance: 4,267 Ω ;
voltage distortion: 0.71%;
rms capacitor voltage: 2966.22 V;
capacitor current distortion: 3.74%;
rms capacitor current: 695.68 A.

The fundamental current full-load current for the 4050-kvar capacitor bank without the series inductor is determined from

$$I_C = \frac{4050 * 1000}{\sqrt{3} * 4160} = 562.08 \text{ A.}$$

The capacitor is subjected principally to four harmonics: the fifth, the seventh, the eleventh, and the thirteenth. This results in 3.40% fifth-harmonic current, 1.51% seventh-harmonic current, 0.18% eleventh-harmonic current, and 0.32% thirteenth-harmonic current (Table V).

Table V summarizes capacitor evaluation for case 1 that is designed to help evaluate the various capacitor duties against the standards.

Finally, Table VI shows that the resultant values all come out well below standard limits.

XI. CONCLUSION

A mathematical model is developed and a solution method is presented for an optimal power factor correction of distribution circuits having nonlinear loads. The main contribution of this

TABLE V
CAPACITOR CAPABILITIES FOR CASE 1 WHEN SUPPLIED BY
NONSINUSOIDAL VOLTAGES

Harmonic No.	Frequency (Hz)	Voltage (%)	Voltage (V)	Current (%)	Current (A)
1	60	100.00	2966.1	100	695.2
2	120	0.00	0.00	0.00	0.00
3	180	0.00	0.00	0.00	0.00
4	240	0.00	0.00	0.00	0.00
5	300	0.68	26.20	3.40	23.70
6	360	0.00	0.00	0.00	0.00
7	420	0.22	6.70	1.51	10.50
8	480	0.00	0.00	0.00	0.00
9	540	0.00	0.00	0.00	0.00
10	600	0.00	0.00	0.00	0.00
11	660	0.02	1.60	0.18	1.20
12	720	0.00	0.00	0.00	0.00
13	780	0.02	0.40	0.32	2.20

TABLE VI
CAPACITOR BANK LIMITS FOR CASE 1

Item	Calculated (%)	Limit (%)	Exceeds limit
Peak voltage	100.94	120.00	No
rms voltage	100.00	110.00	No
rms current	100.07	180.00	No
kvar	100.07	135.00	No

work is the introduction of nonlinear loads on the problem, and also the proposed solution method.

For nonlinear loads, it is suggested to use *LC* compensators. Such compensators have dual purposes. The first is that they act as compensators to improve the power factor of the nonlinear loads. Second, they act as filters of the harmonic load currents; thus preventing the proliferation of the network with these currents. It is shown that the *LC* compensator sizes can be quite different when nonlinear loads are present in a system when compared to those found by neglecting harmonic components.

Four cases are tested, and the general performance of the proposed method is satisfactory, providing transmission losses reduction, improvement of distortion levels, and power factor correction, compared with other published results.

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