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Determining optimum capacitor in relation to load curve in harmonic systems

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SUMMARY

Because of the variable nature of loads and the presence of harmonics in a network, the variation of capacitor bank steps results in the reduction of capacitor life. Previous studies calculated the optimum capacitor in networks with variable loads to maximize the power factor. This paper calculates the optimum capacitor in harmonic networks, taking into consideration the effect on capacitor lifetime of load variation and harmonics. For this purpose, genetic algorithm was employed to determine the optimum capacitor. The proposed method was applied to an actual network in the Province of Markazi in Iran. The results showed this method to be flexible and reliable. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: capacitor lifetime; harmonic; load change; optimum capacitor; distribution engineering; power quality

1. INTRODUCTION

Increased use of semiconductor devices in power networks and the creation of non-sinusoidal voltages and currents have a significant effect on the determination of the optimum capacitor [1], [2]. The equivalent Thevenin impedance of the network can resonate with parallel capacitors [3]; consequently, the resonance amplifies the harmonic component. Using capacitors in a harmonic network may lead to an undesirable power factor. Therefore, the optimum capacitor is one which performs power factor correction while not causing resonance.

R. F. Chu and R. H. Avedano [1] were the first to present a method in which the optimum capacitor was determined by maximizing the power factor. In their method, a mathematical expression was presented to determine the optimum capacitor, considering the equivalent Thevenin impedance of the network. Hence, account was taken of the significance of the network equivalent impedance at the point where the load meets the network, but not of the effect of harmonics on capacitors and their life.

In subsequent studies, the effects of variations in load time and impedance time were considered. It was concluded that considering the variations of load may lead to a significant change in the value of the optimum capacitor [2].

In the two studies mentioned above, harmonics were considered as the constraints of the objective function (OF). This required that the optimum capacitor not cause network resonance. This was accomplished using an intelligent technique called golden area searching technique [2], [4], [5].

In some studies, such economic benefits as loss reduction, increased efficiency of transmission line, correction of power factor, and energy costs are considered as OF to determine optimum capacitor [6],

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[7].The final profit is obtained by subtracting the mentioned benefits from purchase, installation, and maintenance costs. In these methods, harmonics are considered as separate constraints of the OF or are entered in the OF as penalty.

The above-said studies only considered the effects of capacitor on harmonics; i.e. harmonics were the only constraints or penalties of the OF, and the effects of harmonics in capacitor lifetime were not taken into account.

Harmonics have bad effects on capacitor lifetime [8], [9]. This is because the capacitor increases the harmonic elements of the electrical current which passes through the capacitor and causes heat in the capacitor dielectric [8]. This phenomenon leads to a partial discharge in the capacitor and consequently decreases the lifetime.

In this paper, optimum capacitance is calculated on a low-voltage bus in a harmonic system. In addition, this method considers the effect of load curve and interaction of harmonics on the capacitor. Therefore, the structure of capacitor steps is calculated in a way that maximum compensation is achieved at a minimum cost. For this purpose, not only are harmonics taken into account as constraints in the OF, but also the effect of harmonics on capacitor lifetime and consequently on capacitor costs is considered.

2. BASIC FORMULATION

2.1. Interaction between the capacitor and harmonics

Harmonic are generated if the load is nonlinear. In this case, the capacitor, which does not generate harmonics by itself, can change the amplitude of the generated harmonics by changing the equivalent impedance of the network from the point of view of load. For this reason, the capacitor can have adverse effects on the power quality of the network. The parallel resonance of capacitor with network impedance can increase the amplitude of the harmonics, thus affecting the condition of harmonics. Figure 1 depicts, from the point of view of load, the equivalent impedance of the network and the position of the capacitor added to the network.

In any case, the capacitance of the capacitor should be set at an appropriate value so that there is no violation of the harmonic restrictions associated with the point where the load meets the network [10].

The harmonics distortion can cause the capacitor to experience a surge in electrical and current tension. The effect of electrical tension on capacitor lifetime is obtained through Equation (1) below [11]:

$$\begin{cases} \dfrac{L}{L_0} = \left(\dfrac{V}{V_0}\right)^{-N} e^{-B\,DT} \\ N = n - b\,DT, DT = 1/T_0 - 1/T \end{cases} \tag{1}$$

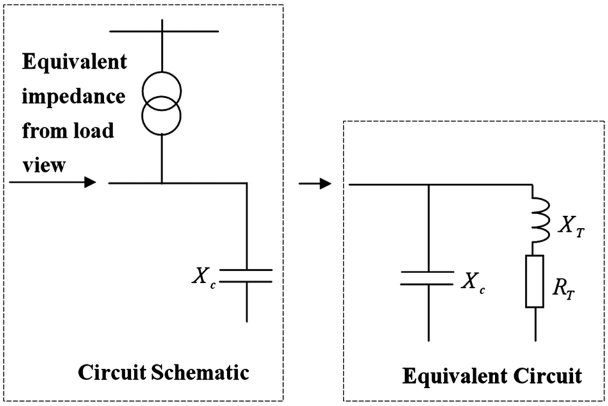

Figure 1. Equivalent network impendence from the point of view of load.

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where L is the harmonic-induced lifetime, b is the constant for the material, T_0 is the room temperature, T is the absolute temperature, n and B are constant values, V is the applied electrical tension or voltage peak, V_0 is the voltage peak below which aging ceases, and L_0 (reported by the manufacturer) is life at $V < V_0$ and room temperature T_0. The voltage peak considerably increases in amplitude under harmonic conditions and is calculated by adding up the voltage peaks of harmonic components (Equation (2)):

$$V = \sum_{h=1}^{50} V_h \tag{2}$$

where V_h is the voltage harmonic component peak.

In order to calculate the effect of current tension on capacitor lifetime, the value of T in Equation (1) should be modified. This is because when a current passes through the capacitor, the temperature increases due to the heat generated as a result of the internal resistance. The following equations indicate the interrelation between active power and current:

$$P = \sum_{h=1}^{50} R_h |I_h|^2 \tag{3}$$

where R_h is the internal resistance of the capacitor at referenced frequency and I_h is the current harmonic component passing throw the capacitor.

Therefore, the active power in the capacitor changes to heat and, according to Equation (4), the generated heat is directly related to the temperature.

$$Q = mc\Delta T \tag{4}$$

where Q is the heat generated in the capacitor in Joules, m is the mass in grams, c is the specific heat capacity in $J/gr.K$, and ΔT is the temperature rise. As is clear in Equations (3) and (4), the square of the effective current is directly related to the temperature. Thus, once it is known under nominal current conditions, capacitor temperature can easily be determined in harmonic conditions using a simple proportion as is shown in Equation (5).

$$T = \frac{\sum_{h=1}^{50} |I_h|^2 \times T_0}{|I_{nom}|^2} \tag{5}$$

where I_h is the harmonic current passing through the capacitor, I_{nom} is the nominal current of the capacitor, and T_0 is the operating temperature of the capacitor in nominal current conditions.

It is clear from Equation (5) that the harmonic current increases the operating temperature of the capacitor, thus, reducing capacitor lifetime according to Equation (1). Mixing Equations (1) and (5) gives Equation (6), which represents harmonic-induced lifetime:

$$\begin{cases} \dfrac{L}{L_0} = \left(\dfrac{V}{V_0}\right)^{-N} e^{-B\,DT} \\ N = n - b\,DT, DT = 1/T_0 - |I_{nom}|^2 / \left(\sum\limits_{h=1}^{50} |I_h|^2 \times T_0\right) \end{cases} \tag{6}$$

The operating temperature of the capacitor in nominal current condition could be related to the height of capacitor unit. More specifically, the more elevated the capacitor is, the higher the operating temperature will be. For a low-voltage capacitor unit, the operating temperature for a height of 10 cm is about 50°c [12].

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2.2. *The effect of switching on capacitor lifetime*

Given the variable nature of the load, it is advisable to use a capacitor bank to correct the power factor. The capacitor bank can change the capacitance by switching its steps. This switching, however, will have two sets of negative effects on the network:

1. Transient effects, which give rise to transient current and voltage component.
2. Steady-state effects, which cause the capacitor to recharge.

These effects will shorten the lifetime of the capacitor. According to [13], in the worst of conditions, a capacitor should be able to recharge at least 1000 times without any noticeable reduction (up to 3%) in its capacitance [13]. Depending on their material and manufacturing technology, the capacitors available on market can withstand a varied number of recharges. This means that a capacitor will no longer be of any use after switching is done a certain number of times.

The actual lifetime of the capacitor (L') is different from either reported lifetime (L_0) or harmonic-induced lifetime (L). Indeed, L' shows the combined effect of harmonics and the number of permissible switchings (SW; reported by the manufacturer). L' can be calculated from Equation (7):

$$L^{'} = L - N_{sw}\left(\frac{L_0}{SW}\right)\left(\frac{L^{'}}{D}\right) \tag{7}$$

where L is harmonic-induced lifetime obtained form Equation (6), N_{SW} is the number of switchings within the specified load profile where a specified number of switchings are done, L_0/SW is the magnitude of lifetime reduction induced by each switching, and D is the duration in hours of the load profile. Simplifying this equation gives Equation (8).

$$L^{'} = \frac{L}{1+\frac{N_{sw}\cdot L_0}{SW\cdot D}} \tag{8}$$

Equation (8) gives the exact capacitor life time in hours. Dividing L' by 8760 (total number of hours in a year) gives us the capacitor life time in years, Equation (9).

$$n_c = \frac{L^{'}}{8760} \tag{9}$$

mixing Equations (6) and (9) gives the final equation:

$$\begin{gathered} n_c = \frac{1}{8760}\frac{L_0\left(\frac{V}{V_0}\right)^{-N} e^{-B\,DT}}{1+\dfrac{N_{sw}\cdot L_0}{SW\cdot D}} \\ N = n - b\,DT, DT = 1/T_0 - |I_{nom}|^2/\left(\sum_{h=1}^{50}|I_h|^2 \times T_0\right) \end{gathered} \tag{10}$$

2.3. *Objective function*

The proposed method aims to find optimum capacitor size with the purpose of maximizing the benefits and satisfying operating constraints. The mathematical model of the problem is represented in Equation (11).

$$\max(f) = \max\left(\sum_{i-1}^{12} B_{P_i} - \left[C_{lc}\frac{h(1+h)^{n_c}}{(1+h)^{n_c}-1} + C_{RC}\right] \times Q_C\right)\cdot n_c \tag{11}$$

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where B_{Pi} is the i^{th} month's financial gain obtained from saving reactive power penalties, h is the annual interest rate, $C_{lc}h/(1+h)\text{\^{}}n/((1+h)\text{\^{}}n\text{-}1)$ is the cost of purchasing each kVAR of reactive power per year considering the interest rate, C_{RC} is the coefficient related to the annual costs of installing and maintaining the capacitor, Q_C is the capacity of the installed capacitor, and n_c was obtained from Equation (10). In this OF, the first part represents the monthly financial gain, and the second part is the installation and maintenance expenses.

2.4. *Constraints*

To solve the problem of reactive power, different constraints should be considered. Chief among these constraints are the allowable ranges of harmonic voltage and current. The total harmonic distortion (THD) and total demand distortion at the point where the substation meets the main network should not violate the values set by the [10]. In addition, in line with the [14], the actual effective voltage must be less than 110% of the nominal value, and the actual voltage peak must be less than 120 % of the nominal value. Also, the actual effective current of the capacitor must be less than 180% of the nominal value. The set of constraints are as follows:

$$\begin{cases} THD_V < THD_{V\,\mathrm{lim}it} \\ TDD_I < TDD_{I\,\mathrm{lim}it} \\ V_{rms} \leq 110\% V_{rms,rated} \\ V_{peak} \leq 120\% V_{peak,rated} \\ I_{rms} \leq 180\% I_{rms,rated} \end{cases} \tag{12}$$

3. PROBLEM-SOLVING ALGORITHM

Because of its nonlinear nature, the OF requires an intelligent method to be maximized. One of the most popular intelligent methods is GA [15], which is an effective search technique considered when conventional techniques do not achieve the desired speed, efficiency, or accuracy. Considering variables of the problem as chromosome, GA obtains the best chromosome through crossover and mutation operators. In the method proposed in this paper, GA is used to maximize the profit. For this purpose, the chromosome is considered as $[A_1\ A_2\ A_3\ \ldots\ A_n]$ where A_i represents the number of capacitor steps with certain capacitance k_i. Thus, total capacitance Q_c is obtained from Equation (13):

$$Q_c = \sum_{i=1}^{n} A_i \times k_i \tag{13}$$

GA tries to find the best chromosome to maximize the OF. For each selected chromosome, GA should calculate all parts of the OF according to network calculation. This means that GA should send the chromosome out as capacitor steps to the network and gets back the OF value. The details can be seen in Figure 2 and Figure 3.

The algorithm first receives initial information about the network, load variations, economic parameters, and so on. This is followed by a random responses which provides values for the three decision-making variables (i.e. capacitance of the capacitor). Each random response is then applied to the calculation procedure which divides the total length of time up into several shorter periods in which the power consumption is constant. This is called load profile and is shown in Figure 4. These subintervals will be studied one by one at a later stage. Before a capacitor is connected to the network, the power consumption (kW.H) and reactive power (kVAR.H) for each subinterval should be measured. Subsequently, with the use of capacitor steps, a part of the capacity of the capacitor is supplied to the network in order to maximally compensate for the reactive power. In the meanwhile, to determine how many times switching is done, the number of repositioned steps should be counted.

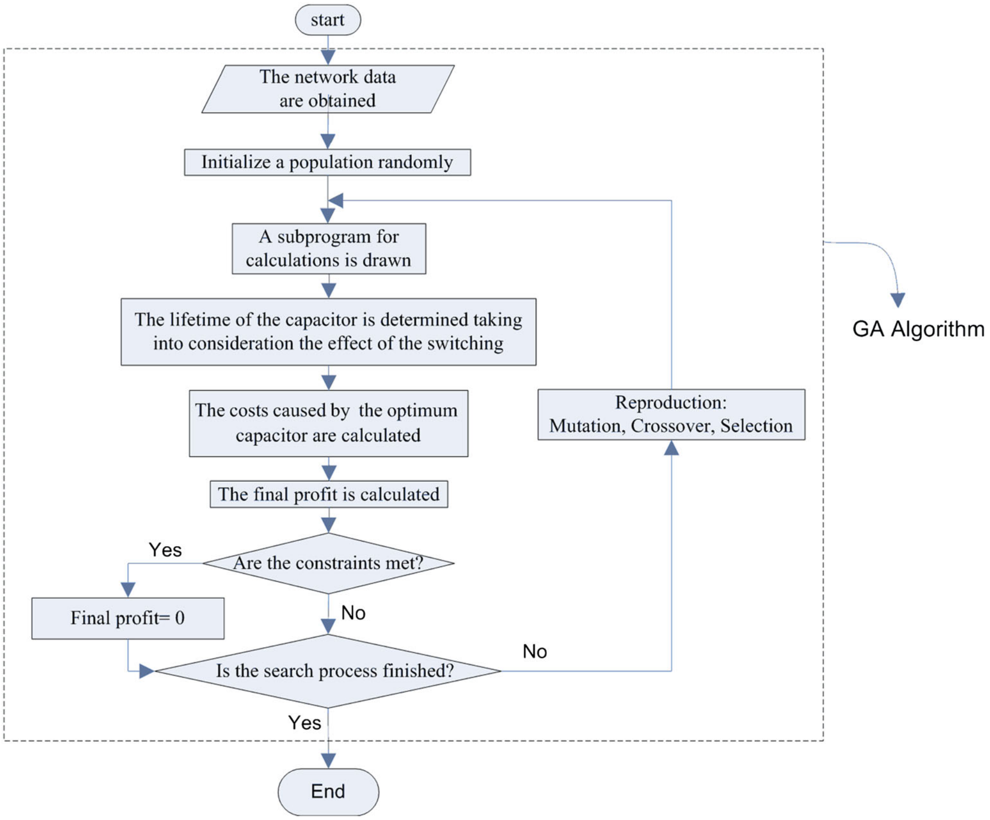

Figure 2. Problem-solving algorithm.

Once the capacitor is connected to the network, the power consumption and reactive power will be measured again. Also, it is ensured that constraints of the voltage and current THD are already in place in each subinterval. With the expenses and earnings associated with capacitor installation being known, the final financial gain can be calculated from Equation (11). However, if it turns out that the constraints were violated during the operation, the final gain will be assumed zero. Accordingly, the economic value of each random response will be known.

4. SIMULATION AND ANALYSIS OF THE RESULTS

To determine the efficiency of the proposed algorithm, a low-voltage network is simulated. This network, which has a displacement power factor of 0.7, is connected to the nationwide network through a 630-kVA transformer with a short-circuit impedance of 6%. The single line diagram is shown in Figure 5.

A four-step capacitor bank is placed in the network which is, however, passive at this stage. Loads are the six-pulse three-phase rectifiers and are therefore harmonic generators. For simulation purposes, two typical networks are taken into account, represented as Case 1 and Case 2 below.

4.1. Case 1

The first network has a displacement power factor of 0.7 and a monthly load variation shown in Table I. Table II shows the condition of the harmonics measured at the point where the load meets the network. After the proposed method was applied, four optimum capacitors were obtained: 15, 20, 25, and 30 kVAR. Table III shows the costs associated with each kVAR of the reactive power in different capacitor steps.

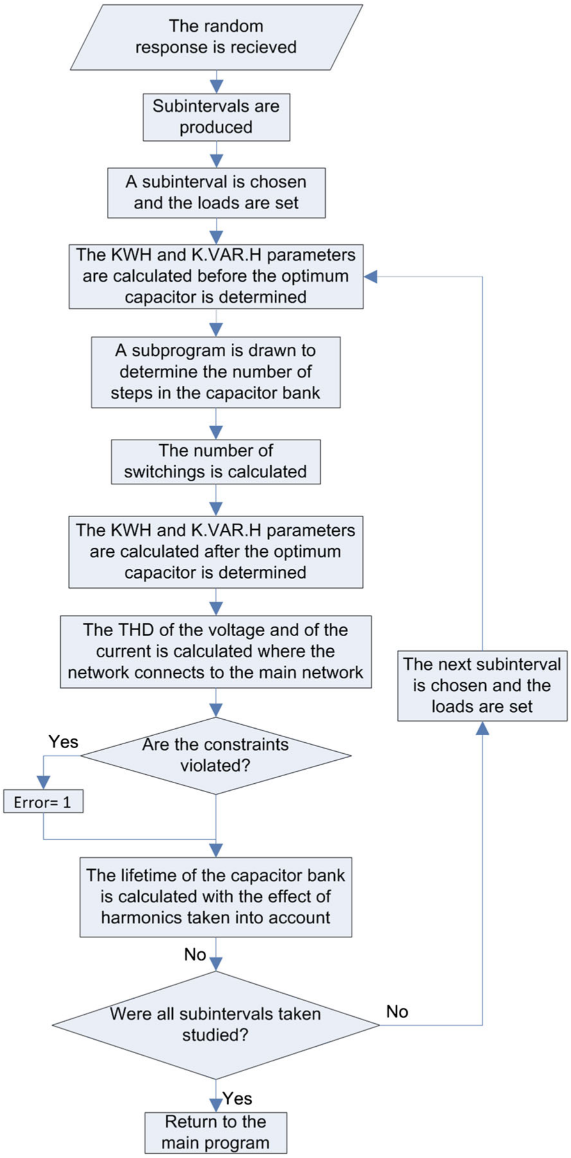

Figure 3. Calculation subprogram.

At this stage, the effect of load and harmonic variation on the optimum capacitor is studied using numerical values. For this purpose, four states were defined.

- State 1: a constant capacitor is calculated for the network by excluding the effect of both switching and harmonics.
- State 2: the capacitor steps are calculated by including the effect of the harmonics and excluding the effect of switching.
- State 3: capacitor steps are calculated by including the effect of switching and excluding the effect of the harmonics.
- State 4: the optimum capacitor is determined using the proposed algorithm, including the effect of both switching and harmonics.

A comparison of these four states is given in Table IV.

In Table IV, the maximum voltage represents the highest daily voltage of the bus to which the capacitors are attached; the minimum voltage represents the lowest voltage. The capacitor used had

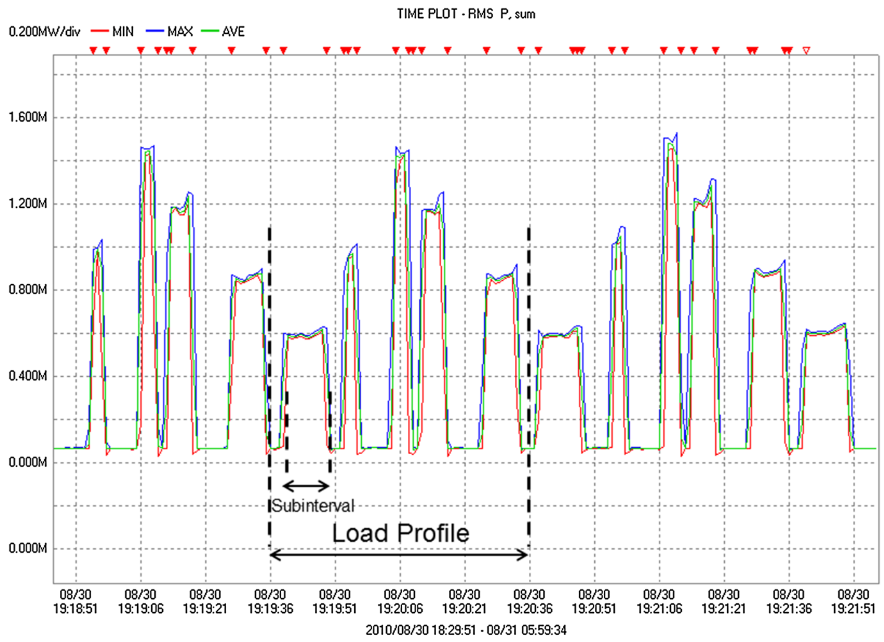

Figure 4. Load profile.

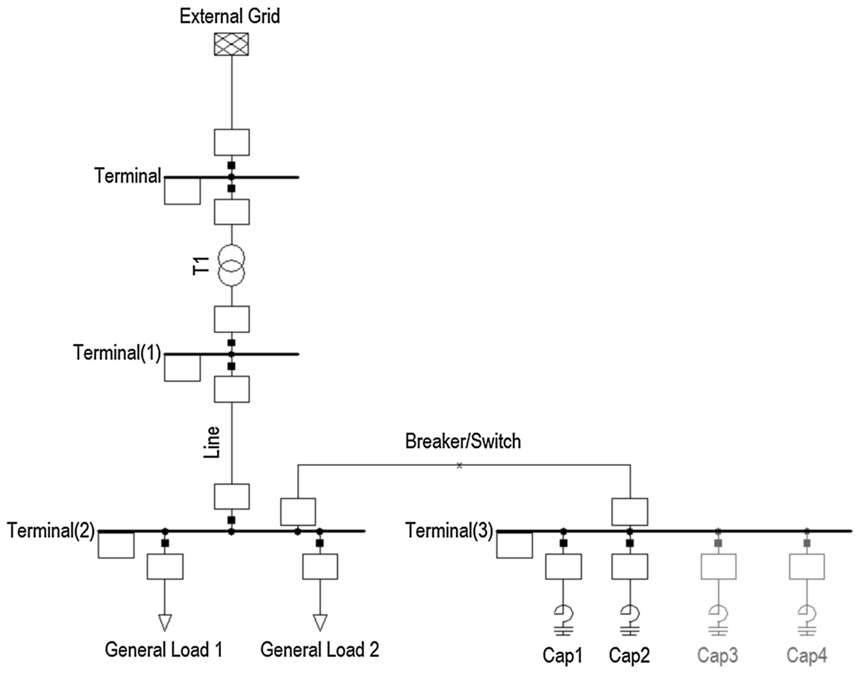

Figure 5. The single-line diagram of the network.

a nominal lifetime of six years. Since the load variation and the harmonics reduce the capacitor lifetime, the final profit is a function of the capacitor lifetime.

It is clear from Table IV that the maximum monthly profit obtained after modification is $542.13. All States can reach this maximum. However, in State 1, the installed capacitor causes effective harmonics to be near the resonance frequency. This leads to the existence of high-amplitude harmonics and consequently reduces the capacitor lifetime to 3.78 years.

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Table I. Load variation in network 1.

The number of month	Average active power (kW)
1	105
2	127
3	98.5
4	95
5	131
6	87
7	97.5
8	92
9	112.2
10	33.93
11	106.7
12	104

Table II. Harmonic condition before the optimum capacitor is determined.

Phase Maximum THD	A	B	C
Voltage (%)	3.8	3.1	4.1
Current (%)	12.52	11.66	12.65

Table III. The capacitance and cost of the capacitors in use.

Capacitance (kVAR)	Cost ($/kVAR)
15	32.2146
20	30.4249
25	28.6352
30	26.8455

Table IV. A comparison of capacitors calculated for the four states.

State	State 1	State 2	State 3	State 4
Description	switching and harmonics excluded	harmonics included; switching excluded	switching included; harmonics excluded	switching and harmonics included
Capacitance (kVAR)	40	155	45	60
Maximum voltage (V)	386.7	389.97	387.35	389.31
Minimum voltage (V)	376.6	384.48	377.26	379.2
Monthly profit ($)	535.7	542.13	542.13	542.13
Final profit ($)	24299	8756	25063	26140
Lifetime of capacitor bank (year)	3.78	1.35	3.86	4.02

With the effect of step variation being ignored, the optimum capacitor will be calculated as a 155-kVAR bank. Therefore, in actual conditions, necessary sequential switching during a day noticeably reduces the lifetime of this capacitor bank to 1.35 years. Excluding the effect of the harmonics in the design stage, the capacitor bank will be calculated as two steps, 20 and 25 kVAR each (45 kVAR in total). The 45-kVAR capacitor is the smallest capacity that can bring the mean displacement power factor to the desired amount at the end of a period. Larger capacitors merely increase the expenses without any gain followed. Now, by considering both parameters of switching and harmonic effect, the optimum answer is obtained as a 60-kVAR capacitor bank. As in the previous case, the switching effect causes the chosen capacitor to require minimum switching. However, in this case, the 45-kVAR capacitor is not considered optimum. This is because by installing the 60-kVAR capacitor, the resonance frequency will be controlled and the amplitude of harmonics will decline. As a result, the capacitor lifetime and the final gain will be increased. This study shows that in the design stage, both of the parameters which affect the capacitor lifetime should be considered. If either parameter is excluded, the obtained answer will be different from the optimum point.

4.2. Case 2

The second network has a displacement power factor of 0.75 and a monthly load variation shown in Table V.

The condition of the harmonics measured at the point where the load meets the network is shown in Table VI.

The calculated optimum state is a capacitor bank with two 15- and 20-kVAR steps. In order to better evaluate the calculated response, several different arrangements of the capacitor bank are tested (Table VII). This table compares the three states of the capacitor bank:

- State 1: a 15-kVAR capacitor bank,
- State 2: a 20-kVAR capacitor bank,
- State 3: a capacitor bank with two 15- and 20-kVAR steps.

In this comparison, account is taken of the THD of the current in a period of 12 months, expenses, benefits, and the final lifetime. The THD of the voltage is excluded because it constantly had a value of less than 3% (less than the standard restriction of 5%).

The comparison of state 1 and state 2 clearly shows how effectively the change in capacitance (from 15 kVAR to 20 kVAR) controls the amplitude of harmonics and restricts the THD of the current. It is also found that most benefit is obtained from using a capacitor bank with two 15-and 20-kVAR steps.

Table V. Load variation in network 2.

The number of month	Average active power (kW)
1	26.35
2	31.44
3	19.7
4	20.54
5	35.6
6	17.76
7	20.65
8	18.15
9	25.96
10	33.93
11	22.7
12	28.16

Table VI. Harmonic condition before the optimum capacitor is determined.

Phase Maximum THD	A	B	C
Voltage (%)	3.8	3.1	4.1
Current (%)	12.52	11.66	12.65

Table VII. A comparison of the three states of optimally arranged capacitor bank.

Number of month	Average active power (kW)	State 1	State 2	State 3
13.8622	26.35	22.55	13.8622	13.8622
13.2406	31.44	213315	13.2406	13.2406
23.269	19.7	23.269	7.027	23.269
13.197	20.54	23.197	7.044	13.197
12.9694	35.06	20.89	12.9694	12.9694
23.357	17.76	23.357	7.0204	23.357
23.187	20.167	23.187	7.054	23.187
23.35	18.15	23.35	7.024	23.35
13.8747	25.96	22.59	13.8747	13.8747
13.0765	22.93	21.058	13.0765	13.0765
22.97	22.7	22.97	7.063	22.97
13.79	28.16	22.35	13.79	13.79
Annual profits from determining the optimum capacitor (in dollars)		2119.02	1211.57	2119.094
Costs of determining the optimum capacitor (in dollars)		174.39	111.8482	210.5223
Lifetime of the capacitor bank (In bank)		1.7875	6	5.7
Final profits (in dollars)		3476.1	6599.54	10879.73

5. CONCLUSION

This paper introduced a method for determining the capacitance of the capacitor and the arrangement of capacitor bank steps in accordance with time-variant loads and harmonic distortions. In this method, the optimum capacitor is determined by considering load variations and the interaction between the capacitor and harmonics. In order to verify the efficiency of the proposed algorithm, a simple network simulation and numerical study was performed, and three different arrangements of the capacitor bank were compared with each other. For the first state, the capacitor bank was chosen as a constant capacitor, only based on the consumed reactive power. For the second state, the capacitor bank was calculated by including the effect of the harmonics and excluding the effect of load variation. For the third state, the capacitor bank was calculated by including the effect of load variation and excluding the effect of harmonics. Finally, for the last state, the effect of both load variation and harmonics was considered.

The results of this study show that, by changing the steps of the capacitor bank in relation to load variation, the proposed algorithm enables us to determine the optimum capacitance and arrangement of the capacitor bank in such a way that minimum reduction in capacitor lifetime and maximum benefit is obtained. Additionally, ignoring the effect of load variation and harmonics in the process of designing the capacitor causes the designed capacitor to move away from the optimum point.

6. LIST OF ABBREVIATIONS AND SYMBOLS

6.1. Symbols

L	The harmonic-induced lifetime
b	The constant for the material
T_0	The room temperature
T	The absolute temperature
n and B	Constant values
E	The applied electric stress
E_0	The electric stress below which electrical aging ceases
L_0	Life at $E<E_0$ and room temperature T_0
V_h	The voltage harmonic component peak
R_h	The internal resistance of the capacitor at referenced frequency
I_h	The current harmonic component passing throw the capacitor
Q	The heat generated in the capacitor in Joules

m	The mass in grams
c	The specific heat capacity in J/gr.K
ΔT	The temperature rise
I_h	The harmonic current passing through the capacitor
I_{nom}	The nominal current of the capacitor
T_0	The operating temperature of the capacitor in nominal current conditions
N_{SW}	The number of switchings within the specified load profile where a specified number of switchings are done
L_0/SW	The magnitude of lifetime reduction induced by each switching
SW	The number of permissible switchings
D	is the duration in hours of the load profile
B_P	The monthly financial gain from saving reactive power penalties
C_C	The cost of capacitor installation and maintenance
n_c	Capacitor lifetime calculated from
B_T	Yearly financial gain
C_{lc}	The coefficient related to the costs of purchasing each kVAR of reactive power
C_{RC}	The coefficient related to the annual costs of installing and maintaining the capacitor
i	The annual interest rate
Q_C	The capacity of the installed capacitor
A_i	The number of capacitor steps
k_i.	The capacitance of capacitor steps

6.2. Abbreviations

OF	Objective function

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