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OPTIMUM SHUNT CAPACITOR FOR POWER FACTOR COMPENSATION IN THE PRESENCE OF HARMONICS

" القيمة المثلى لمكثف القوى لتحسين معامل القدرة في وجود التوافقيات "

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الخلاصة : ان وجود الأحمال الغير خطية فى نظم القوى الكهربية ينشأ عنها توافقيات فى كل من موجات التيار والجهد المغذية لهذه الأحمال. ونظرا لأن تصميم مكثفات القوى المستخدمة لتحسين معامل القدرة لهذه الأحمال كان يعتمد أساسا على فرضية أن الجهد والتيار موجات جيبية ، بالتالى فان معامل القدرة لهذه الأحمال سوف يتأثر بوجود التوافقيات ، بالاضافة الى امكانية حدوث رنين كهربى بين مكثف القوى المستخدم ونظام القوى الكهربى مما قد ينتج عنه انهيار لهذا المكثف وكذلك معدات النظام الكهربى.

لذا فان البحث يقدم طريقة مستحدثه و مباشرة لتعيين القيمة المثلى لمكثف القوى المستخدم لتحسين معامل القدرة لحمل فى وجود التوافقيات مع تجنب حدوث رنين كهربى او ارتفاع فى الجهد عند هذا الحمل. وشمل هذا البحث ايضا دراسة تاثير كل من مستوى التشوه للتوافقيات وتغير مستوى الحمل ومستوى القصر عند مركز هذا الحمل على القيمه المثلى لمكثفات القوى وكذلك على قيم ترددا ت التوافقيات المسببة لحدوث رنين بالنظام الكهربى وذلك من خلال تطبيق هذه الطريقه على نظام شبكة التوزيع الفعلية لمصنع الغزل والنسيج بمدينة المنصورة

Abstract. Power consumers require both reliable service and acceptable voltage profile. The presence of nonlinear loads in a power system generate harmonics which affect, in particular, the shape and magnitude of the supplied voltage. Classical design of capacitors for power factor compensation has been based on the fundamental frequency analysis. However, in the presence of harmonics and distortion, the compensated power factor is generally worse. Additionally, according to the short circuit capacity at the load bus, the calculated capacitor value could result in harmonic resonant conditions.

A direct search technique known as Fibonacci Method [11] has been employed to determine the optimum capacitor bank size, and at the same time avoiding harmonic resonance in a power system with harmonic distortion. The method takes into account the effect of time variation of harmonic distortion, load level and short circuit impedance at load bus on the optimal solution. The proposed method has been illustrated through some actual cases of industrial loads existing in an Egyptian distribution network. The results highlighting the influence of harmonic distortion level, load level, and short circuit impedance have also been discussed in this paper.

1. INTRODUCTION

Modern industrial processes place high demands on electric power supply quality. Voltage fluctuations, voltage interruptions as well as harmonic distortion all create stress on electric equipment and are often unacceptable as they cause deterioration of the proper functioning and thereby the economy of the process in question. Nonlinear devices inject harmonic currents into the system. The system impedance versus frequency characteristic determine the harmonic voltage distortion levels.

The use of shunt capacitors for power factor compensation may be more exposed to the effect of harmonic currents flowing in the electrical system, with the possibility of thermal over loading and increased voltage stress. Furthermore, the possibility of resonance or near resonance occurring must not be over looked . High harmonic voltage occur under such conditions may cause current and voltage over loading, which in extreme cases up to ten times greater than the nominal values [1].

Conventional methods for optimal power factor compensation neglect the effect of harmonics and employ only the fundamental frequency analysis. In fact, harmonic distortion has an effect on the value of power factor [2]. Also, shunt capacitors can offer only a partial power factor compensation. The total compensation can be achieved only through highly sophisticated active devices which are far from being economical [3,4].

The concept of using a linear shunt capacitors was the source of motivation for a number of studies dedicated to the task of identifying the optimum value of capacitor for power factor compensation in a power system with non-sinusoidal voltages and currents. In [5], an expression is given to the value of optimum capacitance resulting in maximum power factor operation under the assumption of constant voltages, currents and impedances. A recent studies [6,7,8,9] has improved the model given in [5], by taking into account the short circuit impedance of the system at load bus, but not taken into consideration any constraint on the harmonic resonance conditions. Under this assumption, the implementation of optimum capacitor value calculated will result in resonance or near resonance condition. High harmonic voltages occur under such conditions may give rise of the current in the shunt capacitor to the damage limit.

This paper presents a direct novel technique to determine the optimum shunt capacitor for power factor compensation and at the same time avoiding harmonic resonance. The method take into account the effect of time variation of harmonic distortion, load level, and short circuit impedance at load bus in the compensated system on the optimal solution.

2. FORMULATION OF MATHEMATICAL MODELS

In a power system with harmonic distortion, the definition of power factor as cosine of the displacement between the voltage and the current at fundamental frequency is not true. The true power factor is best described as the ratio of the active power to the apparent power as in [2].

2.1 Objective Function

The objective in solving the optimum capacitor bank size for power factor compensation in a power system with harmonic distortion, is considered here as minimizing the total line power loss. Considering the schematic diagram and the equivalent circuit given in fig.1. The harmonic source is assumed to be a generator of harmonic current $I^{(h)}$ which can be calculated as in [10], or determined by measurement. The harmonic current is divided between the capacitor $I_c^{(h)}$ and the supply $I_s^{(h)}$ ($Z_l >> Z_{sc}$).

The total r.m.s line current is composed from fundamental component $I_s^{(1)}$, and harmonic components $I_s^{(h)}$. The fundamental component is due to the power source, where the harmonic components are due to the harmonic source.

$$I_s^{(1)} = [\, I_a^2 + (I_r - I_c)^2 \,]^{1/2} \tag{1}$$

or,

$$I_s^{(1)} = [(P/V)^2 + ((Q/V) - \omega C V)^2]^{1/2} \tag{2}$$

and

$$I_s^{(h)} = \frac{X_c^{(h)}}{X_c^{(h)} + Z_{sc}^{(h)}} I^{(h)} \quad ,h = 2,3, \quad ,H \tag{3}$$

$$X_c^{(h)} = 1/(jh\,\omega\, C) \tag{4}$$

$$Z_{sc}^{(h)} = R_{sc} + j\, X_{sc}^{(h)} \tag{5}$$

or,

$$I_s^{(h)} = \sum_{h=2}^{H} \frac{I^{(h)}}{[(1-h\,\omega\, C\, X_{sc}^{(h)})^2 + (h\,\omega\, C\, R_{sc})^2]^{1/2}} \tag{6}$$

where,

- I_a , I_r : load active and reactive current at fundamental.
- P, Q : load active and reactive power per phase.
- V : load voltage at fundamental frequency.
- I_c : capacitor current at fundamental frequency.
- $Z_{sc}^{(h)}$: short circuit impedance at load bus.
- $X_c^{(h)}$: capacitive reactance of shunt capacitor.
- ω : fundamental frequency.
- C : capacitance of shunt capacitor.
- h : harmonic order.
- H : highest harmonic order of interest.

Equations (2) and (6) provide the r.m.s values of line current at fundamental and harmonic frequencies. The total line power loss is given by:

$$P_L = (I_s^{2(1)} + I_s^{2(h)})\, R_{sc} \tag{7}$$

or

$$P_L = R_{sc}\, \{(P/V)^2 + ((Q/V) - \omega C V)^2\} + R_{sc} \{ \sum_{h=2}^{H} \frac{I^{2(h)}}{(1 - h\,\omega\, C\, X_{sc}^{(h)})^2 + (h\,\omega\, C\, R_{sc})^2} \} \tag{8}$$

The objective function (8) is a function of the following parameters:

- *Short circuit level at load bus or, system configuration.*
- *Load level (P , Q).*
- *distortion level ($I^{(h)}$) .*

- *Size of capacitor banks installed.*

At certain levels of load, distortion, and short circuit, the objective function is only determined by the capacitor bank size (C). So, equation (8) can be rewritten as

$$P_L = \sum_{h=1}^{H} f^{(h)}(C) \qquad (9)$$

2.2 System Constraints

The distribution system must regulate the voltage at which power is delivered to users within certain prescribed limits as load demand varies. The capacitor banks size which can lead to voltage rise problem or leading power factor , and resonance conditions are considered here as system constraints.

2.2.1 Leading Power Factor constraint

The minimum capacitor value can be chosen as a standard minimum bank size available. And to avoid leading power factor problem , the capacitor bank size must be upper bonded . This can be stated as,

$$C < C_{max}. \qquad (10)$$

where, C_{max} is the maximum capacitor size which cause a leading power factor at certain level of load.

2.2.2 Resonance constraint

When power factor compensation capacitor is installed, there is always a risk of harmonic resonance between the capacitor and inductive parts of the network impedance at one or more frequencies. Harmonics injected into the system at coincident frequencies will be amplified and produces extreme voltage difference across all circuit elements. These high voltages can blow fuses, causing failure of capacitors due to the increased voltage stress and overheating. The equivalent circuit in fig.1.b is redrawn as shown in fig.2.

The driving point impedance $Zd^{(h)}$ as seen by harmonic source for the circuit shown in fig.2 is given by:

$$Zd^{(h)} = Rl + \frac{Gsc^{(h)}}{Gsc^{2(h)} + (Bsc^{(h)} - h\,\omega\,C)^2}$$

$$+ j\left(Xl^{(h)} + \frac{(Bsc^{(h)} - h\,\omega\,C)}{Gsc^{2(h)} + (Bsc^{(h)} - h\,\omega\,C)^2}\right) \qquad (11)$$

where,

$$Gsc^{(h)} = \frac{Rsc}{R^2_{sc} + X^{2(h)}_{sc}} \qquad (12)$$

$$Bsc^{(h)} = \frac{Xsc^{(h)}}{R^2_{sc} + X^{2(h)}_{sc}} \qquad (13)$$

The harmonic resonance condition will occur if,

$$Xl^{(h)} = \frac{h\,\omega\,C - Bsc^{(h)}}{Gsc^{2(h)} + (Bsc^{(h)} - h\,\omega\,C)^2} \qquad (14)$$

Arranging equation (14), yields

$$A^{(h)}\,C^2 + D^{(h)}\,C + E^{(h)} = 0.0 \qquad (15)$$

where,

$$A^{(h)} = h^2\,\omega^2\,Xsc^{(h)} \qquad (16)$$

$$D^{(h)} = -h\,\omega\,(1 + 2\,Xl^{(h)} .\, Bsc^{(h)}) \qquad (17)$$

$$E^{(h)} = Xl^{(h)}\,(Gsc^{2(h)} + Bsc^{2(h)}) + Bsc^{(h)} \qquad (18)$$

The solution of equation (15) gives the values of capacitor bank size $Cr^{(h)}$ at each harmonic order, which will result in harmonic resonance conditions. This constraint can be stated as,

$$C \neq Cr^{(h)} \qquad (19)$$

3. DESCRIPTION OF THE SOLUTION ALGORITHM

The objective function to be optimized here is a one variable non-linear convex constrained function. So, the solution of objective function to determine the optimum capacitor size and achieving the system constraints in a power system with harmonic distortion, can be obtained using one of direct search techniques. A direct search technique known as the Fibonacci Method has been employed for solving the problem.

The Fibonacci search algorithm for minimizing the objective function given in equation (9) can be explained as:

1- Designate the original search interval as L_1 with boundaries $C_{min} < C < C_{max}$, where C_{min} is the minimum standard capacitor size available, and C_{max}, is the maximum size of capacitor bank limited by a leading power factor as in equation (10).

2- Introduce the first two points, C_1 and C_2 ($C_1 < C_2$) within L_1, and evaluate the objective function at C_1 and C_2 as $F(C_1)$ and $F(C_2)$.

3- Narrow the search interval as follows

$$C_{min} < C^* < C_2 \qquad \text{for} \qquad F(C_1) < F(C_2)$$

$$C_1 < C^* < C_{max} \qquad \text{for} \qquad F(C_1) > F(C_2)$$

where C^* is the location of the optimum.

4- Determine the new search interval L_2 with lower and upper boundaries , and place the third point C_3 in the new subinterval, symmetric about the remaining point.

5- Evaluate the objective function at C_3 as $F(C_3)$ and compare with the function for the point remaining in the interval and reduce the interval to L_3.

6- The process is continued per the preceding rules for N evaluations, and the interval where the optimum is located is thus determined.

4. APPLICATION

4.1 Case Study

The proposed technique described in this paper has been applied to a case study shown in fig.3. The case study is an actual distribution system which feeds an industrial load in Dakahlia Textile Company located in Mansoura city. The power system of the plant consists of a main sectionalized 11 KV switchboard. Each section supplies a different load centers. In this case study one load center is chosen and supplied at low voltage from 3 step down transformers each rated at 1000 KVA and 11 /0.4 KV.

The following measurements are recorded hourly during one week on low voltage side:

. Active and reactive power.
. Three phase currents.
. Power factor.
. Harmonic contents up to 39th harmonic order for the current and voltage waveforms.

For this load center, the variation of required active and reactive power with time were very low. Also, the three phase currents were very balanced throughout the measuring period. Table 1 illustrates the average values of active and reactive power, power factor, and the essential harmonic contents for current and voltage waveforms.

Table 1 Average values of recorded data

h	3	5	7	9	11	13
% V	0.33	1.36	0.5	0.0	0.06	0.05
% I	6.6	2.1	0.4	0.3	0.3	0.2
P			1.06 MW			
Q			1.41 MVAR			
Power factor			0.6 lag.			

4.2. Results and Discussions

The proposed method was applied to the case study in fig.3. Table 2 illustrates the results obtained such as, optimal capacitor size, fundamental power factor and actual power factor. Table 3 gives the resonance conditions under harmonic distortion.

Table 2 Optimal results obtained by the proposed method.

$C_{opt.}$ (F)	0.02255
Fundamental power factor	0.9374
Actual power factor	0.9127

Table 3 Resonance conditions.

h_r	C_r (F)	I_s (p.u.)
5	0.0158	1.272

Figure 4 shows the variation of line current I_s in p.u. versus capacitor size C (mF). The figure also indicates the range in capacitor size at which harmonic resonance will occur.

To highlight the effect of distortion level on the optimal solution, different levels of distortions are used where the results are tabulated in tables 4 and 5. The optimal capacitor size and the value of capacitor size which will result in harmonic resonance does not effect as the distortion level is increased. Where as, the load power factor is worse and the line current is highly amplified.

Table 4 Effect of distortion level on optimal results.

h	3	5	7	9	11	13
% V	0.5	2.0	0.7	0.0	0.08	0.06
% I	10.0	4.0	0.8	0.6	0.6	0.4
Copt.(F)				0.02255		
Fundamental power factor				0.9374		
Actual power factor				0.8721		

Table 5 Effect of distortion level on resonance conditions.

h_r	C_r (F)	I_s (p.u.)
5	0.0158	2.59

Table 6 illustrates the effect of change in the infeed network configuration on the optimal solution and resonance condition. In case of high values of MVA_{sc} at load bus, the capacitor size C_r which will result in resonance is also high and out of operating range due to leading power factor constraint. For lower values of MVA_{sc}, the harmonic order h_r which will result in resonance is lowered with high amplification in line current.

Table 6 Effect of change in system configuration on the optimal solution and resonance conditions.

MVA_{sc}	$C_{opt.}$ (F)	h_r	C_r (F)	I_s (p.u.)
30	0.02236	does	not	exist
25	0.01885	5	0.0219	1.233
18*	0.02255	5	0.0158	1.272
10	0.01777	5	0.0087	1.339
5	0.02236	3	0.0120	2.057

* Base Case.

Table 7 shows the effect of varying load level on the optimal solution and harmonic resonance conditions. The optimal capacitor size $C_{opt.}$ is more pronounced, where as the resonance conditions are slightly affected. This is because, the load impedance is more higher as compared with the short circuit impedance at load bus.

Table 7 Effect of varying load level on the optimal solution.

% of load level	$C_{opt.}$ (F)	h_r	C_r(F)	I_s(p.u.)
150	0.03136	5	0.01578	1.314
120	0.02543	5	0.01557	1.288
100*	0.02255	5	0.01588	1.272
80	0.01359	5	0.01578	1.238

* Base Case

5. CONCLUSIONS

The main conclusions of this paper are summarized as follows:

- The harmonic resonance conditions (C_r and h_r) can be easily calculated in electric power system without need to multiple harmonic power flow analysis. So, the proposed method can be successfully used as a good and faster tool to predict harmonic resonance conditions in a power system.
- The line current is highly amplified to extreme value and the power factor is generally worse as distortion level increase.
- The variation of harmonic distortion has an insignificant effect on the optimal capacitor size and also on the capacitor size which will result in harmonic resonance.

- The system configuration is strongly affect the optimum capacitor size and resonance conditions. Therefore, the representation of system equivalent at load bus by an ideal source is not true.
- The results shows that the proposed method has fewer steps towards a convergence, good accuracy ,and more efficient.

6. REFERENCES

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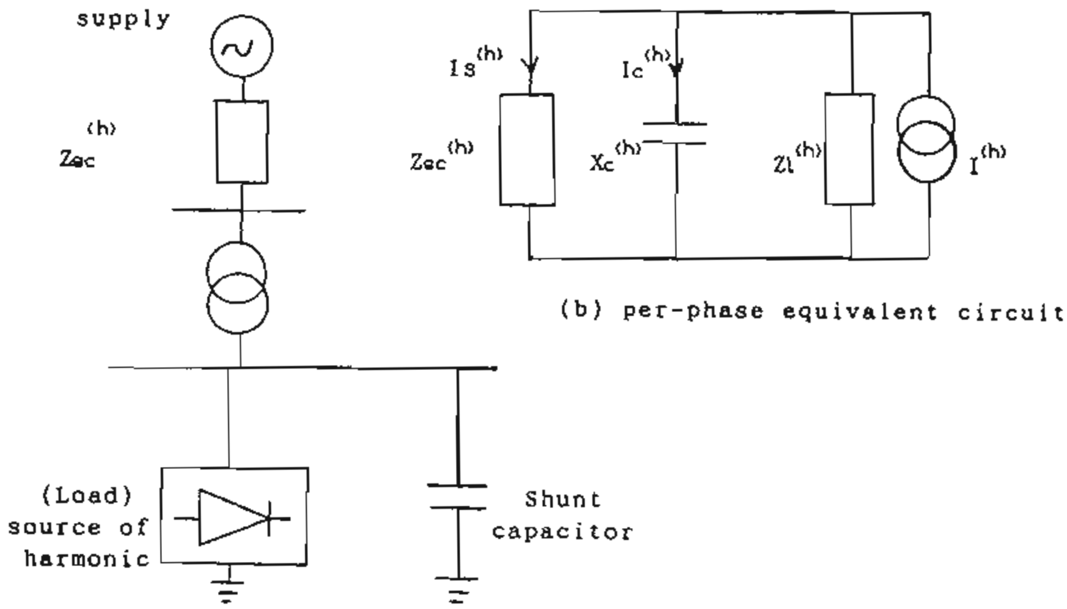

(b) per-phase equivalent circuit

(a) one-line diagram of system with source of harmonic

Fig.1

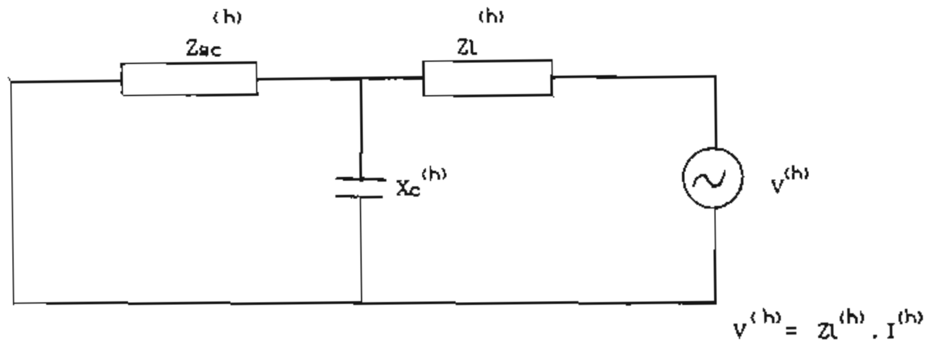

Fig.2 System equivalent circuit

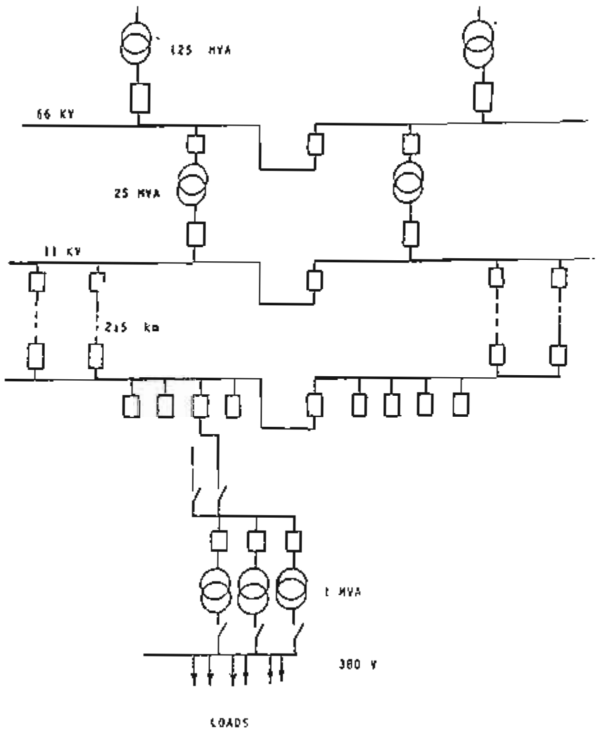

Fig. 3 Single line diagram of case study.

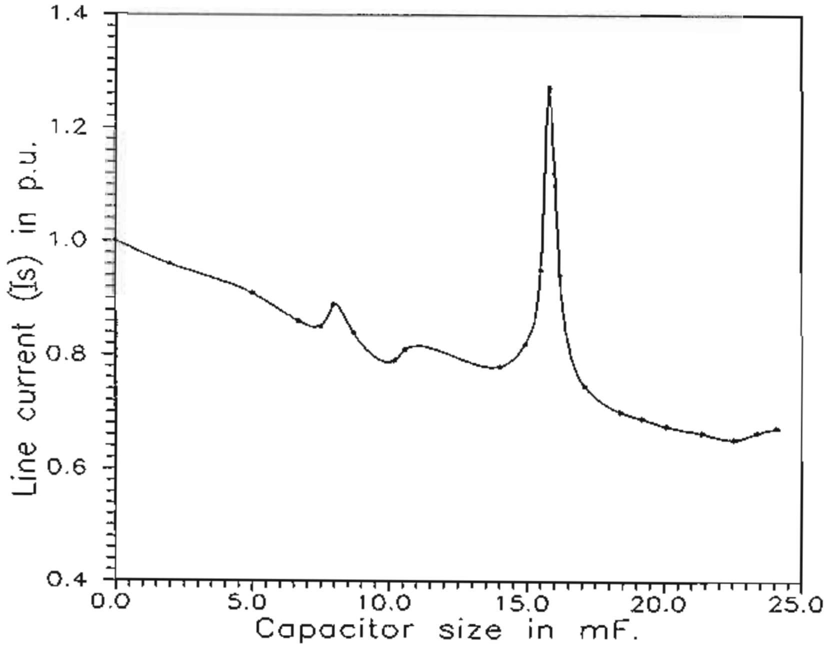

Fig.(4) Variation of line current with capacitor size.