OPTIMAL SHUNT COMPENSATORS FOR DEMAND-SIDE MANAGEMENT OF INDUSTRIAL LOADS IN NON SINUSOIDAL SYSTEMS

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ABSTRACT

Industrial end users often use capacitors to improve the power factor and thus reduce the power factor penalty charged by the utility. Unfortunately, the influence of shunt capacitors on harmonics could affect the quality of power supply in the industrial loads and provide a disincentive for the industrial end users to install power factor improvement capacitors. This paper presents the solution for calculating the optimal shunt capacitor compensators under the constraints of the power quality impacts of demand-side management technologies. The method is based on the voltage distortion at the utility supply bus and applied for both the linear and the non-linear load models.

Keywords: Reactive power compensation , Harmonics , Non-linear load model, Industrial consumers .

1. INTRODUCTION

The use of capacitors to improve power factor is well-documented and cost-effective means of reducing demand and system losses. Industrial loads in general are inductive and have poor power factors. For major industries, power is supplied by the utility at high voltage. In effect these loads imposed higher MVAR demands on the utility system and thus a penalty charge is passed through to industrial end users by the retail utility. Utilities routinely employ capacitors on transmission and distribution systems. However, for demand-side management (DSM) purposes, it is better to locate the power factor compensators within the industrial side rather than on the utility transmission and distribution systems. Unfortunately, many industrial consumers have serious problems with capacitor installation because of interactions with harmonic distortion from the "polluted" power network. There is a great tendency for harmful resonances than in utility distribution systems where the damping is relatively high for capacitors located on feeders. The capacitors themselves may be damaged or the resulting voltage distortion may make it impossible to operate some process equipment. Therefore , it is prudent to perform the proper calculatios for sizing shunt capacitors before they are implemented to avoid capacitor values that cause resonance at a significant harmonic frequency .

Optimization of shunt capacitor planning for nonsinusoidal systems has received considerable attention[1-5] . While references [1-2] have concentrated on the selection of an optimum capacitor size for DSM purposes ,references [3-5] have developed their techniques for the optimal location and size of compensation for distribution systems with harmonic distortion. Ronnie et. al. [1] assumed linear load model and used a non-linear optimization technique to solve the objective functions for the line losses, power factor and the transmission efficiency independently. El-Amin et. al. [2] have modified the method of [1] by using a penalty function approach to minimize the line losses while power factor and transmission efficiency are included as inequality constraints for both linear and non-linear load models Although Baghzouz et. al. [4] have included the harmonic effects for the shunt capacitor placement problem ,they assigned designated locations of the capacitors according to the judgement of system operators. In [5] the location of shunt capacitors are found by considering the sensitivity of voltage variation, real power loss and harmonic distortion to the reactive power. In this paper ,the optimum sizing of shunt capacitor compensators at industrial end users, fed from slightly distorted bus voltage ,are found by considering the economic feasibility of power factor correction . The power quality impacts of DSM is taken into consideration during the optimization procedure so as to avoid customer dissatisfaction with DSM and expensive retrofitting corrective equipements .

2. NOMENCLATURE

C_p : the cost of per unit power loss ($/kw-year)

C_e : the cost of per unit energy loss($/kwh)

C_r : the annual cost of per unit fixed type capacitor($/kvar-year)

$\cos\varphi_o$: the uncompensated load P.F.

G_L, B_L : the shunt conductance and susceptance of linear load simulation model (mho)

h : harmonic order (h=1,2,3,..n)

I_{sh} : the r.m.s supply current at significant harmonic frequency (KA)

I_s : the r.m.s supply current (kA)

I_{ch} : the r.m.s capacitor charging current (KA)

L.F : the load factor

P_{50}, Q_{50} : the uncompensated active MW, and reactive MVAR at 50 Hz fundamental frequency .

P.F : the compensated load power factor .

P^{pk}_{loss} : the peak power loss(kw)

R_{Th} : the total resistance from source to load bus at any significant frequency (ohm)

S_o : the uncompensated total load MVA apparent power

S_{50} : the uncompensated load MVA apparent power at 50 Hz fundamental frequency .

S_{c50} : the compensated load MVA apparent power at 50 Hz fundamental frequency

S_c, P_L : the compensated load MVA apparent power and MW active power ;respectively

x : the compensation factor (p.u)

X_T : the total reactance from source to load bus (ohm)

V : the line-to-line nominal supply voltage (KV)

V_{sh}, V_{Lh} : the line-to-line r.m.s supply and load voltages at significant harmonic frequency (KV)

V_L : the r.m.s line to neutral load voltage (KV)

3-PROBLEM DESCRIPTION AND FORMULATION

Figure (1) shows the equivalent circuit of a compensated linear load simulating model of a major industrial load fed from a slightly distored substation bus via a transmission line.

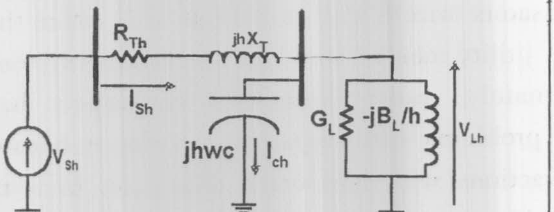

Fig.1 Nonsinusoidal source feeding a compensated linear load
$G_L=P_{50}/V^2, B_L=Q_{50}/V^2, wc=xBL$

For the simulated equivalent circuit shown in fig 1, the following relations at full load condition hold

$$V_{Lh} = \frac{V_{Sh}}{(A_{1h}^2 + A_{2h}^2)^{0.5}} \quad (1)$$

Where

$A_{1h} = 1 + R_{Th}G_L - B_L X_T(h^2x-1)$

$A_{2h} = hX_TG_L + R_{Th}B_L(hx-1/h)$

$$V_L = \left(\frac{V^2}{3} + \sum_{h=2}^{n} V_{Lh}^2\right)^{0.5} \quad (2)$$

$$I_s = \left(\sum_{h=1}^{n} I_{sh}^2\right)^{0.5} = \left(\frac{P_{50}^2 + (x-1)Q_{50}^2}{3V^2} + \sum_{h=2}^{n} \frac{G_L^2 + B_L^2(hx - \frac{1}{h})^2}{A_{1h}^2 + A_{2h}^2}\right)^{0.5} \quad (3)$$

$$S_c = 3V_LI_s{*}10^3 \quad (4)$$

$$P_{loss}^{pk} = \sum_{h=1}^{n} P_{lh}^{pk} = 3R_{Th}.10^3\left(\frac{S_{50}}{S_{c50}}\right)\sum_{h=1}^{n} I_{sh}^2 \quad (5)$$

$$P_L = P_{50} + \sum_{h=2}^{n} G_L V_{Lh}^2 \quad (6)$$

$$P.F = P_L/S_c \quad (7)$$

$$I_{ch} = V_{Lh}hxB_L \quad (8)$$

Assuming that the choice of the cross sectional areas of the transmission elements is based on certain prespecified values for the current densities in the transformer windings and line conductors ,then the total resistance R_{th} in eqn.5 will increase by the factor(S_{50}/S_{C50});where S_{50} and S_{C50} are the load MVA apparent power for the uncompensated and the compensated systems, at fundamental frequency, respectively.

3.1 Development of objective function:

Using the above relations , the different annual utility cost saving items achieved by reactive power DSM can be derived as follows :

1-The annual saving in the cost of investment of transformer and transmission line is

$$F_1(x) = A_oA_c(S_o - S_c) \quad (9)$$

where ($A_o=C_T+C_l l$) is the initial capital cost of the transformer (C_T in \$/kVA) and the transmission line (C_l is in \$/ kVA/km)and l is the line length in Km. A_c is the initial annual cost in p.u. of the initial investment which includes the cost of the capital, annual operation and maintenance cost, income tax rate and the depreciation rate [6] .

2-The annual saving in the cost component required to increase the power system generating capacity by an amount of power equal to the peak power loss is

$$F_2(x) = C_p(P_{loss_o}^{pk} - P_{loss}^{pk}) \quad (10)$$

where $P_{loss_o}^{pk}$ is the peak power loss without compensation and can be obtained from eqn.5 at x=0

3-The annual saving in the cost of energy losses of transformer and transmission line is

$$F_3(x) = C_eT\left(\sum_{h=1}^{n} LSF_{ho}P_{lho}^{pk} - \sum_{h=1}^{n} LSF_h P_{lh}^{pk}\right) \quad (11)$$

where LSF_{ho} and LSF_h are the annual loss factor at h^{th} harmonic (Appedix A) for the uncompensated (at x=0) and the compensated systems; respectively . P_{lho}^{pk} is the full-load uncompensated system power loss at the h^{th} harmonic.T is annual hours (=8760 hours).

4-The annual cost for shunt capacitor compensation is

$$F_4(x) = C_rxQ_{50}.10^3 \quad (12)$$

The above relations can then be used to evaluate the total annual utility cost saving achieved by the shunt compensation as

$$F(x) = F_1(x) + F_2(x) + F_3(x) - F_4(x) \quad (13)$$

3.2 Power factor constraint :

Industrial end users often use capacitors to increase the power factor and thus reduce the power factor penalty charged by the retail utility for cases of power factors below 92% . Also, an upper limit for the power factor should be imposed to avoid the problems associated with over-excitation of the individual corrected induction motors when disconnected from the mains during running condition. If the connections between motor and supply are restored while the motor is over-excited, there is a risk of a violent electrical transient producing mechanical shock. Such types of problems can be reduced much, when using centralized correction installed at the main switchboard busbars. However, world engineering experiences recommend that the augmented power factor at full-loading condition must be limited to 0.97 lagging so as to avoid transient over-voltage problems at no-load or light-load conditions. Thus , the power factor constraint is assumed by the inequality:

$$0.92 < PF(x) < 0.97 \qquad (14)$$

3.3 Assessment the degree of resonance :

The potential of harmonic resonance is judged from the capacitors currents. One harmonic should be dominant and could exceed the fundamental. The degree of resonance can thus be assessed by evaluating the total harmonic distortion (THD) or rms value or the magnitude of individual harmonic capacitor currents[7]. Capacitor failures resulting from harmonic distortion can be attributed to one of the following:

1-The peak voltage causes dielectric breakdown

2-Excessive rms. currents exceeds thermal capabilities

The peak voltage is generally limited by standards to 120%. Table 1 shows the amount of rms capacitor current needed to exceed the 120% voltage rating at few harmonics assuming the fundamental is 100%

Table 1.

h	rms capacitor current
3	116%
5	141%
7	172%
9	205%

The common upper current limit for capacitor fuses is 135% of the rated current. The 135% limit nearly coincides with the value of fifth harmonic that would cause excessive operating peak voltage. The THD value corresponding to the 135% rms current limit is 91% [7].

Now, the power quality impacts of DSM can be represented by the following inequality constraint:

$$THD = \frac{\left(\sum_{h=2}^{n} I_{ch}^{2}\right)^{0.5}}{I_{c1}} \cdot 100 < 91 \qquad (15)$$

3.4 Optimization procedure

Finally, the capacitor sizing problem for DSM of industrial end user is formulated as

$$\max : F(x) \qquad (16)$$

Subjected to

$$0.92 < PF(x) < 0.97$$

$$THD(x) < 91$$

It is proposed to use the penalty function approach for the inequality constraint given in [8] to convert the constrained problem as

$$\min : P(x;\underline{K}) = -F(x) + \sum_{i=1}^{2} k_l [g_i(x)]^2 u_i(g_i) \qquad (17)$$

where

$u_i(g_i)=\{0 \text{ if } g_i(x)\leq 0$

$\{1 \text{ if } g_i(x)>0$

$g_1(x)=0.92-PF(x)$

$g2(x)=PF(x)-0.97$

$g3(x)=THD(x)-91$

The positive constants weighting factors $\underline{K}=[K_1,K_2]^T$ on the objective function represented penalties for not satisfying the constraints.

For certain values of $\underline{K}$,the unconstrained non-linear programming problem eqn.17 can be solved by the parabolic interpolation algorithm of Brent[9]. The algorithm is implemented by the subroutine FMIN which is given in [10]. According to the penalty function method the value of $\underline{K}$ is updated and the process is repeated till convergence.

4.THE USE OF POWER FACTOR COMPENSATOR FOR DSM OF NON-LINEAR LOADS

The effect of nonsinusoidal currents at the non-linear industrial end users is to produce harmonics which cause system disturbances at both source and load terminals,and possibly some neighbouring loads may be affected. Under this condition the harmonic resonance problems are mitigated by converting the power factor shunt capacitor compensator into harmonic filter by adding a reactor in series. The function of the tuning reactor is to form a series resonant branch so that the harmonic current "escaping" into the system is reduced or eliminated .

The non-linear load is represented by a current source injection harmonics $\overline{I_{nh}}$ into the system fig.(2).

The shunt-type filters consist of resonant arms for the 5th,7th,11th,and 13th harmonics and a second order high-pass arm [12]. The R_{fh} and L parameters of the resonant arms are determined ,in terms of the compensation factor x, according the filter design criteria given in [12]. Thus ,the equations of harmonic supply current and the harmonic load voltage must be modified as follows:

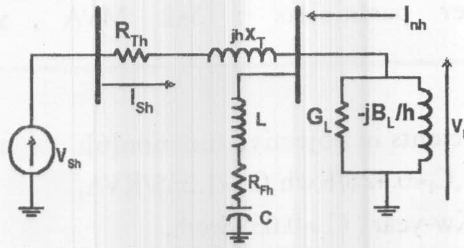

Fig.2 Nonsinusoidal supply feeding a compensated nonlinear load

$$\overline{I_{sh}} = \frac{\overline{V_{sh}}\ \overline{Y}}{1+\overline{Z_{Th}}\ \overline{Y}} - \frac{\overline{I_{nh}}R_{Fh}}{R_{Fh}+\overline{Z_{Th}}} \quad ....(18)$$

$$\overline{V_{Lh}} = \frac{\overline{V_{sh}}}{1+\overline{Z_{Th}}\ \overline{Y}} - \frac{\overline{I_{nh}}R_{Fh}\overline{Z_{Th}}}{R_{Fh}+\overline{Z_{Th}}} \quad .....(19)$$

where $\overline{Z_{Th}}=R_{Th}+jhx_T$

$\overline{Y}=(1/R_{Fh})+G_L-j(B_L/h)$

The annual cost function F(x) in eqn.(13) must be modified to include the annual cost F_5 for the shunt-type filter inductances as :

$$F(x)=F_1(x)+F_2(x)+F_3(x)-F_4(x)-F_5(x) \quad (20)$$

where the annual cost of the inductances can be estimated as given [6].

5. CASE STUDIES AND RESULTS

Two examples, as case studies, are presented. The first is a case with linear industrial load fed from a nonsinusoidal utility bus . The second illustrates a case where the harmonic "pollution" is caused by both the utility and the non-linear industrial end user [11,15]. The following relevant numerical data are assumed :

Utility: MVA_{sc}=500 , V=11.55KV
Load : P_{50}=4MW ,$\cos\Phi_o$=0.8(lag.), L.F=1
Overhead line parameters :
l=3KM,R=1.159Ω/Km ,x=0.98Ω/Km

Transformer parameters : 3x2 MVA , x=6% ,X/R=9.75

Cost coefficients in objective function[6]:
A_c=26.03%,C_l=0.42$/Kwh,$C_T$=1.25$/KVA,
C_p=130 $/Kw-year , C_e=0.03$/kwh,
C_r= 1.3$/KVAR-year.

A main cause of utility harmonic distortion are the power converters used in adjustable-speed drives converters in rolling mills, printing works, electrolytic plants as well as in uninterruptible power supplies and in many systems on board vehicles . An approach to predicting harmonic problems with capacitor application when the appropriate voltage and current distortion measurements are not available is to assume that such types of non-linear loads would produce high-typical main bus distortion according to national or international standard limits. Accurate models of the resistance of the power delivery, transformer and transmission line at a significant harmonic frequency are used as given in [12] to yield more realistic estimates of the actual r.m.s current by properly including damping effects .

Case1 : The optimisation technique is supplied on a linear load model supplied from a voltage distorted utility bus with 8% THD of voltage (IEC standared 1000-2-2 1990). The results are summarised in Table 2.

It can be concluded that the propagation of harmonic currents through the system results in a degardation of the compensated power factor , increasing the transmission line losses and hence decreasing the optimum annual cost saving .

Case2 : Figure 2 shows the one-line diagram of case 2 . The non-linear load is represented by a current source $\overline{I_{nh}}$ injecting harmonic current with 10% THD of current (IEEE standard 519-1981) .The results are summarized in Table 2 and the complete circuit diagram is shown in Fig.3

It can be concluded that the mitigated harmonic currents through the use of shunt-type filter result in increasing both the compensated power factor and the optimum anual cost saving.

To illustrate the effects of the utility voltage distortion and the nonlinearity of the load on the optimum solution ,the results of the theoretical unconstrained optimum solution [13] as well as the constrained solution using sinusoidal voltage source with linear load models are included in Table 2

Table 2

Condition of circuit	Optimum compensation x-factor	Annual saving in $*10³	Compensated P.F	%THD of charging current
Theortical unconstrained optimum solution [13]	0.925	30	0.998	-
Constrained solution using sinusoidal voltage source with linear load	0.65	25.5	0.97	-
Case 1	0.55	12.45	0.95	52.9
Case 2	0.72	21.18	0.97	43

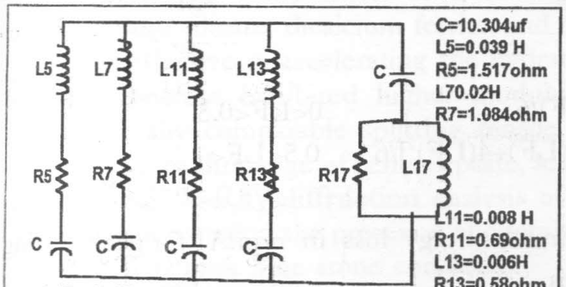

Fig.3 The filter design of the non-linear load model

6. CONCLUSION

In this paper, a method has been developed to determine the optimal size of the shunt capacitor compensators to be installed within the industrial consumer facilities when fed from nonsinusoidal utility busbars. The method is based on maximising the annual utility cost saving items under the constraints of the power impacts of the DSM technologies. The choice of the capacitor values (or the compensation factor) is constrained by the values that cause capacitor failure resulting from harmonic distortion . The use of capacitor r.m.s values is more accurate in predicting the resonance condition than simple resonance frequency checks. Two case studies including linear and non-linear industrial load modelds are selected to verify the effectiveness of the proposed method . It is concluded that the method presented is more accurate in predicting harmonic characteristics of new industrial installations and harmonic mitigation is accomplished at the least cost.

7. REFERENCES

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Appendix A

The annual energy loss of the compensated system at a significant harmonic frequency is given by

$$E_{lh} = \int_0^T P_{lh}(t)dt = \int_0^T 3I_{sh}^2(t)R_{Th}dt$$

$$= 3R_{Th}\int_0^T[(\frac{P(t)}{V^2})^2 + (hx\frac{Q_{50}}{V^2} - \frac{Q(t)}{hV^2})]V_{Lh}^2dt$$

$$= (\frac{3R_{Th}V_{Lh}^2}{V^4})[(1+\frac{\tan^2\Phi_o}{h^2})TP_{rms}^2 + (hxP_{50}\tan\Phi_0)^2T -$$

$$2xP_{50}\tan^2\Phi_0(LF)P_{50}T] \qquad \text{(A1)}$$

where

$$P_{rms} = (\frac{1}{T}\int_0^T P^2(t)dt)^{0.5}$$

is the effective value of the load active power demand ,assumed $=\lambda P_{50}$. The following approximate relations between the load factor and λ^2 are derived in [11]

$$\lambda^2 = 5(LF)/6 \qquad 0<LF<0.5$$

$$= [1+(LF)+4(LF)^2]/6 \qquad 0.5<LF<1$$

The annual energy loss in eqn.A1 for peak loading becomes

$$E_{lh}^{pk} = (\frac{3R_{Th}V_{Lh}^2}{V^4})[(1+\frac{\tan^2\Phi_o}{h^2})TP_{50}^2 +$$

$$(hxP_{50}\tan\Phi_0)^2T - 2xP_{50}^2\tan^2\Phi_0T] \qquad \text{(A2)}$$

The annual loss factor for the compensated system at a significant harmonic frequency is defined as

$$LSF_h = \frac{E_{lh}}{E_{lh}^{pq}}$$

$$= \frac{\lambda^2 + (h^2x^2 - 2x(LF))(\frac{\tan^2\Phi_o}{1+\frac{\tan^2\Phi_o}{h^2}})}{1+(h^2x^2 - 2x)(\frac{\tan^2\Phi_o}{1+\frac{\tan^2\Phi_o}{h^2}})} \qquad \text{(A3)}$$