

# Sizing of capacitors to optimize the power factor at non-sinusoidal frequencies

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Received 13 May 2002; received in revised form 13 May 2002; accepted 8 July 2002

## Abstract

Optimization criteria are presented which allows proper calculation of optimal power factor. Optimization minimizes the line loss, maximizes the power factor and maximizes the efficiency taking into consideration the skin effect. The performance of the obtained capacitor is discussed by means of numerical example.

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*Keywords:* Network harmonics; Power factor compensation and conditioning; Optimization techniques

## 1. Introduction

It is well known that an inductive load in a power system causes higher loss and a higher voltage drop in the lines than would be the case for a resistive load requiring the same active power. Consider the system shown in Fig. 1. The power system delivers electrical energy to the load that is assumed to have a non-unity power factor. The purpose of the shunt capacitor is to increase the power factor of the load and hence to reduce the transmission line current and the transmission loss. If the voltages and the currents are sinusoidal, straight forward techniques exist to compute the capacitance which yields a desired power factor improvement; the optimal capacitance is such that it exactly generates the reactive power required by the load; then non-reactive power is to be supplied by the power system [1,2].

However, owing to the increasing use of semiconductor devices, voltage harmonics are generated in the power system. The question arises how power factor correction and optimization should then be designed. Note that even the definition of reactive power is not clear for distorted voltages [3]. Power factor correction

is an important topic since voltage distortion generally causes low power factor operation.

In conventional methods for the design of the compensating capacitor, the voltage harmonics are neglected and the capacitor which would be optimal in the sinusoidal steady state is also used in the distorted state. As is shown in some papers [3,4], this may lead to poor power factor operation. Kusters and Moore [3] compute the optimal capacitance by neglecting the source and transmission line impedance; it is shown by Chu and Avendano [4] that this impedance may have a non-negligible effect on the power factor correction. Chu and Avendano [4] and Saleh and Emanuel [5] take into account the voltage distortion as well as the source impedance (source impedance and transmission line impedance are used interchangeably in the sequel). However, they do not distinguish power factor maximization and line current minimization. It was proved that the optimal capacitance derived by Chu and Avendano does not correspond to optimal power factor operation.

The important question is that what wanted to be achieved by the use of a shunt capacitor at the load, and hence which criterion should be considered to determine its optimality. The purpose of the shunt capacitor is to generate capacitive reactive power which (completely or partially) compensates the inductive reactive power required by the load. This yields an increased power

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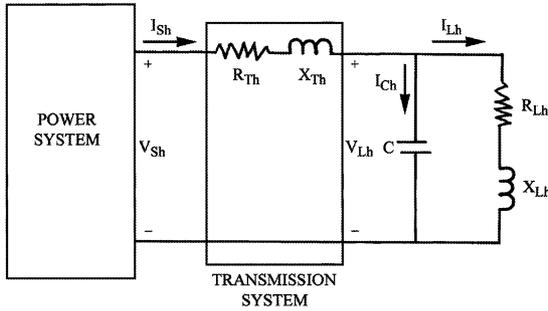


Fig. 1. Configuration of the study system.

factor (the ratio of active power to apparent power) at the load. It also reduces the magnitude of the current to be delivered by the source; this implies less power in the transmission system and an increased transmission efficiency. Moreover, the voltage drop in the transmission line is reduced so that more power can be delivered to the load for the same source voltage.

Hence the following criteria could be envisaged for optimizing the value of the capacitance:

- maximizing the power factor,
- minimizing the line loss, and
- maximizing the transmission efficiency.

One could also think of maximizing the power delivered to the load; this criterion is not considered, since the power delivered to the load is independent of the capacitance if the source impedance is zero. More importantly, if the source impedance is not zero, the voltage at the load (and hence the power delivered to the load) can be increased to an undesired level by increasing the capacitive current through the inductance of the transmission line.

Williams [6] discussed the different criteria for the design of the compensating capacitor. In this paper, the application is discussed taking into consideration the skin effect.

## 2. Identification of skin effect

Rice [7] defines the ratio of AC resistance to DC resistance as

$$\frac{R_{AC}}{R_{DC}} = 1 + Y_{CS} + Y_{CP}, \quad (1)$$

where  $Y_{CS}$  is the component of resistance due to skin effect and  $Y_{CP}$  the component of resistance due to proximity effect.

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. This is due to the fact that the flux linkages are not of constant density throughout the conductor,

but tend to decrease near the outer surface lowering the inductance and increasing the current flow. The result is that because of the unequal current distribution for AC waveforms, the effective resistance is greater for alternating current than for direct current.

The component of resistance due to skin effect can be expressed as

$$Y_{CS} = f(x). \quad (2)$$

The value of the function  $f(x)$  can be determined once the factor  $x$  is determined according to the following formula [7]:

$$x = 0.027678 \sqrt{\frac{f\mu}{r}}, \quad (3)$$

where  $f$  is the frequency in hertz,  $\mu$  the magnetic permeability of conductor (equal to 1 for non-magnetic material) and  $r$  the DC resistance in ohms per 1000 ft at operating temperature.

Rice [7] gives a table from which  $f(x)$  can be determined for solid and concentric-stranded round conductors.

Proximity effect is caused by magnetic flux linking the cable because of nearby current in multi-conductor cable, or cables in the same duct, or even currents induced in nearby magnetic enclosures such as steel conduits, trays, etc. Rice [7] indicates that the component of resistance due to proximity effect can be expressed as

$$Y_{CP} = f(x)k^2 \left( \frac{1.18}{f(x) + 0.27} + 0.312k^2 \right), \quad (4)$$

where  $k$  is the conductor diameter divided by the axial spacing between conductors.

Given the relationships in Eqs. (1)–(4), the values for  $R_{AC}/R_{DC}$  for a number of harmonic orders can be calculated. The conductor insulation thicknesses used to calculate the  $k$  factor in Eq. (4) were based on those listed in the NEC code for type THHN or THWN cable. It was assumed that the insulated conductors were immediately adjacent to each other in order to maximize the proximity effect.

A simple method to determine the skin effect on the resistance for harmonic frequency is by representing the distribution lines and cables with their equivalent pi model [8]. An estimated correction factor for skin factor was applied by increasing its resistance  $R$  with frequency as

$$R = R \left[ 1 + \frac{0.646h^2}{192 + 0.518h^2} \right] \quad \text{for lines,} \quad (5)$$

$$R = R[0.187 + 0.532h^{1/2}] \quad \text{for cables.} \quad (6)$$

Eq. (6) is used in the analysis for the transmission system.

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