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OPTIMAL COMPENSATION OF REACTIVE POWER IN WIRE NETS WITH HIGHER HARMONICS OF VOLTAGE AND CURRENT

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ABSTRACT
Special attention in this paper is given to the choice of ideal condenser for compensation of reactive power through the process of optimization with the following criteria: increase of power factor, reducing of cable current and increase of system efficiency. Analyses from theoretical and practical aspects have been carried out for different cases as well as for the least favorable ones: when the net is with a big harmonic distortion, when the impendence of transmission system cannot be avoided and when the receiver is non-linear. On the basis of carried out analyses and simulation for the number of cases, appropriate conclusions are made as contribution to the actual problematic.
Key words: reactive power, compensation, higher harmonics, optimization, ideal condenser.

1. INTRODUCTION
In modern industrial networks there is a great number of electric energy receivers which use for their normal work both active and reactive energy. As a consequence of work of such receivers, increasing voltage falls appear and additional losses of energy in generators, transformers and cables. By compensation of reactive energy i.e. reactive power at the receivers themselves, discharge of existing energy sources and transmitting paths is performed, thus equipment for production and transmission of electric energy can produce and transmit energy with bigger active power. Non-linear receivers of electric energy such as: regulated electromotor drives, electric arc furnaces, different converters, systems for continual feeding, bulbs with electric discharge, endanger the quality of electric energy to a great extent and present a significant source of higher harmonics of voltage and current in the net. Increase of higher harmonics in the net as a consequence of the work of non-linear receivers makes serious problems in the work of other linear receivers, and definition of reactive power and power factor in such nets is different from definition in nets where there is no big harmonic distortion which makes the whole process of compensation of reactive energy additionally more complex.

2. ANALYSIS OF HIGHER HARMONICS
Analysis of higher harmonics is based on the postulate of J.B.J. Fourier, meaning that any continual function with repetition period T can be presented by the sum of the fundamental sinusoidal component and the series of higher-order sinusoidal components at frequencies which represent integer multiples of the fundamental frequency.
In accordance with Boudeanu theory, the equivalent reactive power in the presence of higher harmonics is difined by:

$$Q = \sum_{h=1}^{\infty} Q_h = \sum_{h=1}^{\infty} U_h I_h \sin\varphi_h \qquad (1)$$

It can be concluded that in the case of presence of higher harmonics in an electrical network, apparent power of the load can be presented by the part which corresponds to the apparent power of single harmonics and by the part that is a result of nth and hth harmonics. The second component is called distorsion power and is given by:

$$D = \sqrt{\sum_{\substack{h \neq n \\ h=1, n=1}}^{\infty} U_h^2 \cdot I_n^2} \tag{2}$$

Apparent power is given by:

$$S = \sqrt{P^2 + Q^2 + D^2} \tag{3}$$

In electrical circuits that are characterised by the presence of higher harmonics of current and voltage, power factor is not equal to cosφ. As a result of this, power factor λ is presented by more complex equation:

$$\lambda = \frac{P}{S} = \frac{\sum_{h=1}^{\infty} U_h I_h \cos\varphi_h}{\sqrt{\sum_{h=1}^{\infty} U_h^2} \cdot \sqrt{\sum_{h=1}^{\infty} I_h^2}} \tag{4}$$

3. PROCESS OPTIMISATION CRITERIA

Figure 1. shows the power system that delivers elelectical energy to the load L which is assumed to have a non-unity power factor. The purpose of the parallel capacitor C is to increase the power factor of the load and therefore to reduce the transmission line current and the transmission loss as well. If the voltages and the currents are sinusoidal, then the standard techniques are used to compute the capacitor that would lead to the desired power factor improvement. The optimal capacitor is the one that exactly generates the reactive power required by the load. As a result of this, there would be no reactive power assumption from the power system.

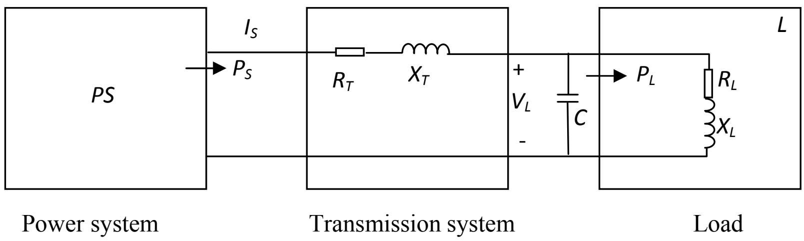

Figure 1. Compensation of the reactive power of the load

The question is how the optimisation and power factor correction can be done in power systems that contain higher harmonics of current and voltage, having in mind that the definition of reactive power in such cases is not that clear. In conventional methods for calculating the compensating capacitor, higher harmonics are neglected and the capacitor that would be optimal in the case of sinusoidal steady state would also be used in the distorted state. This would lead to the power factor with poorer characteristics. There are several ways for determining the optimal criteria depending on what is required by using of the parallel capacitor connected to the load.
Following critera can be considered for the optimisation process:

A. Maximise the power factor

The power factor PF is defined by the equation:

$$\lambda = \frac{P_L}{I_S \cdot V_L} \tag{5}$$

where P_L, I_S , V_L respectively denote the power delivered to the load, the total current through the load and the capacitor, and the voltage at the load.

B. Minimise the line current

The purpose of this critera is to minimise the power loss in the line and the current density in the conductors.

C. Maximise the transmission efficiency

This is caracterised by the ratio P_L / P_S, where P_S denotes the power delivered by the power system and P_L the power of the load.

Maximising the power that is delivered to the load as a possible criterion is not considered as the energy that is delivered to the load is independent of the capacitance if the source impendance is zero. More importantly, if the source impendance is not zero, the voltage at the load (and also the power delivered to the load) can be increased to an unwanted level by increasing the capacitive current through the transmission lines.

In th paper, emphasis is put on usage of different criteria for choosing the optimal capacitor, with special review of the analysis that would give as an idea to what extent those critera are equivalent.

Usage of mentioned criteria is analysed in the following cases:

1) Sinusoidal or distorted voltage, power system impendance neglected.
2) Sinusoidal voltage, power system impendance taken into account.
3) Distorted voltage, power system impendance taken into account.

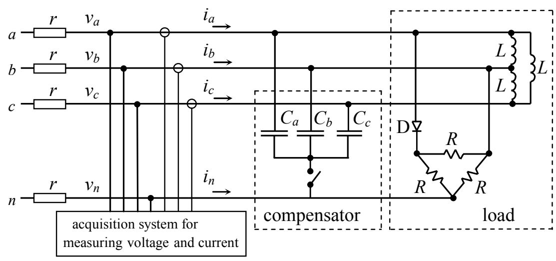

Figure 2. Compensation of the reactive power of the three-phase load

The figure 2 shows the case of compensating the reactive power using ideal compensator of the three-phase load with distorted and balanced voltages and asymetrical (unballanced) currents. The load consists of three-phase asynchronous motor (L=0,05 H) and three resistors (R=160 Ω) with the diode D that are connected between the two phase conductors and the neutral conductor. Simulation of the optimal compensation of the reactive power of the load, taking into account the ressistance of the transmission line is carried out using the Matlab Simulink environment.

Feeder line of the load is modeled by the resistors with resistance of r = 1 Ω. Figure 3 shows active, apparent and reactive power during the compensation of the reactive power of the load using the ideal compensator. The power factor of the load is shown in figure 4.

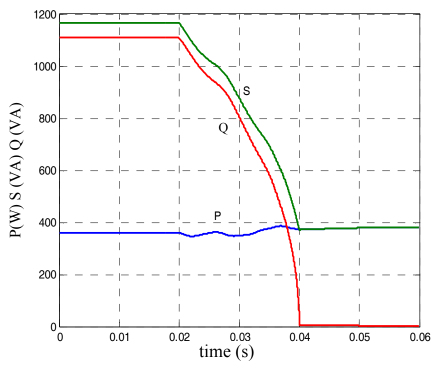

Figure 3. Active, apparent and reacitive power during the compensation of the reactive power of the load using an ideal compensator

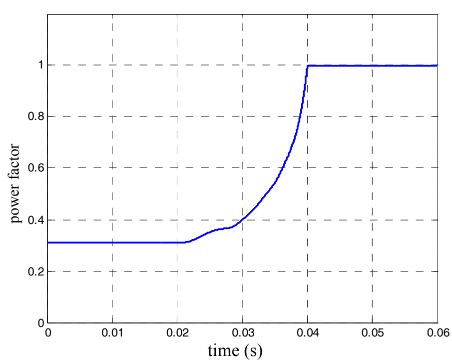

Figure 4. Power factor of the load during the compensation of the reactive power using an ideal compensator

3. CONCLUSION

The above mentioned criteria, maximisation of the power factor, minimisation of the line current and maximisation of the transmission efficiency lead to different optimal capacitance values, although the corresponding performance may not be very different.

Approximate techniques corresponding to neglecting the transmission line impendance and/or the voltage harmonics may lead to capacitance values with poor power factor correction.

Linear capacitor may have little influence over the compensation of the reactive power if the voltage contains higher harmonics. Better power factor correction can be achieved using more complex reactive filters, whose caracteristics can independently be designed at the frequencies that correspond to the voltage harmonics of the power system.

Economic analysis is necessary in order to chose the ecconomicaly most acceptable capacitor, taking into account the cost of the capacitor, the cost of the energy losses, and the source impedance. As the power factor is the combined function of the capacitance, in some cases much cheaper capacitor can be used at the expense of the insignificant performance deterioration.

The optimal capacitance value for correction in power systems may be very sensitive in respect to the parameters of the model. For this reason a more robust value that is not optimal can be appropriate.

One more question is whether the optimisation procedure can be applied according to the measurements taken at the load. This requirement excludes the optimisation of the transmission efficiency.

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