The Efficiency of Reactive Power Compensation of High Power Nonlinear Loads

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Abstract—The paper presents and discusses the problems associated with reactive power compensation of nonlinear loads. Analytical results and simulation studies for selected high power drive used in mine when apply dynamic compensation together with active harmonics filters are presented. It was found that application of active power filters allows for compensation high current harmonics in general, and suppression of as reactive power flows as well as current harmonics in the network. On the basis of results conclusions on efficiency of the active on-line compensation of non-linear loads of a high power are formulated.

Index Terms—Reactive power, compensation, non-linear load, high power.

I. INTRODUCTION

In industrial applications there are high power motor drives which require speed control. In mining, they include mine host drives, the main ventilation and drainage engines, large air compressors and various pumps. As electric motors are used both DC motors, asynchronous and synchronous. In order to provide variable speed control there are used rectifier systems or systems of high power converters (in which rectifiers are also employed). For drives of a low rated power (up to about 300-400kW) uncontrolled rectifiers (diodes type) are commonly used, while for high power- the controlled rectifiers respectively. They draw current of highly distorted sine waveforms so we include them for non-linear loads. The rapid increase in application of rectifier and converter systems creates serious problems with their impact on the supplying networks. It is related to the presence of distorted voltage waveform and the associated significant flows of reactive power together with power factor value degradation of any power source. Waveform of the current consumed by the rectifier is strongly deformed and in the case of use of the controlled rectifier is moreover shifted with respect to the source voltage. As a result voltage drops along impedances of as transmission, distribution and reception systems are also distorted. In effect quality of the output voltage at common connection points (intermediate switchgear) supplying other receivers sensitive to the shape deformation of the voltage is not acceptable. To overcome

this problem an application of active power filters is necessary. They can be developed based on selected electric energy concept. We found that the most convenient is the use of theory of the physical current components [1]. The paper presents and discusses the problems associated with reactive power compensation of non-linear loads. Analytical results and simulation studies of compensation for selected high power non-linear load using dynamic compensation combined together with application of active current harmonics filter are presented.

II. THEORETICAL BACKGROUND

For the analysis of periodic non-sinusoidal waveform commonly used is the Fourier representation being the series of trigonometric terms of frequencies as follows [2]

$$i = I_{h1} \cdot sin(\omega_1 t + \varphi_1) + \sum_{n>1} I_{hn} \cdot sin(n\omega_1 t + \varphi_n), \quad (1)$$

where I_{hn} - the amplitude of the current harmonic of n-order; n - harmonics order; ω_1 - angular frequency of basic harmonic; φ_n - initial phase of n-th harmonic.

Such waveforms are usually characterized by total harmonic distortion factor THD [3]

$$THD = \frac{\sqrt{\sum_{n>1} |I_{hn}|^2}}{|I_{h1}|}. \quad (2)$$

Depending on the number of pulses of the rectifier system applied the characteristic is the presence of certain current harmonics

$$n = p \cdot k \pm 1, \quad (3)$$

where n - harmonics number; p- number of pulses of the rectifier; k= 1,2,3 …

For example, the most commonly used 6-pulses rectifiers (p=6) produce only odd current harmonics numbered:
5, 7, 11, 13, 17, 19… .

According to the Fourier representation amplitude of the following harmonics should decreases with the increase in their number, which may not always occur in real electric power systems.

To describe and to interpret the phenomena of electric energy concept the following theories are currently use:

1) instantaneous power theory with its many variations,
2) theory of the physical current components,

which were developed and published in the 80,s of last century. The first of these describes the phenomena in the time domain, while the second-in the frequency respectively. One of the most important contemporary problems regarding electric non-linear circuit is to create relevant effective tools to reduce (eliminate) the flow of reactive power consumed by this type of load.

III. REACTIVE POWER COMPENSATION OF NON-LINEAR LOADS

In the case of a linear load RL type, reactive power compensation is performed based on the resolution of the current into two components

$$I = \sqrt{I_a + I_r} \qquad (4)$$

where I- rms value of the load current; I_a - active current component ($I_a=I\cdot\cos\varphi$); I_r – reactive current component ($I_r=I\cdot\sin\varphi$).

As devices for compensation are used static battery banks and/or overexcited synchronous motors (rotating compensators). For the non-linear loads current waveform indicates presence of numerous harmonics. Broad spectrum of the current harmonics may result in thermal damage of the capacitors, the insulation of power cables, transformers as well as electrical machines (i.e. capacitive reactance decreases with the increase in frequency therefore, an overload due to high harmonics is a key factor). Thus, for large non-linear loads as an unit to compensate for the negative impact on the network there are used the series connected passive LC filters and capacitive banks together with protective reactors. The series LC filter of resonant frequency

$$f_{rez} = \frac{1}{2\pi\sqrt{LC}} \qquad (5)$$

for given harmonics displays small value of equivalent reactance seen from the terminals of a high power non-linear load. Current (currents) flowing out of this load must be bridged by the filter LC (Fig. 1) without affecting the network itself.
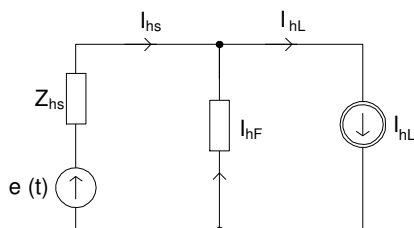

Fig. 1. Equivalent electric circuit with non-linear load, I_{hL} – current of non-linear load; I_{hF} - current of passive filter; I_{hs} - current of supplying network.

In real systems one deals with distorted voltage. However, these deformations are relatively small and their level is determined by the applicable law ($THD_U \leq 2\%$). In spite of a small voltage waveform deformation the high current harmonics flowing through batteries and passive filters can, in customer installation, reach significant values. Therefore, the only way to limit or to eliminate the high current harmonics is the use of appropriately selected active filters.
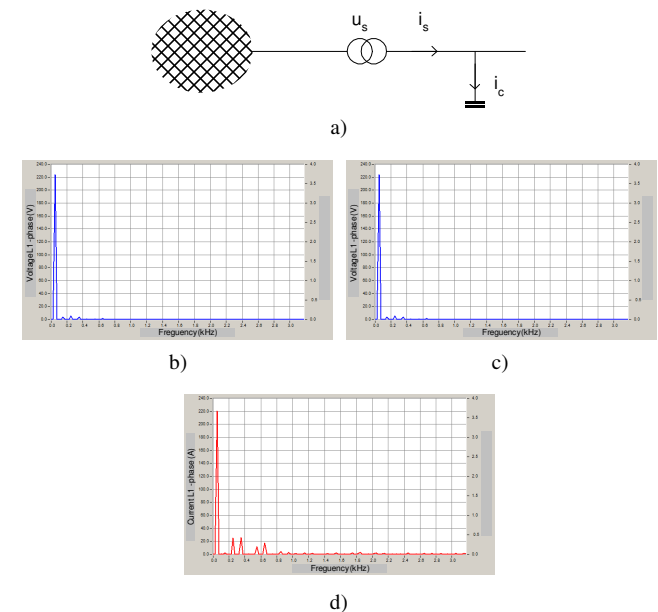

Fig. 2. Electric circuit supplied with distorted voltage: (a) – scheme of the circuit; (b) – voltage and current waveforms; (c) – voltage harmonics spectrum; (d) – current harmonics spectrum.

In circuits with nonlinear loads the voltage and current analysis is more complex. Therefore, in these cases simulation methods are widely used. They allow carrying out research for changes of various electric parameters over a wide range [4].

IV. ANALYSIS FOR SELECTED NONLINEAR LOAD OF HIGH POWER

In order to demonstrate the usefulness of active power filters for nonlinear loads appropriate simulation tests were carried out for selected real drives of a high power used in exhaust mining machines. The drive is composed of two DC electric motors each of rated power equal to 3.9 MW (690 V) working on a common shaft. The engines are supplied with controlled thyristor rectifiers. The models for simulation have been developed in Matlab-Simulink package [3]. For comparison both commonly used method of static reactive power compensation by means of capacity banks and this with use of active power filters (APF) was considered. Electrical circuit diagrams for simulation are presented in Fig. 3.

Fig. 4 shows, for example, variation of current and voltage with time in selected, characteristic points of the system (network) and their harmonics spectrum for the case of compensation with capacity banks. Here is seen the phase shift between currents in the secondary windings of the transformer connected in star and triangle respectively. Primary winding current corresponds to a pulse of 12-th, despite the fact that each of the rectifier is a 6-pulse.

In spectrum of the load current in the primary winding are visible the higher harmonics characteristic to the 12-pulse rectifier i.e. 11 and 13th.
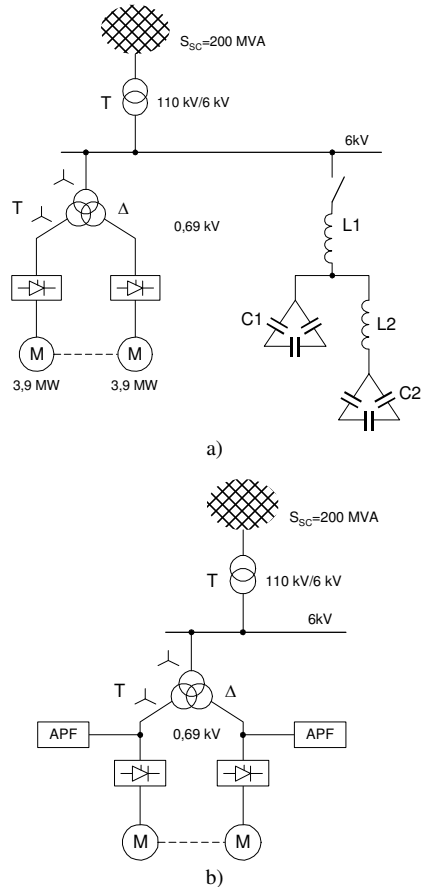
a)

b)

Fig. 3. Equivalent electric circuits for modeling study: (a) – reactive power compensation with static capacity banks; (b) – by means of active power filters (APF); S_{sc} – short circuit power of supplying system.

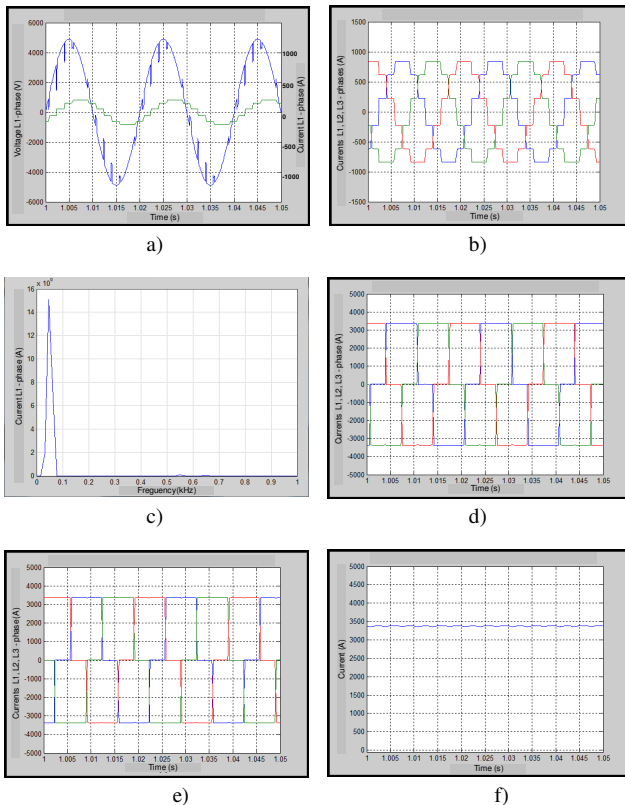a)

b)

c)

d)

e)

f)

Fig. 4. Voltage and current waveforms in supplying system (network); (a) - voltage and current in primary windings of transformer in one phase; (b) current in primary winding of transformer; (c) - current harmonics spectrum (in primary windings of transformer); (d) - current in secondary windings connected in star; (e) - current in secondary windings connected in triangle; (f) – load current for one thyristor brige.

In Fig. 5 the results of reactive power compensation (in circuit as in Fig 3(a)) by means of static capacity banks are shown. One can see the change in shape of the current in the primary winding of the transformer due to the presence of the capacity banks. However, across the C1 and C2 capacitor are flowing currents containing high harmonics which are responsible for the rapid damage of the capacitors due to related thermal effect. The presence of capacity improves as a result the power factor value.
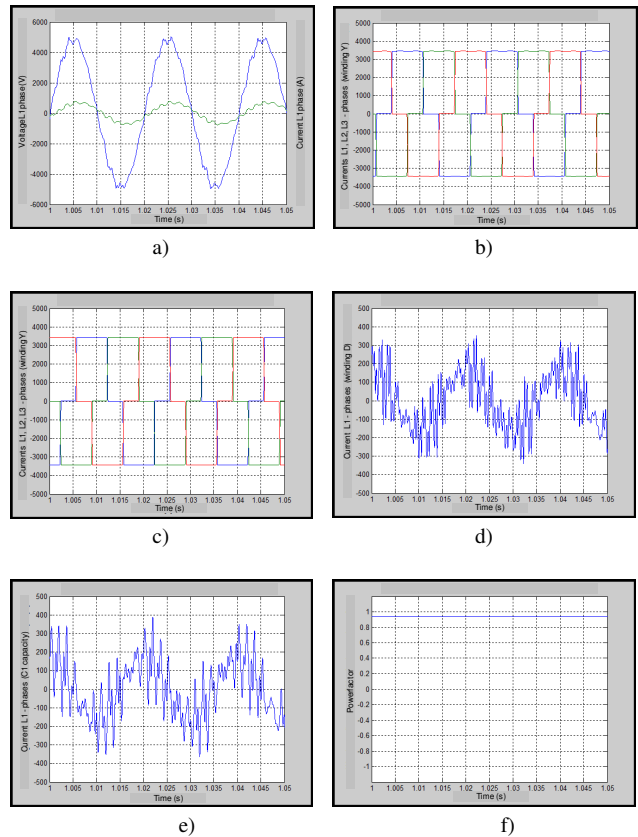

a)

b)

c)

d)

e)

f)

Fig. 5. Voltage and current waveforms when supply nonlinear load with reactive power compensation performs by means of static capacity banks; (a) - voltage and current in L1 phase (primary winding), (b) - currents in secondary winding of the transformer connected in star, (c) - currents in secondary winding connected in triangle, (d) - current through the C1 capacity, (e) - current through the C2 capacity, (f) - power factor value after compensation.

In Fig. 6 is visible the effect of reactive power compensation with active power filter (APF) applied for nonlinear load (Fig. 3(b)). One can see here high efficiency in eliminating high current harmonics in primary winding of the transformer (the current drawn from the network Fig. 6(d)) and no phase shift between supplying voltage and current waveforms what confirms perfect compensation effect when employ the (APF) devices (Fig. 6(f)). All current of the network is equal of the active current.

From the investigated results it is clear that application of APF systems is much more useful with compare to the common static ones.

For control of the active power filter may be used the algorithm basing on instantaneous power theory (analyses voltage and current waveform in the time domain) or on physical current components (analyses voltage and current waveform in harmonic domain). More popular is algorithm basing on the Instantaneous Power Theory. In our work was

using algorithm basing on currents physical components. This algorithm is presented in Fig. 7.
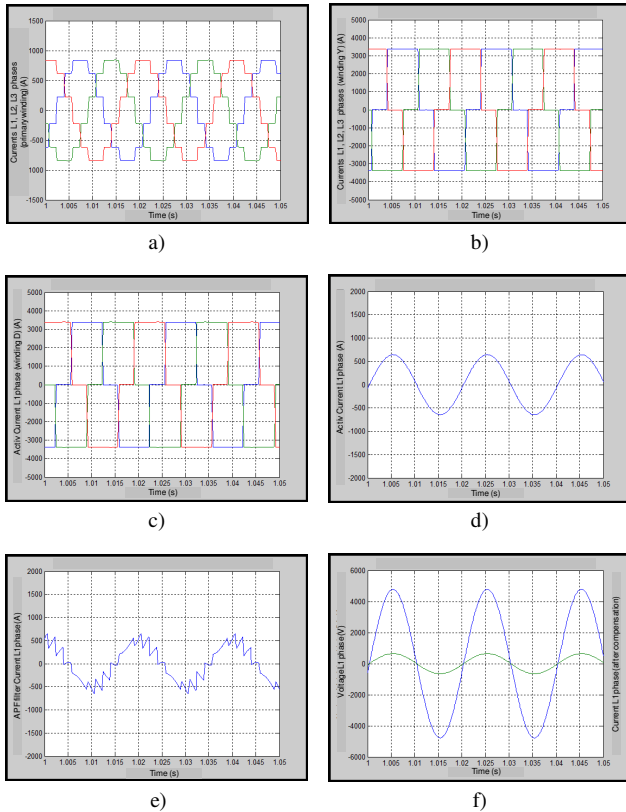

a)   b)

c)   d)

e)   f)

Fig. 6. Current and voltages in supplying network for nonlinear load with power compensation by means of active power filter (APF); (a) - currents and voltages in primary winding of the transformer, before compensation; (b) - currents in secondary winding of the transformer connected in star, before compensation; (c) - currents in secondary winding connected in triangle, before compensation; (d) - current waveform in secondary winding after compensation; (e) - APF current waveform; (f) - phase voltage and current in primary winding of the transformer, in L1 phase.
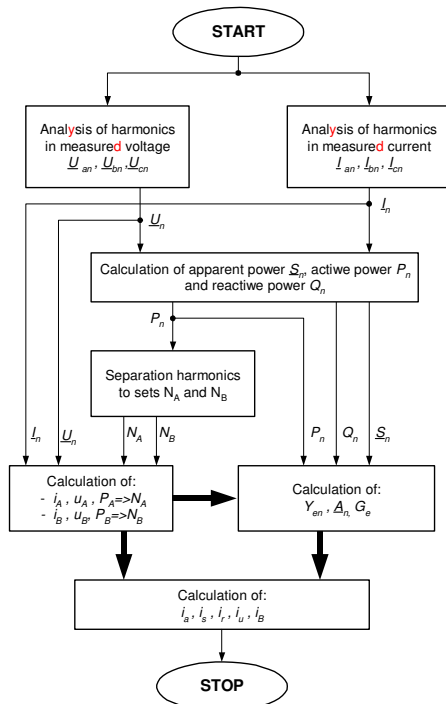
V. CONCLUSIONS

The use of static capacity banks for reactive power compensation in electric power systems with high power nonlinear loads allow only to compensate the power of the fundamental current component. There appears however, the risk of damage of the compensation arrangement components due to overload because of higher current harmonics.

Application of active power filters allows reactive power compensation also due to high current harmonics. It allows for compensation high current harmonics in general, and suppression of as reactive power flows as well as current harmonics in the network.

Due to increasing amount of nonlinear loads it is expected to involve widely, in a close future, the compensating active filters because of their high efficiency unattainable by use of static compensation.

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Fig. 7. Algorithm of control Active Power Filter basing on current physical components theory (CPC).