Active Power Filter with Relay Current Regulator and Common DC Link for Compensation of Harmonic Distortion in Power Grids

Maksim Maratovich Habibullin[1], Igor Sergeevich Pavlov[1],
Viktor Nikolaevich Mescheryakov[1], and Stanimir Valtchev[2]

[1] Lipetsk State Technical University, Moskovskaya 30, 398600 Lipetsk, Russia
maximuum@rambler.ru, mesherek@stu.lipetsk.ru
[2] Campus de Campolide, 1099-085 Lisboa, Portugal
ssv@fct.unl.pt

Abstract. The growing number of consumers representing non-linear loads has led to an increase in the level of harmonics and poor power quality. It is not news to apply active power filtering (APF), but the drawback is the lower efficiency and complexity. The described here active power filter control system is simpler and more efficient. It is based on a relay current regulator and its converter uses the existing DC bus of the rectifier. The theoretical basis of the APF is described. A model of the proposed APF (with its suggested control system and the common DC link) is simulated in Matlab. The result of this simulation demonstrates that the level of the Total Harmonic Distortion (THD) of the input current is less than 3 %. The input current matches the phase of the input (mains) voltage: i.e. the consumption of reactive power from the grid is minimized. The simulation is confirmed by experimental study of the relay current controller. The corresponding results are provided.

Keywords: Non-linear load, Quality of electric energy, Total harmonic distortion, Relay current control, DC-link, Active power filter.

1 Introduction

1.1 Power Quality

Less than twenty years ago the harmonic components of current and voltage in the electric alternating current were negligible and their impact on the grid could be ignored. Currently, in most countries the level of harmonic components in power grids has increased in several times. The tendency for further growth is here to stay [1]. The high level of harmonic components should be considered seriously because it has a negative impact both on the grid and its users.

The reason for the growth of the harmonic current and voltage is the growing number of electricity customers that use non-linear load, both in the industrial and domestic sectors. The main negative effect of the non-linear load consists in the specific nature of the harmonics in the consumed current from the grid. The harmonic components frequencies can be so high that they provoke electromagnetic disturbance

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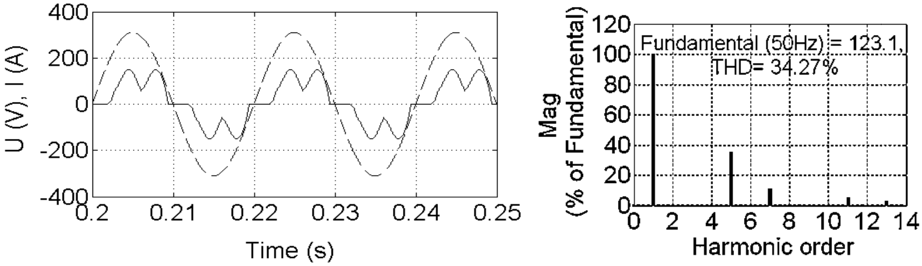
but the low frequency harmonics are also a problem because their filtering requires large reactive elements. Currently, 60 % of the electrical consumption is due to the nonlinear load and now the requirements for power supply quality from the grid is one of the main tasks of the electrical energy industry [2].

The existence of higher harmonic contents in the grid current results in significant economic damages. These include the additional losses in rotating electrical machines, the loss in transformers, vibration in electric machine systems, single-phase ground short circuit, capacitor breakdowns, insulation aging, disruption and failure of high-precision measuring instruments, protective gears, control systems and microprocessor-based systems, interference and distortion of signals in telecommunication networks and systems. In addition, the nonlinear load has high level of reactive energy circulation; hence the losses in the energy transport system rise, as well as the overloading of generators, transformers and transmission lines. Oscillations of system voltage are then more probable. In general, the quality of the supplied energy goes downward [3].

1.2 Outlining the Research Question and Its Motivation

The harmonic components in the power network variables are produced in the consumer environment and they are originated by the load characteristics. This means that the consumers must themselves control the influence exercised by their equipment onto the grid.

The most characteristic behavior of the power grid working on active-inductive load has been modeled in Matlab in order to analyze the influence of a nonlinear load application. The above mentioned load is connected to a three-phase classical uncontrolled semiconductor bridge rectifier. The adopted for this simulation parameters, are: $U = 380\ \mathrm{V}$, $f = 50\ \mathrm{Hz}$, $R_L = 4.5\ \mathrm{Ohm}$, $L_L = 10\ \mathrm{mH}$, $C_d = 30\ \mathrm{mF}$. The simulation results are presented in Fig. 1 (a, b).



(a) (b)

Fig. 1. (a) Waveforms of phase A current (solid line) and phase A voltage (dotted line); (b) Spectral contents of the phase A current, $THD_i = 34.27$.

As it is seen in Fig. 1 (a), the current and the voltage waveforms show a certain phase difference. The load requires reactive power from the supplying network and the THD_i is higher than normally is [4]. The usually applied equipment to correct the electric power quality parameters of the consumed power have been the passive power filters of high order harmonics, the compensating capacitor batteries and synchronous compensators. Based on the achievements in power electronics, it became possible to solve this issue by means of active power filters (APF) [5], [6], [7]. The APF that is currently applied consists of a voltage converter (with fully controlled power switches) and a capacitor battery in a dedicated DC link. However, the most non-linear consumers, having a rectifier incorporated, already possess a capacitor in their output DC link. It is suggested therefore that a new type of APF will use this already existing DC link: the converter of the filter is connected to the DC output voltage tank. This will reduce the number of circuit elements and simplify the control system of the APF [8]. The chosen control system is based on the relay (bang-bang) current controller. This control system is characterized by simplicity, stable performance, high speed and high accuracy [9], [10], [11].

The APF is supposed to operate as a step-up converter, i.e. the output voltage (the output filter's DC link voltage) will be always higher than the voltage applied to the APF converter (the damaged voltage that is necessary to correct). The main task in the development of this APF is the construction of the control system based on the balance of the power consumed by the nonlinear load from the AC supply and the power injected into the DC link. The other task is the control of the voltage level at the output of the APF converter in order to correspond to the consumed power.

2 Relationship to Collective Awareness Systems

The increase in the number and the power of non-linear loads is due to the rapid development of the modern electronics. From the point of view of the economy, the power electronics made the energy use more efficient. Unfortunately the electronic devices applied in the energy sector have led to quality problems of the power grid. Those problems our society needs to solve by the effort of both the energy producers and the electric power consumers.

In the industry, the modern static power converters and the frequency controllers for motor drives made possible by the high-power IGBT transistors and other emerging devices to facilitate the control of the induction motors, the cheapest and most common type of electric motors. The application of electronic devices brought certain effects in the general electric network: massively the controlled AC drives have been upgraded by introducing a frequency controlled converters in already existing power system and this distorted the consumed current.

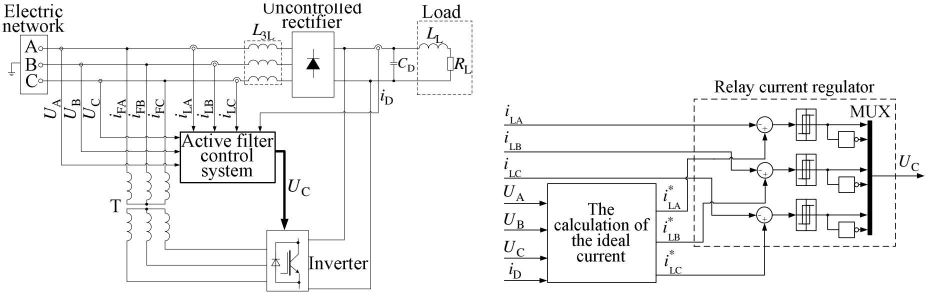
In the domestic applications the switching power supplies increased dramatically in number. The switched power converter is highly efficient but the massive use of it created problems. For example, the millions of laptops, tablet PCs and mobile phones, the necessary servers, routers, etc., all of these electronic devices operate at a constant voltage supply, but they are connected to the AC mains. The converters from the AC to DC in the millions of devices and other equipment represent a non-linear load. As a final result, the quality parameters of the AC grid deteriorated.

In fact, it is not possible to avoid the non-linear load in the energy system. A promising solution to this problem is the use of APF in order to compensate the damage made to the grid parameters. This filtering is also a must for the interconnections between the numerous generators and consumers in the future smart grids. If a simple and reliable solution like the proposed one will be adopted, the manufacturers of electronic equipment will produce massively equipment that will be more easily made compact and cheap.

The consumers connected to the mains will be able to have their nonlinear influence compensated: the APF will be cheaper and more acceptable to be used in massive number to compensate for harmonic distortion. This will contribute to the development of Collective Awareness Systems, where the price of the nonlinear load compensation will be equally divided between the consumers and the producers of electric energy.

3 Theoretical Bases

The schematic diagram of the proposed APF is shown in Fig. 2 (a). A transformer is used as the matching element between the APF converter output (here it is an inverter) and the electric grid.



(a) (b)

Fig. 2. APF: (a) its connection to the load and grid; (b) its control system

The operation of the suggested APF control system is planned to compensate for the difference ΔI_L between the real I_L and the ideal I_L^* load current that passes through the system in any instant of time [8]:

$$\Delta I_L = I_L^* - I_L \ . \tag{1}$$

The “Ideal” current, flowing from the mains, is defined by the power that the DC consumer requires.

The active power P_1 at the input should correspond to that DC power, and P_1 is:

$$P_1 = \sum_{k=1}^{\infty} \sqrt{3} \cdot U_{k1} \cdot I_{kL} \cdot \cos \varphi_k \ , \tag{2}$$

where I_{kL} is the current drawn from the grid by the uncontrolled rectifier,

U_{k1} is the AC input voltage,

φ_k is the phase shift between the voltage and current (in fact, the first harmonic of the input current is the only harmonic contributing to the DC output power!).

The reactive power Q_1 at the input is:

$$Q_1 = \sum_{k=1}^{\infty} \sqrt{3} \cdot U_{k1} \cdot I_{kL} \cdot \sin \varphi_k \ \cdot \tag{3}$$

The apparent power S_1 at the uncontrolled rectifier input is:

$$S_1 = \sqrt{P_1^2 + Q_1^2}\,. \tag{4}$$

According to the required (and expected) result from the filtering, it is assumed that the phase angle between the current and the voltage will be zero ($\varphi = 0$). Then the total power at the input of the scheme is:

$$\begin{aligned} &Q_1 = 0; \\ &S_1 = P_1 = \sqrt{3} \cdot U_1 \cdot I_L. \end{aligned} \tag{5}$$

The power P_2 that is expected to be consumed by the load is:

$$P_2 = k_u \cdot U_1 \cdot I_d\,, \tag{6}$$

where $k_u = 1.35$ is the DC/AC voltage ratio of the full bridge rectifier,

and I_d is the DC current drawn by the load.

The power balance between P_1 and P_2 will be:

$$P_1 = P_2 + \Delta P\,, \tag{7}$$

where ΔP represents the total losses in the APF, the rectifier and the transformer.

In general, the lost part ΔP can be represented as a function of the current I_d multiplied by the coefficient $k_{\Delta P}$. Then the balance of power is:

$$\sqrt{3} \cdot U_1 \cdot I_L = k_u \cdot U_1 \cdot I_d + k_{\Delta P} \cdot I_d\,. \tag{8}$$

The peak value of the “ideal” current consumed from the grid is:

$$I_L^* = \frac{I_d}{\sqrt{3}}\left(k_u + \frac{k_{\Delta P}}{U_1}\right). \tag{9}$$

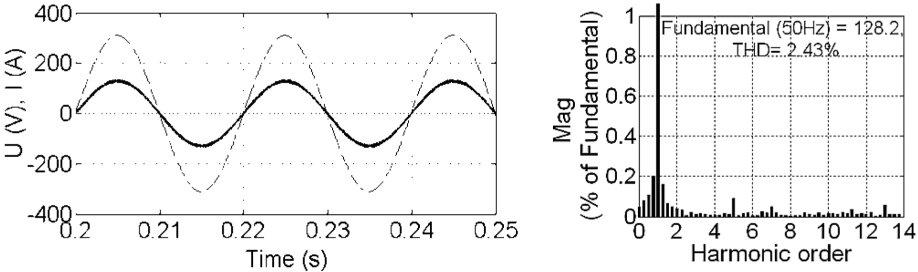
The instantaneous values of the “ideal” phase currents are:

$$\begin{aligned} &i_{LA}^*(t) = \frac{I_d}{\sqrt{3}}\left(k_u + \frac{k_{\Delta P}}{U_1}\right) \cdot \sin(\omega t); \\ &i_{LB}^*(t) = \frac{I_d}{\sqrt{3}}\left(k_u + \frac{k_{\Delta P}}{U_1}\right) \cdot \sin(\omega t + 120°); \\ &i_{LC}^*(t) = \frac{I_d}{\sqrt{3}}\left(k_u + \frac{k_{\Delta P}}{U_1}\right) \cdot \sin(\omega t - 120°). \end{aligned} \tag{10}$$

As a general outlook, the APF control circuit is shown in Fig. 2 (b). The relay current control (RCC) is configured by adjusting the hysteresis value in order to determine the precision by which to process the signal from the current sensors. The difference between the “ideal” and real current is delivered to the RCC together with the signal from the DC current feedback i_D. The RCC block calculates and compares continuously the instantaneous “ideal” load currents and the real load currents. The control signals for the converter (it is an inverter in Fig. 2 are generated by RCC. These signals are aimed to form the APF output current instantaneous value. The instantaneous values of APF output currents are supplied to a step-up transformer. The secondary of the transformer supplies the missing instantaneous current continuously and thus compensates for the non-sinusoidal waveforms of the consumed current in the load. As a result, the current that the grid supplies to the whole circuit, becomes sinusoidal with a reasonable precision. The physical basis of this current waveform shaping, as in all the active filter circuits, is the temporary energy storage implemented by passive reactive devices. The particular difference in this method is the use of the output voltage: the filter capacitor or the battery, and not constructing a separate DC link as it is usually done.

4 Simulation Results

Following the described operation principle of this APF, a computer model has been developed in Matlab. The connection to the nonlinear load corresponds to the shown in Fig. 2 (a). The simulation parameters are: $U = 380\ \text{V}$, $f = 50\ \text{Hz}$, $R_L = 4.5\ \text{Ohm}$, $L_L = 0.1\ \text{mH}$, $C_d = 30\ \text{mF}$, $L_{3L} = 0.1\ \text{mH}$. The results shown in Fig. 3 demonstrate the current, supplied to the uncontrolled rectifier, having a sinusoidal form and a phase coincident with the mains voltage phase. As a result, no reactive power is consumed from the grid and the level of harmonic distortion of the current (THD_i) is close to ideal. This is illustrated by Fig. 3 (b) where THD_i = 2.43%.



(a) (b)

Fig. 3. Current in the phase A of the uncontrollable rectifier: (a) Graphically compared (solid line) to the phase A voltage (dashed line); (b) The spectral composition of the current

5 Experimental Results

The APF control system (RCC) was experimented in a real implementation. The parameters of the experimental study are: $U = 24\ \text{V}$, $f = 50\ \text{Hz}$, $R = 0 - 20\ \text{Ohm}$, $L = 0.1\ \text{mH}$. In Fig. 4 a general view of the construction is shown.

The power module is “Mitsubishi PS22054” connected to a ”Mitsubishi 1200V DIP IPM (PS2205X) EVALUATION BOARD”, used for debugging converter circuits. The module “Piccolo TMDX28069USB” of Texas Instruments” is a DSP controller, used here as the RCC. The module “CSLA1CH” of Honeywell is a linear current sensor (for measurement of the current in the load circuit). The waveforms were observed by oscilloscope “HANTEK DSO8060” and the values were measured by multimeter “MASTECH M890F”. The power supply was a regulable block supplying 24 V at a maximum current of 2A) is connected to converter input. A single-phase load is experimented being a combination of a resistor and an inductive coil, connected to the power converter output.

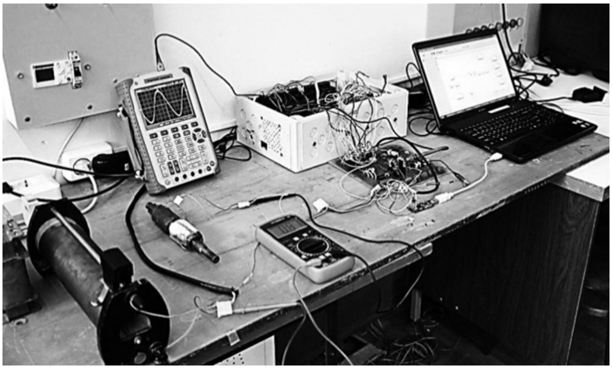
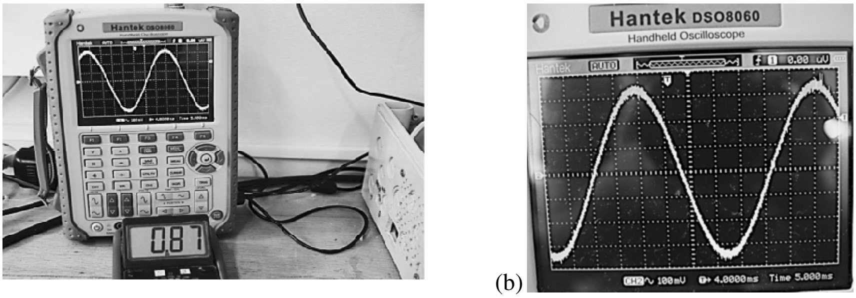


Fig. 4. General view of set up to research RCC

The mathematical model of the RCC based APF control system as shown in Fig. 2 (b) was first implemented as a simulation in Matlab 8.1 and then was loaded to the DSP controller. The RCC control was supposed to maintain a sinusoidal current at a frequency 50 Hz and amplitude of 1.2 A. This task and the width of the hysteresis gap of the RCC were programmed in the DSP controller and the program was not changed during the experiment. The current feedback obtained from the current sensor placed in series with the load was introduced to the DSP controller too (analogue input). The signal processing speed is 3 MSPS. The "bang-bang" operation produced by the RCC control resulted in driving signals applied to the power converter of the APF. The signals depend on the programmed task, the width of the hysteresis gap and the signal from the current feedback. The driving signals from the DSP controller were sent to the power converter switches (through drivers). The correct waveforms from the experiments are shown in Fig. 5 (a, b).



(a) (b)

Fig. 5. Operation of the RCC: (a) Waveform and numerical value of the load current; (b) closer view of the signal of the load current sensor

As it is verified from the waveform in Fig. 5 (a, b) and the multimeter readings, the load current (DC) is corresponding to the sinusoidal input current from the grid at a correct magnitude, phase and frequency. The variation of the load (resistance of the variable resistor) across a range of values left the waveforms always correctly corresponding to the frequency, phase and amplitude required from the energy qualiy point of view.

6 Conclusions and Future Work

According to the results from the theoretical analysis, mathematical modelling, and experiments, the proposed APF based on the power rectifier filter capacitor as a DC link is designed and verified. The APF control based on RCC and limited calculation based on "ideal" load current was investigated. According to the simulation results, the uncontrolled rectifier combined with the new APF system is an effective means of compensation for harmonic current distortion and reactive power. For the experimental verification the APF set-up has been designed, and it confirmed the good performance of the simple “bang-bang” RCC control of the APF. The application of the proposed APF control system to non-linear power converters will improve the electromagnetic compatibility of the “naturally” nonlinear consumers and the power grids. It will have a positive influence on the power system and its customers. It provides increased reliability and energy efficiency. This will be especially important for the future smart grids construction. Further work on the APF will be in experimental studies of “uncontrolled rectifier – APF” to improve the construction and control system of the proposed APF.

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