UPFC with Matrix Converter

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Acknowledgement

The Polish State Committee for Scientific Research, Project KBN No 8 T10A 050 19 supported this work.

Keywords

<<Power transmission, Distribution of electrical energy, Power conditioning, Power Quality, Active filters >>

Abstract

This paper describes unified power flow controllers (UPFC) with matrix converter. The basic problems of UPFC are discussed. The main aim of this paper is to present selected results of the analyses of the new UPFC based on matrix converter. This paper describes models of matrix converters and control rules for UPFC. Some results of simulation research are also presented in the paper.

Introduction

The developing interest in tools for power flow control in a power system has increased significantly during the last 10 years. Demand for research in this field is motivated by rapid transformations in both technology and organization of the power system industry [1]. Among the main requirements for such tools is the need to precisely satisfy in a short period of time the demand conditions for electrical energy supply. Deregulation in the power industry has led to an increasing number of competing companies, which implies a need for power flow to be controlled flexibly and locally, sometimes even at neighbourhood level. These requirements cannot be fulfilled by traditional electrical energy distribution networks [2], in particular because of sluggishness.

Flexible power flow control and high dynamics can be achieved by applying electronic power converters. It is particularly beneficial to use converters built of fully controlled switches, such as GTO, IGBT or IGCT. This technology allows the maintaining of high quality power levels. It seems that UPFCs (Unified Power Flow Controllers) are the most promising among all the available tools for power flow and quality control. Today the UPFCs are used to control power up to 180 MVA [3, 4].

The published papers [e.g., 7] deal with matrix converters that are connected in series between two AC systems. In this case the matrix converter transmits the entire amount of energy. Considering the energy properties used here, a matrix converter is more reliable as a classical UPFC. This aspect has not been proposed or analysed in previously published materials. The main aim of this paper is to present selected results of the analyses of the new UPFC proposal put forward here.

The basic relationships of UPFC

The model for power flow control between two energy systems "1" and "2" is presented in Fig. 1. The two systems represented by two voltage sources V_1 and V_2, are given by equations

$$\vec{V}_1 = V_1\, e^{j0^0}, \quad \vec{V}_2 = V_2\, e^{j\delta} \ , \tag{1a,b}$$

where: δ – the phase angle between voltages V_1 i V_2.

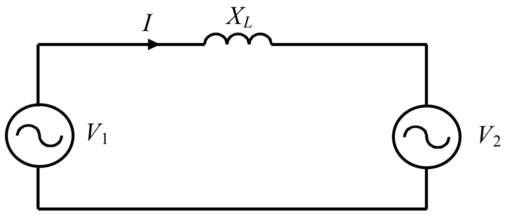

Fig. 1. Simplified diagram for the connection of two systems

The voltage sources V_1 and V_2 are connected by a power line that has inductance L. The circuit in Fig. 1 can be described by the equation

$$\vec{V}_1 = \mathrm{j} X_L \vec{I} + \vec{V}_2 \quad , \tag{2}$$

where: $X_L = \omega L$ – the line reactance.

The complex power S is

$$\vec{S} = \vec{V}_2 \cdot \vec{I} = \vec{V}_2 \left[\frac{\vec{V}_1 - \vec{V}_2}{\mathrm{j} X_L} \right] = \frac{V_1 V_2}{X_L} e^{j(90-\delta)} - \mathrm{j} \frac{V_2^2}{X_L} ; \tag{3}$$

active power P and reactive power Q are

$$P = \mathrm{Re}\left[\vec{S}\right] = \frac{V_1 V_2}{X_L} \sin\delta \ , \quad Q = \mathrm{Im}\left[\vec{S}\right] = \frac{V_1 V_2}{X_L} \cos\delta - \frac{V_2^2}{X_L} \ . \tag{4a,b}$$

Power transfer on a transmission line in an integrated network is governed by line impedance, voltage magnitudes, and phase angle difference at the ends.

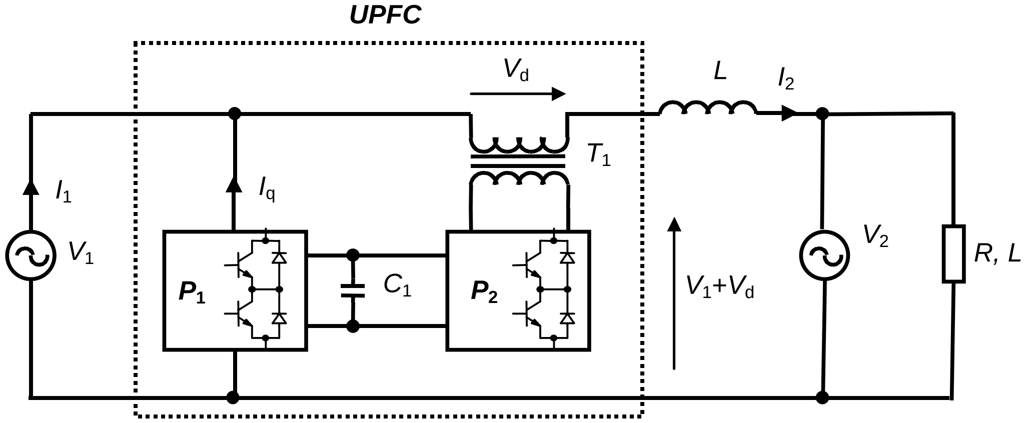

Fig. 2. Conventional UPFC built on two active power filters: parallel P_1 and series P_2

The UPFC circuit depicted in Fig. 2 consists of two controllable elements: voltage source V_d connected in series and current source I_q connected in parallel with the line at the midpoint. Series controller P_2 takes the main control. The main task for parallel controller is to provide active power for controller P_2. In addition to that, controller P_1 can compensate reactive power. The properties of the UPFC built as in Fig. 2. is well recognized. Controllers P_1 and P_2 are typical universal structures of DC/AC converters.

The same principles as above are applied to regulation performed by UPFC and it can be explained by using the phasor diagram in Fig. 3. Equation (4a) indicates that power flow control is based on the changes:

- line voltage amplitudes V_1 i V_1+V_d,
- phase shift between voltages V_1 and V_1+V_d,
- line impedance X_L.

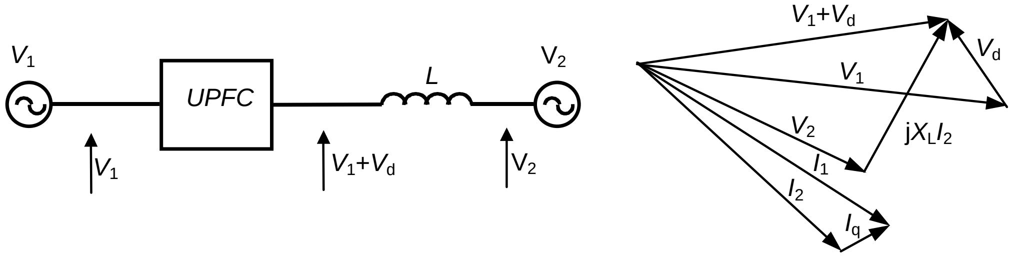

Fig. 3. Phasor representation of voltages and currents in a power flow control circuit with UPFC

The phasor representations of voltages and currents in a UPFC circuit for compensating current equal to zero is presented in Fig. 4.

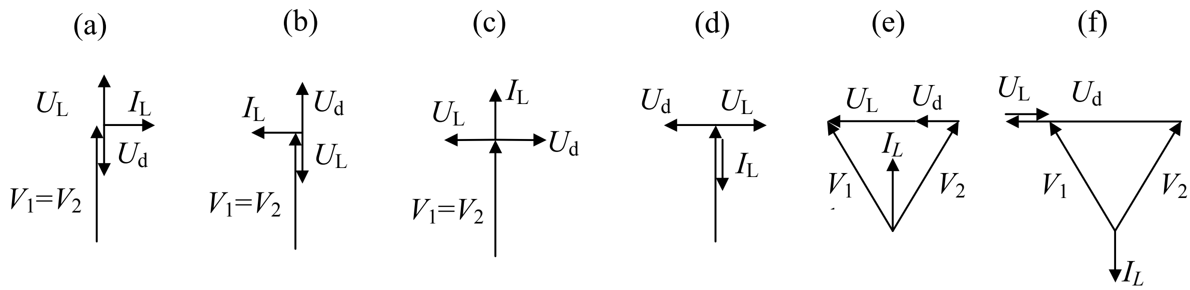

Fig. 4. The phasor representation of voltages and currents in a UPFC circuit for compensating current equal to zero: (a), (b), (c), (d) equal magnitudes and phase angles of V_1 and V_2; (e), (f) equal magnitudes of V_1 and V_2

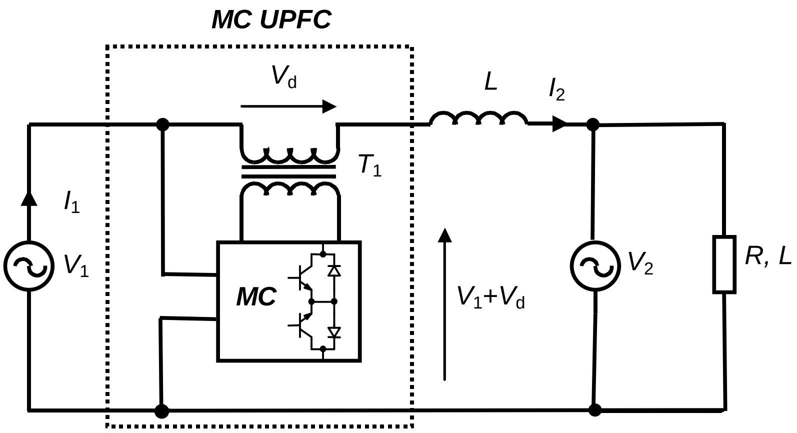

Fig. 5. A simplified diagram of a UPFC with matrix converter

As an alternative to the classical UPFC based on AC/DC and DC/AC converters it is possible to use matrix converters. Matrix converters are also accepted as the most universal power electronics units [6]. In a typical solution the matrix converter transmits the entire amount of energy [7]. In Fig. 5 the proposed UPFC based on a matrix converter is presented. This solution has the following advantages:

- only part of the transmitted energy is flowing through the matrix converter,
- the matrix converter is simpler than two AC/DC and DC/AC converters,
- the matrix converter has more future potential.

Model description of the three phase matrix converter

The presented three-to-single-phase matrix unit is shown in Fig. 6. This unit is useful for all kinds of loads, if one of the bidirectional switches is closed. In such case the modulation functions for the models are: $m_A(t)$, $m_B(t)$, $m_C(t)$. These functions must fulfil the condition

$$m_A+m_B+m_C=1 \quad . \tag{5}$$

Output voltages and input currents are given as

$$[u_L(t)]=[m_A(t), \quad m_B(t), \quad m_C(t)]\begin{bmatrix} u_A(t) \\ u_B(t) \\ u_C(t) \end{bmatrix} \quad , \tag{6}$$

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} m_A(t) \\ m_B(t) \\ m_C(t) \end{bmatrix} [i_L(t)] \quad . \tag{7}$$

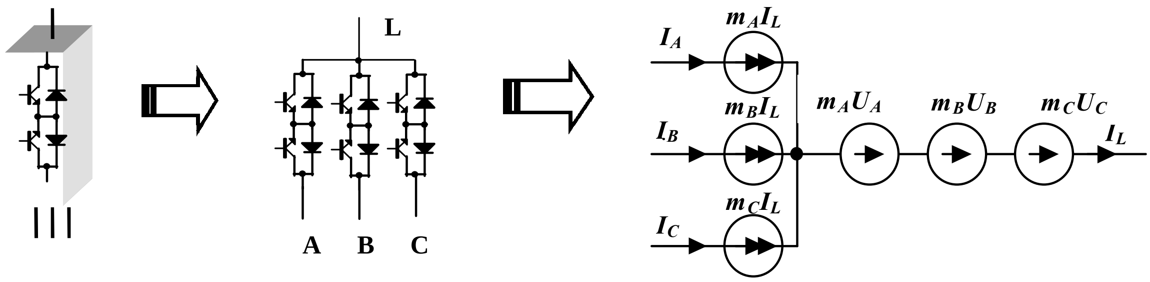

Fig. 6. The three-to-single-phase matrix converter

A similar approach can be used for building models for another matrix converter. The two models shown in Fig. 7 can represent particularly the three-to-single-phase bridge. Different modulation functions are used in this case: $m_A(t)$, $m_B(t)$, $m_C(t)$ and $m'_A(t)$, $m'_B(t)$, $m'_C(t)$. Output voltages and input currents for this bridge are given by the equations:

$$[u_L(t)]=[m_A-m'_A, \quad m_B-m'_B, \quad m_C-m'_C]\begin{bmatrix} u_A(t) \\ u_B(t) \\ u_C(t) \end{bmatrix}, \tag{8}$$

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} m_A-m'_A \\ m_B-m'_B \\ m_C-m'_C \end{bmatrix} [i_L(t)] \quad , \tag{9}$$

where the modulation functions: $m_A=m_A(t)$, $m_B=m_B(t)$, $m_C=m_C(t)$, $m'_A=m'_A(t)$, $m'_B=m'_B(t)$, $m'_C=m'_C(t)$ fulfil the conditions

$$m_A+m_B+m_C=1 \text{ and } m'_A+m'_B+m'_C=1 \quad . \tag{10a, b}$$

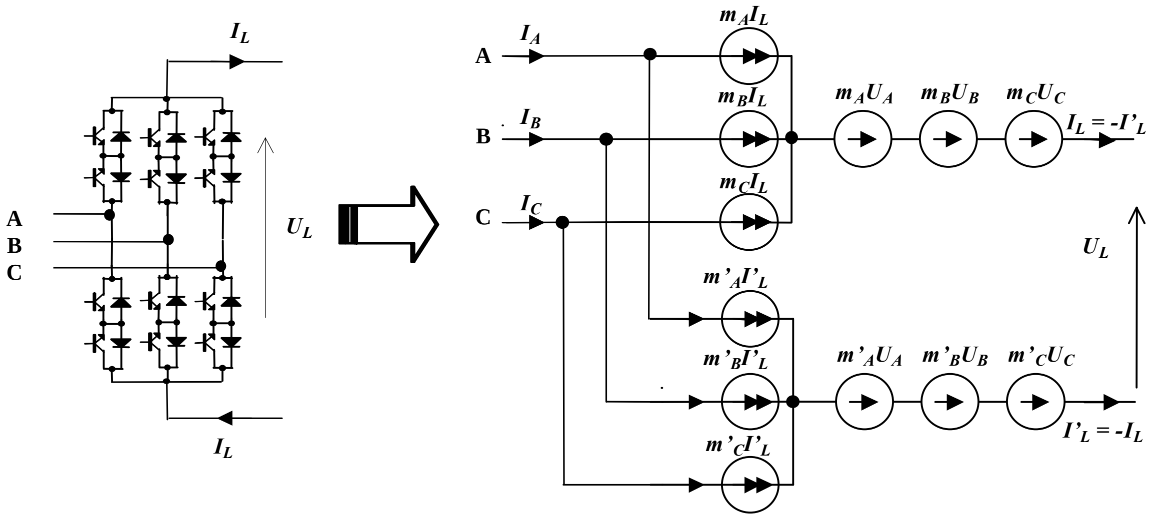

Fig. 7. Model of a three-to-single-phase matrix bridge

The matrix converter with multi-phase input and output are described by the equations

$$[u_{Li}(t)] = [M_{ij}(t)][u_j(t)] \quad , \tag{11}$$

$$[i_j(t)] = [M_{ij}(t)]^T [i_{Li}(t)] \text{ , for } i,j=1,2,... \quad , \tag{12}$$

$$\begin{bmatrix} u_{LA}(t) \\ u_{LB}(t) \\ u_{LC}(t) \end{bmatrix} = \underbrace{\begin{bmatrix} m_{AA}(t) & m_{AB}(t) & m_{AC}(t) \\ m_{BA}(t) & m_{BB}(t) & m_{BC}(t) \\ m_{CA}(t) & m_{CB}(t) & m_{CC}(t) \end{bmatrix}}_{M(t)} \begin{bmatrix} u_A(t) \\ u_B(t) \\ u_C(t) \end{bmatrix} , \tag{13}$$

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \underbrace{\begin{bmatrix} m_{AA}(t) & m_{BA}(t) & m_{CA}(t) \\ m_{AB}(t) & m_{BB}(t) & m_{CB}(t) \\ m_{AC}(t) & m_{BC}(t) & m_{CC}(t) \end{bmatrix}}_{M^T(t)} \begin{bmatrix} i_{LA}(t) \\ i_{LB}(t) \\ i_{LC}(t) \end{bmatrix} \tag{14}$$

where: $i_{Li}(t)$, i=1, 2, … – output voltages; $u_j(t)$, j=1, 2, … – input voltages; $M_{ij}(t)$ - the matrix of modulation functions.

To apply the above model we need to increase the number of controlled current and voltage sources. For example, models with three phase input and output circuits consist of three separate three-to-single-phase models connected by input circuits (Fig. 6 and Fig. 7.). For this particularly important case the equations (13) are modified to equations (14). The input and output phases A, B, C are related to the i,j=1, 2, 3.

The control of a matrix UPFC

It is the main requirement for a UPFC to allow the power factor to be controlled or to be equal to one. In such circumstances the three phase matrix converter does not take reactive power from a power system and can even control and compensate the reactive power circulation. For this purpose the matrix converter must be controlled using a linear combination of modulation functions. The matrix of modulation functions (if the converter works with a power factor equal to one) is the sum of two independent matrixes:

$$\left[M_{ij}(t)\right]=\left[M_{ij}^{+}(t)\right]+\left[M_{ij}^{-}(t)\right] \tag{15}$$

The three-phase UPFC with matrix converter is presented in Fig. 8. In this particular case, because the output frequency is equal to input frequency [8], the modulation functions are given by the equations:

$$m_{ij}^{+}(t)=\frac{1}{6}-\frac{\gamma_{+}}{6}\cos\left[2\omega_{L}t-(j-1)120^{\circ}-(i-1)120^{\circ}+\chi\right] \quad , \tag{16}$$

$$m_{ij}^{-}(t)=\frac{1}{6}+\frac{\gamma_{-}}{6}\cos\left[-(j-1)240^{\circ}-(i-1)120^{\circ}+\chi\right] \quad , \tag{17}$$

where: $\gamma\in$ (0, 1) - amplitude coefficient and $\gamma=\gamma_{+}+\gamma_{-}$, χ - voltage phase shift.

Using equations (13) and (15) we can prove that modulation functions (17) permit matrix converter output voltages given by the equations:

$$u_{di}(t)=\frac{\gamma}{2}U_{m}\sin\left(\omega_{L}t+\chi-(i-1)120^{\circ}\right) \quad \text{for configuration like in Fig. 6 ,} \tag{18}$$

$$u_{di}(t)=\gamma U_{m}\sin\left(\omega_{L}t+\chi-(i-1)120^{\circ}\right) \quad \text{for configuration like in Fig. 7 .} \tag{19}$$

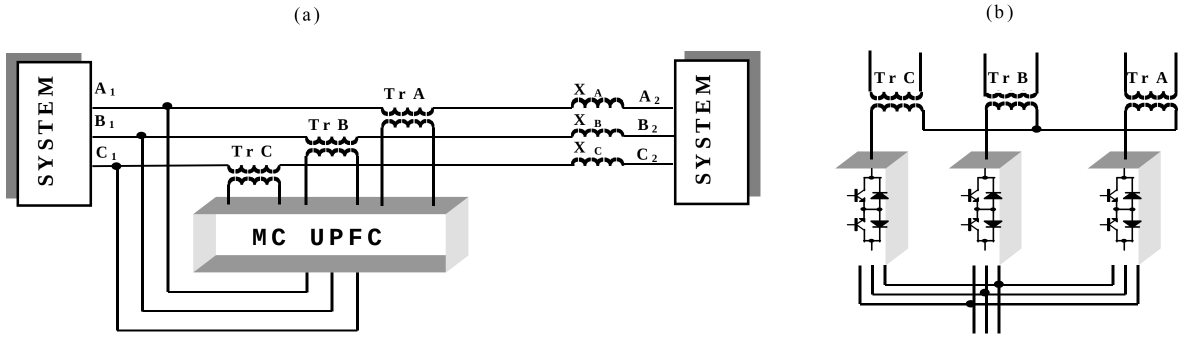

Fig. 8. The three-phase UPFC with matrix converters: a) scheme, b) example of the converter

These voltages are obtained when the power factor is equal to one. Changing the coefficient γ and phase shift χ (a shift between input system voltage and UPFC output) we can achieve regulating capability in a power system. This control of a power system appears to be the same as a traditional UPFC [2, 3, 4].

Simulation results

All the simulations were made using Matlab Power System Blockset. The simulation results of the UPFC with matrix converter are the subject of this section. These results are obtained based on continuous modulation functions. One of the methods for transforming continuous functions to impulse functions is presented in Fig. 9. From a practical point of view the results obtained by using this model and continuous functions have enough precision. The analysis of complex electric systems could also be simplified by applying this approach.

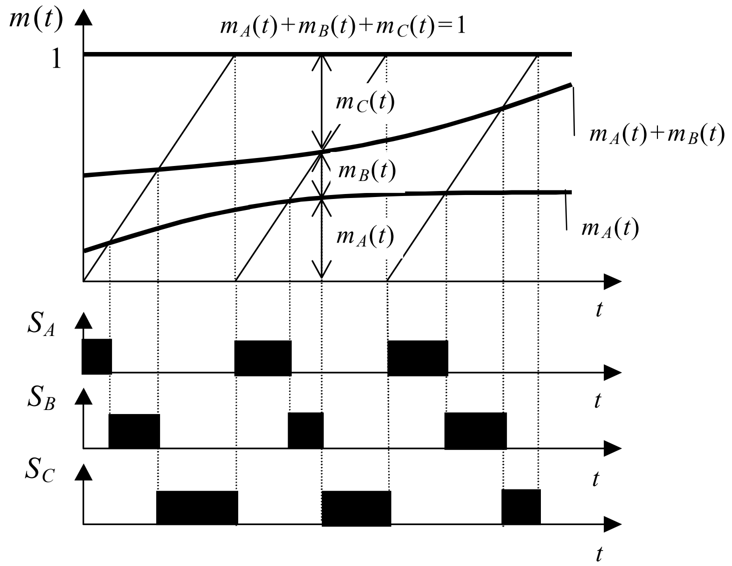

Fig. 9. Method employed for transforming continuous functions to impulse functions

The simulations were made for input V_i and output V_o voltage frequency equal to f_o=50 Hz. Spectrum of output voltage V_o for different switching frequency is presented in Fig. 10. For MC UPFC the switching frequency f_n=5 kHz is chosen. The control algorithm is described by the equation

$$\begin{bmatrix} u_{oa} \\ u_{ob} \\ u_{oc} \end{bmatrix} = \begin{bmatrix} m_+(1)+m_-(1) & m_+(2)+m_-(3) & m_+(3)+m_-(2) \\ m_+(2)+m_-(2) & m_+(3)+m_-(3) & m_+(1)+m_-(2) \\ m_+(3)+m_-(3) & m_+(1)+m_-(2) & m_+(2)+m_-(1) \end{bmatrix} \cdot \begin{bmatrix} u_{ia} \\ u_{ib} \\ u_{ic} \end{bmatrix} , \tag{20}$$

and amplitude modulation coefficients for functions m_+ and m_-

$$\gamma_+ = (V_o/V_i)(1-(\tan(\varphi_i)/\tan(\varphi_o))) , \quad \gamma_- = (V_o/V_i)(1+(\tan(\varphi_i)/\tan(\varphi_o))) . \tag{21a, b}$$

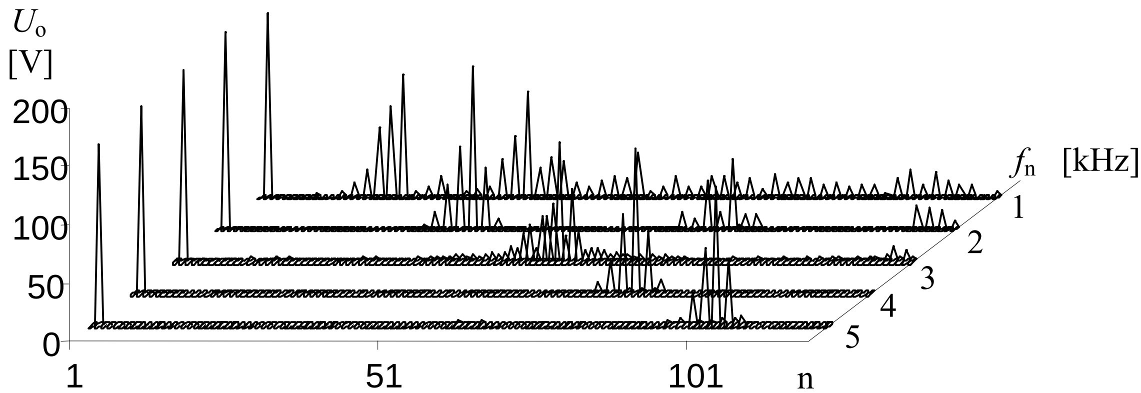

Fig. 10. Spectrum of output voltage V_o for different switching frequency

The linear dependence of output voltage to modulation coefficient γ is depicted in Fig. 11. Dependence of output power to modulation coefficients is illustrated in Fig. 12. Output voltage and output current for different power coefficients is shown in Fig. 13.

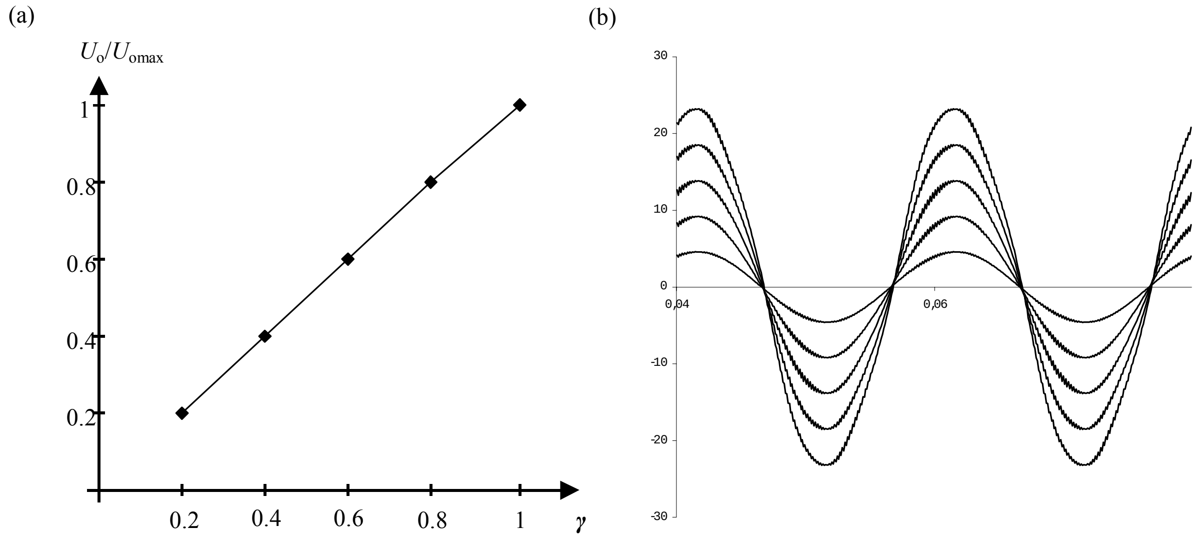

Fig. 11. Dependence of output voltage to modulation coefficient γ (a), output current for controlling output voltage for: γ=0.2, γ=0.4, γ=0.6, γ=0.8, γ=1 (b)

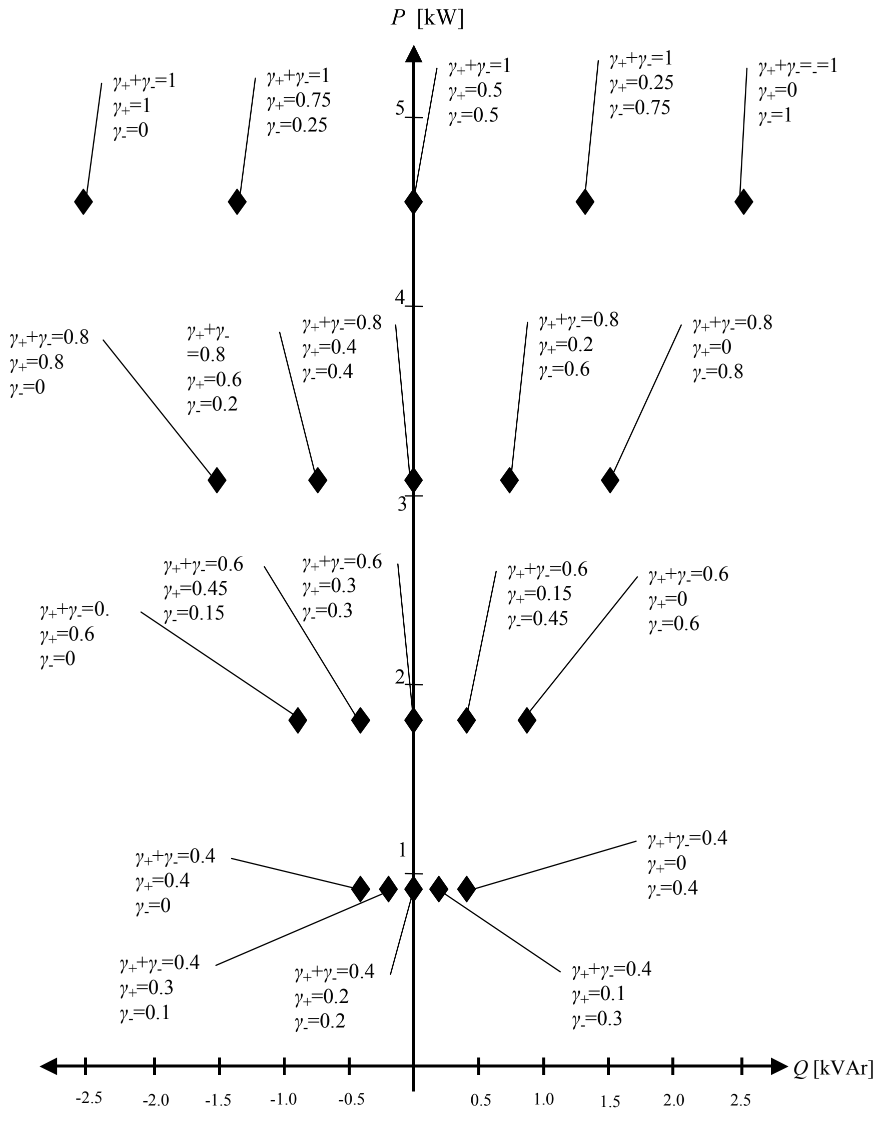

Fig. 12. Dependence of output power to modulation coefficients

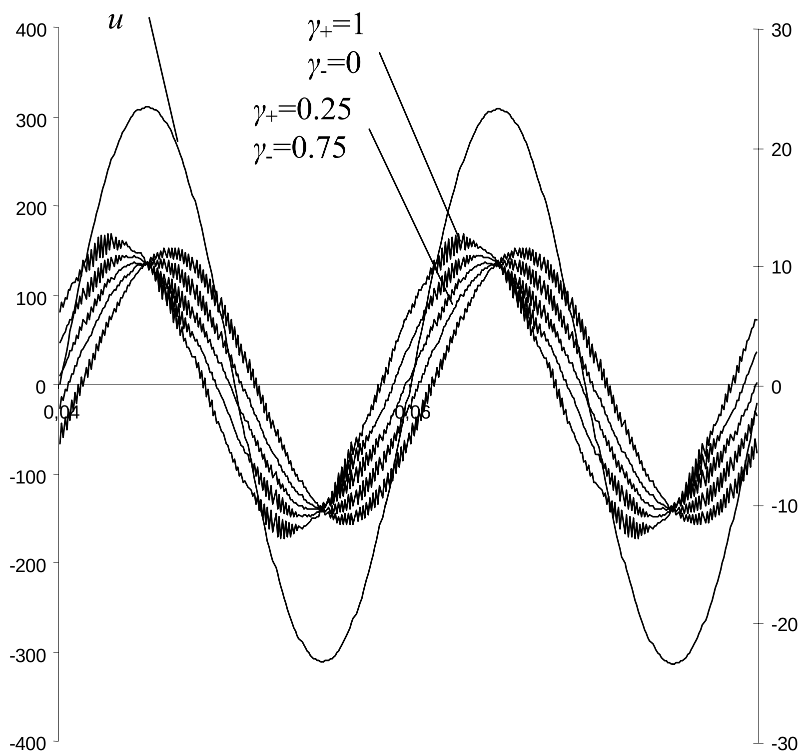

Fig. 13. Output voltage and output currents for different power coefficients

Conclusions

The main advantages of a UPFC based on a matrix converter is functional flexibility dependent on control algorithms. The proposed UPFC is able to control the full range of power flow and the power coefficient as is a conventional power flow controller. A UPFC based on a matrix converter is not suitable for application where supply voltages are asymmetrical because the converter does not store energy. A UPFC with matrix converter is useful only for multiphase circuits.

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