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THE MATRIX CONVERTER – – A UNIVERSAL POWER ELECTRONIC UNIT

SUMMARY

The main purpose of this paper is to point out the universality of matrix converters under the proposed control strategy. This strategy, being invented from mathematical description of the matrix converter, allows solving the problem of transformation of an N-phase system of voltages and currents with frequency f_1 to an M-phase system with frequency f_2 maintaining their symmetry. The example of the 3x3 matrix converter shows how to create, so called, conducting areas of matrix converter switching elements. It has been pointed out that such a matrix converter constitutes a universal power electronic unit, whose functions can be stimulated by the choice of an elementary conducting area.

1. INTRODUCTION

The topology of the matrix converter is known for some time and various strategies of its control have been devised [1] [3] [4] [6] [7] [9]. In this paper a specific strategy is investigated which follows from mathematical description

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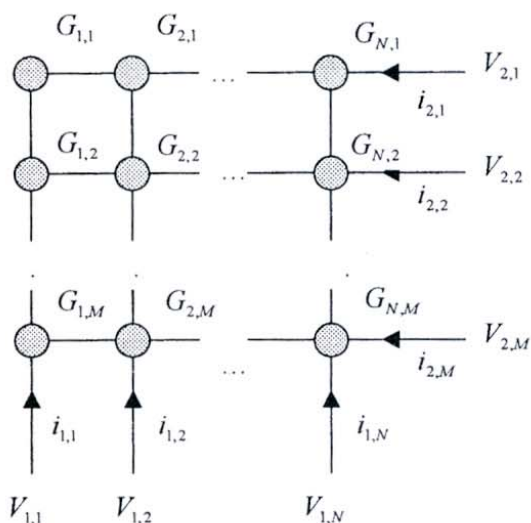


Fig.1. The topology of the $N \times M$ matrix converter.

points of input and output lines and constitute a matrix with rows and columns.

of the matrix converter [4]. The matrix converter is a typical AC-AC converter without any intermediate DC link. Generally, it is expected that such converters constitute an energy source with any required parameters, i.e. a voltage or current source with required amplitude, phase and frequency, and for multi-phase case also a number of phases with a required sequence and a symmetry level.

The topology of the matrix converter transforming energy form N -phase system to M -phase system is shown in Fig.1. The switching elements are located in the cross

2. A UNIVERSAL CONTROL STRATEGY

The required task of the matrix converter from Fig.1 is to transform an N -phase, symmetric system of voltages and currents with pulsation ω_1 to an M -phase symmetric system of voltages and currents with pulsation ω_2 . To do it, a special strategy for the changes of the states of the matrix converter switching elements has been proposed in [4] and now is recalled.

By intuition it can be stated that these state changes should depend on both input and output pulsations. Let the switching elements to be assumed as ideal, i.e. conducting current in both directions and switching on and off in an arbitrary time instant, and represented by conductances $G_{n,m}$. Then, all switching elements can be modeled by conductances which vary in time both with respect to the period of input quantities $T_1 = 2\pi / \omega_1$ and with the period at the output $T_2 = 2\pi / \omega_2$, i.e. double-periodically with time.

In this paper a control strategy is investigated which assumed that if the conductance $G_{1,1}$ varies in time according to the double-periodical function $G(t)$ having the Fourier series:

$$G_{1,1} = G(t) = \sum_{r=-\infty}^{\infty} \sum_{s=-\infty}^{\infty} G_{r,s} e^{jr\omega_1 t} e^{js\omega_2 t} \quad (2.1)$$

the conductances $G_{n,m}$ of other switching elements should vary with time according to the formula:

$$G_{n,m} = \sum_{r=-\infty}^{\infty} \sum_{s=-\infty}^{\infty} G_{r,s} e^{jr[\omega_1 t - (n-1)\frac{2\pi}{N}]} e^{js[\omega_2 t - (m-1)\frac{2\pi}{M}]} \quad (2.2)$$

The main advantage of such control strategy is: it maintains the symmetry of multiphase systems of voltages and currents for both the input and output, if the connected systems on both sides of the converter are symmetrical. The symmetry of a multiphase system means, that for each frequency, the phase and line quantities constitute symmetrical systems of a given sequence.

However, the conductance functions $G_{n,m}$ in the form of double Fourier series are practically useless for finding the time instants of the state changes of the matrix converter switching elements. The following geometrical interpretation of those functions is very useful. Let two auxiliary variables:

$$x = \omega_1 t \quad \text{and} \quad y = \omega_2 t \quad (2.3)$$

the introduced. The function $G(t)$ determining the changes of the state of the element $G_{1,1}$ can be considered as a function $G(x, y)$ of two independent variables which is periodic with respect to both of them:

$$G(x, y) = G(x + 2\pi, y) = G(x, y + 2\pi) \quad (2.4)$$

The conductance function of the element $G_{1,1}$ can now be described by the function:

$$G_{1,1} = G(x, y) = \sum_{r=-\infty}^{\infty} \sum_{s=-\infty}^{\infty} G_{r,s} e^{jrx} e^{jsy} \quad (2.5)$$

An exemplary function is shown in Fig.2. It assumes a rather big value over the conducting area $G_{1,1}$ and is equal to zero outside.

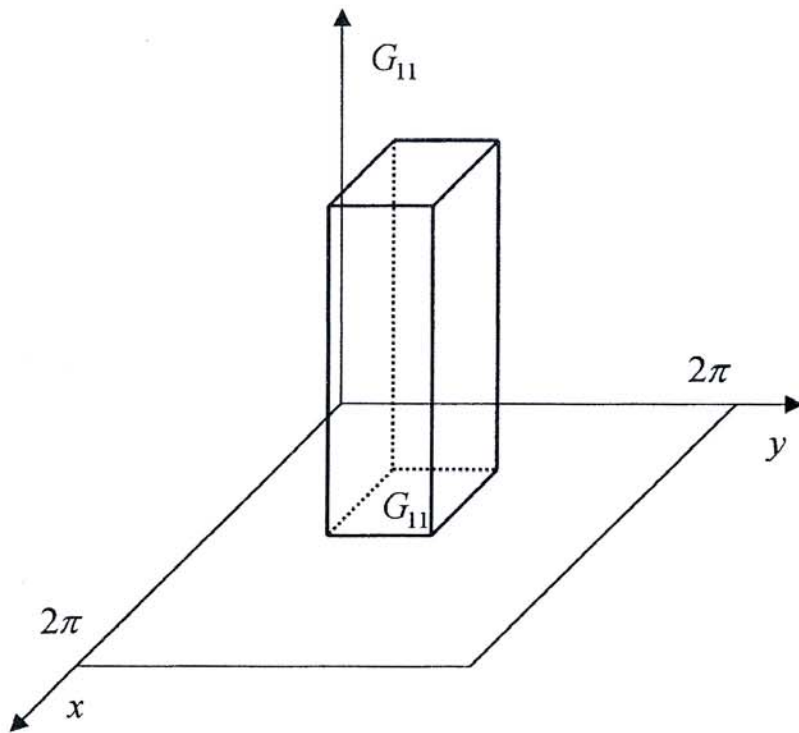


Fig.2. An exemplary conductance function $G_{1,1}$.

The other conductances $G_{n,m}$ are described by the series:

$$G_{n,m} = \sum_{r=-\infty}^{\infty} \sum_{s=-\infty}^{\infty} G_{r,s} e^{jr[x-(n-1)\varepsilon_N]} e^{js[y-(m-1)\varepsilon_M]} \quad (2.6)$$

where: $\varepsilon_N = 2\pi / N$ and $\varepsilon_M = 2\pi / M$. Comparing series (2.5) and (2.6) it can be stated that the conductance function $G_{n,m}$ is displaced on a plane x, y with respect to the function $G(x, y)$ according to the formula:

$$G_{n,m} = G[x - (n-1)\varepsilon_N, y - (m-1)\varepsilon_M] \quad (2.7)$$

The placements of conducting areas over which the switching elements $G_{1,1}$ and $G_{n,m}$ are in the on-state are shown in Fig.3.

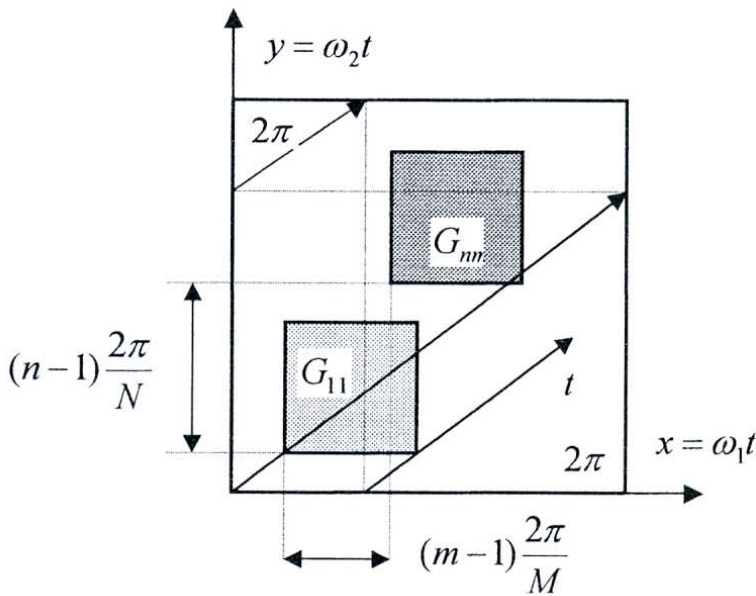


Fig.3. The idea of a control strategy.

That interpretation of the conductance functions leads to very simple determination of the time instants of the state changes of each switching element of the matrix converter. Therefore, it is enough to draw the conducting areas of all switching elements in the square $0 \leq x \leq 2\pi$ and $0 \leq y \leq 2\pi$, since all functions are periodic. On this square time runs along a trajectory described by actual values $x(\bmod 2\pi)$ and $y(\bmod 2\pi)$, found by (2.3). When the time trajectory enters an area $G_{n,m}$, the element $G_{n,m}$ switches to the on-state. When the trajectory is coming out of an area $G_{n,m}$, the element $G_{n,m}$ switches to the off-state. In this way the time instant of the states of all switches can be determined by the

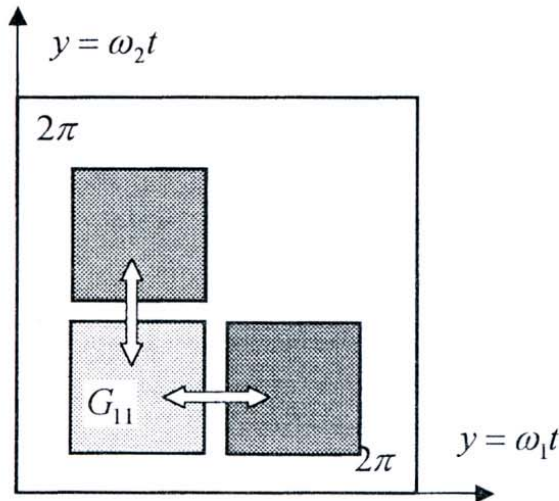


Fig.4. The idea of control by shifting the area $G_{1,1}$.

shape and placement of the area $G_{1,1}$ only. Then, the shape and placement of area $G_{1,1}$ determine the state changes of all elements of a matrix converter and in consequence, they determine relations between input and output voltages and currents. Then, modifying or shifting the area $G_{1,1}$ it is potentially possible to control voltages and currents on both sides of the converter. It is explained by Fig.4 and Fig.5.

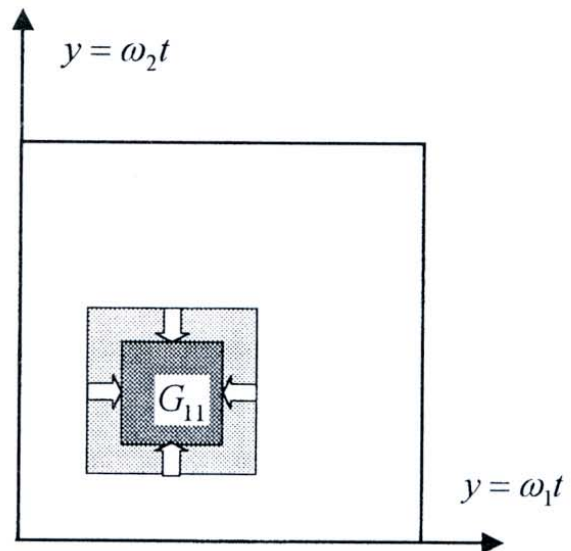


Fig.5. The idea of control by modifying the area $G_{1,1}$.

3. AN EXAMPLE – THE 3×3 MATRIX CONVERTER

The 3×3 matrix converter is investigated here, being promising for power applications. Its topology is given in Fig.6.

For such a converter the conducting area $G_{1,1}$ shown in Fig.7 can be considered as the basic one [4] [5]. The conducting areas of other converter elements are shown in Fig.8.

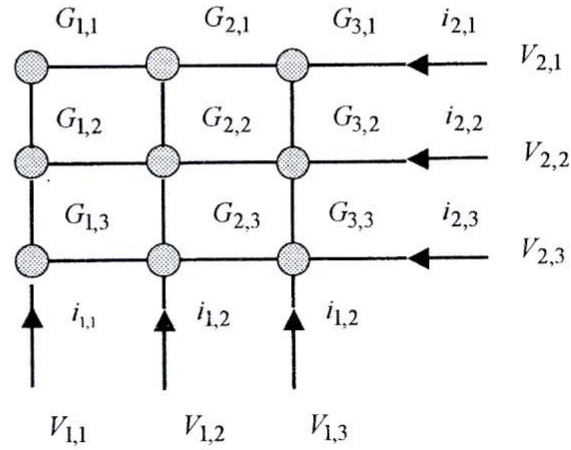


Fig.6. Topology of the 3×3 matrix converter.

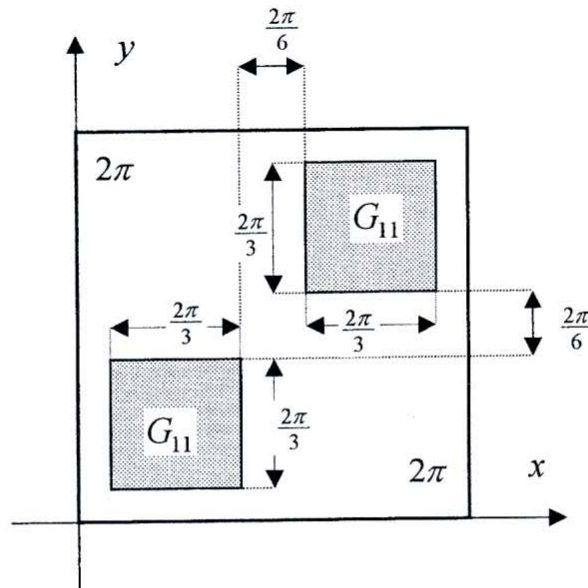


Fig.7. Basic conducting area $G_{1,1}$ of the 3×3 matrix converter.

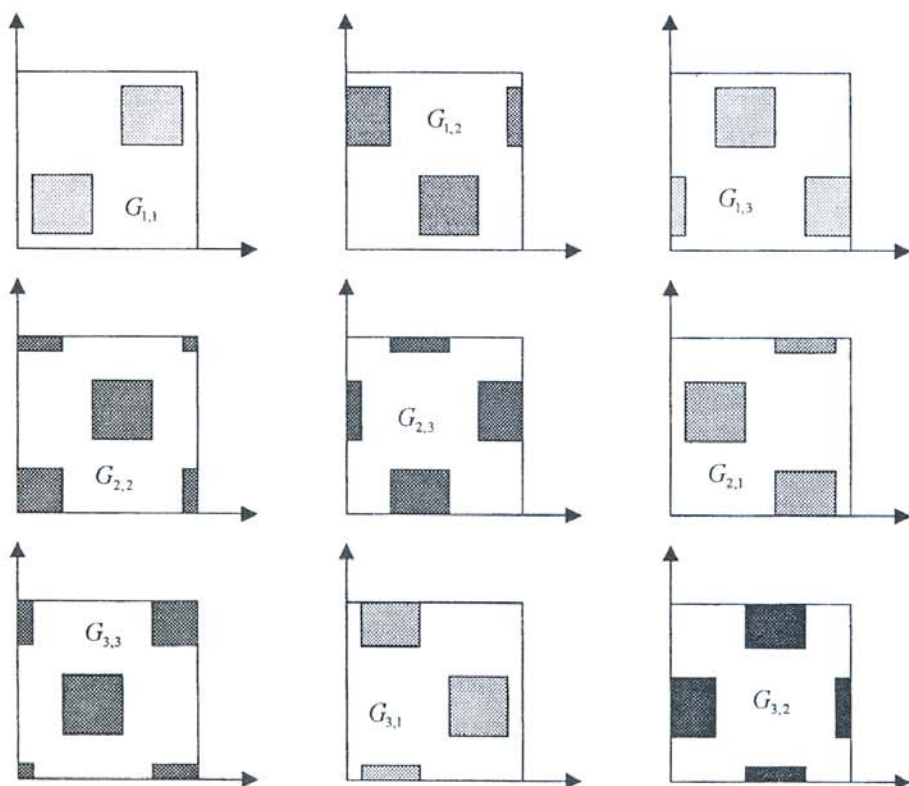


Fig.8. Conducting areas of each converter element.

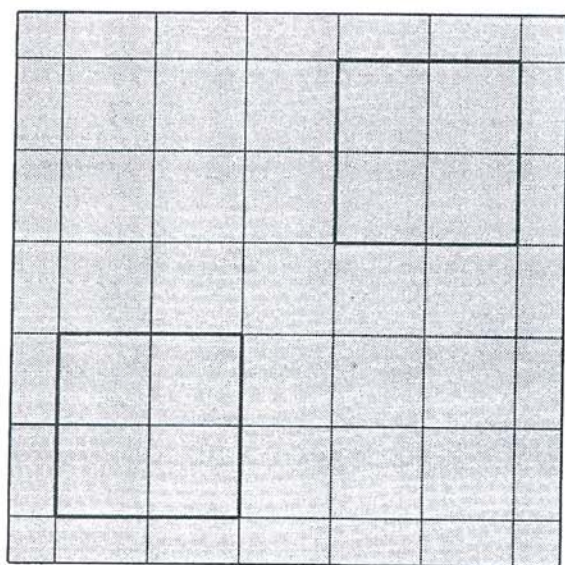


Fig.9. Elementary areas for the basic area $G_{1,1}$.

Putting together all these areas it is easy to conclude that the square $(0 \leq x \leq 2\pi, 0 \leq y \leq 2\pi)$ is exactly divided into 36 elementary areas. The conducting areas of two different elements cover each of them twice. It means that two and only two elements are always in the on-state and no short circuit can appear in the converter for external voltages. Such elementary areas are shown in Fig.9.

However, when the area $G_{1,1}$ is modified, i.e. is smaller in both directions, the elementary areas change to those shown in Fig.10 (the basic area $G_{1,1}$ from Fig.7 is presented by dashed lines in this figure). There are areas covered twice by conducting areas of two different elements, thus there are closed loops for current, but there are also areas where a closed loop is not created and the current cannot flow.

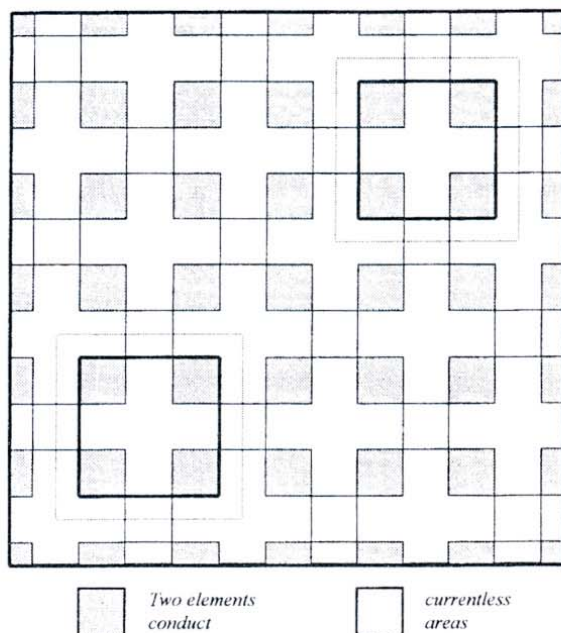


Fig.10. Elementary areas for a modified area $G_{1,1}$.

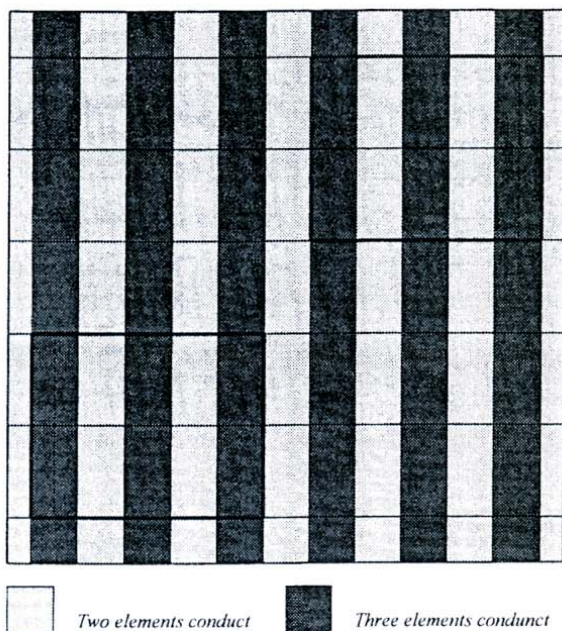


Fig.11. Elementary areas for the area $G_{1,1}$ modified in the x direction only.

Enlarging the area $G_{1,1}$ in the x direction only (the basic area $G_{1,1}$ is shown by dashed lines), the elementary areas are quite different and are shown in Fig.11. There are the areas three times covered by conducting areas of different elements (then three elements are in the on-state) and there are areas covered twice, as before. It should be noticed that when three elements are in the on-state a short circuit has to arise. In the considered case short circuits for input voltages appear.

Choice of the conducting area $G_{i,j}$ is a rather fundamental problem for the proposed control strategy of the matrix converter. The basic conducting area in Fig.7 and its simple modifications in Fig.10 and Fig.11 (other similar ones are possible) have been predicted basing on the knowledge of "classical" rectifiers and inverters. The experience in power electronics and engineering intuition suggest shapes of the conducting area $G_{i,j}$ corresponding to the PWM technique for the DC-AC inverters. The idea of such shapes is presented in Fig.12a. In this elementary case there are six pulses per period only but chosen in such a way that always two elements are in the on-state and a short circuit cannot appear, like for the basic area in Fig.7. More advanced analysis leading to multi-pulse conducting areas $G_{i,j}$ for the 3×3 matrix converter and for the $N \times M$ matrix converters is presented in [5] and [8], [9] respectively.

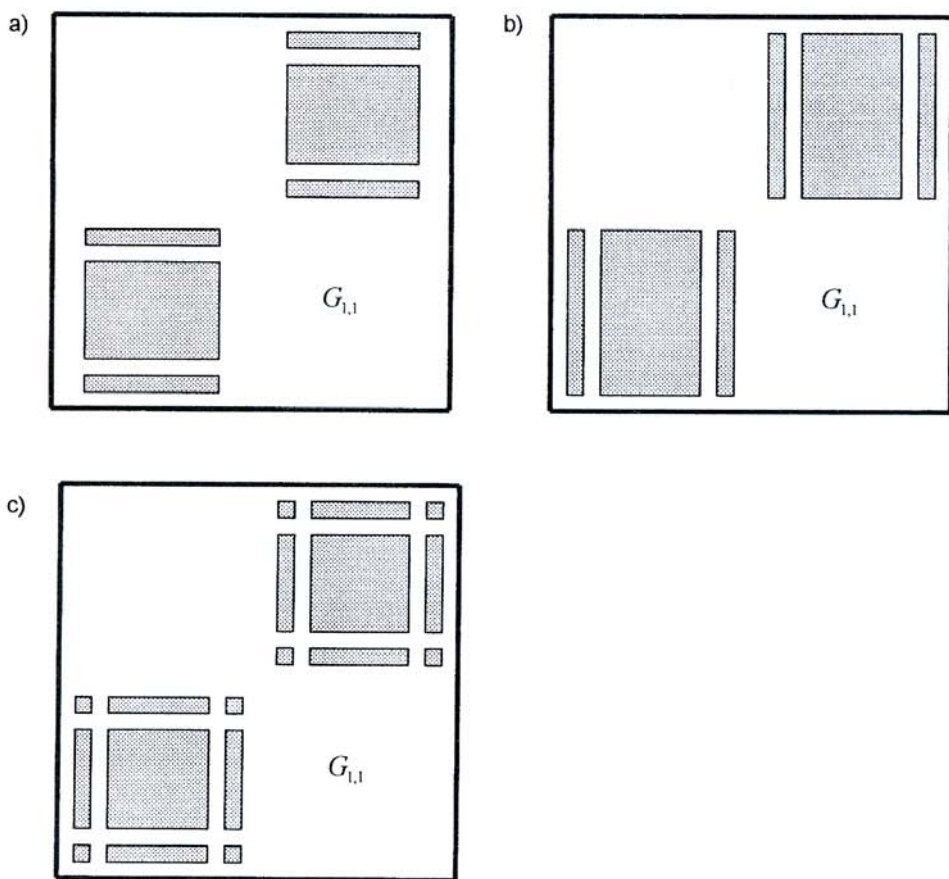


Fig.12. An exemplary multi-pulse conducting area $G_{i,j}$.

The same can be done for the direction y , which leads to the area shown in Fig.12b, or for both directions as it is shown in Fig.12c.

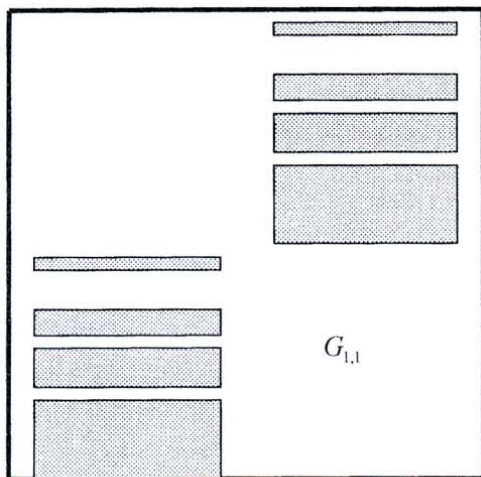


Fig.13. A modified multi-pulse conducting area $G_{1,1}$.

Another possible shape of the conducting area $G_{1,1}$ is presented in Fig.13. It is also the area of the PWM type, but the symmetry is lost with respect to $y = \pi/2$ and $y = 3\pi/2$. For such a shape two elements are also always in the on-state and a short circuit cannot appear.

It is a big advantage of the proposed control strategy that all possible states of the matrix converter can be precisely predicted by very simple geometrical considerations - just drawing the areas of all elements and looking for areas covering each other. The generated states of the converter are

independent of frequencies both at input and output. At the end, the time trajectory in the square ($0 \leq x \leq 2\pi, 0 \leq y \leq 2\pi$) can also be almost arbitrarily created by an external control system.

All $G_{1,1}$ areas, presented in this chapter, have been determined by intuition basing on the knowledge of power electronics. However, the problem how to find a required or an optimum conductance area $G_{1,1}$ using mathematical methods is generally not solved.

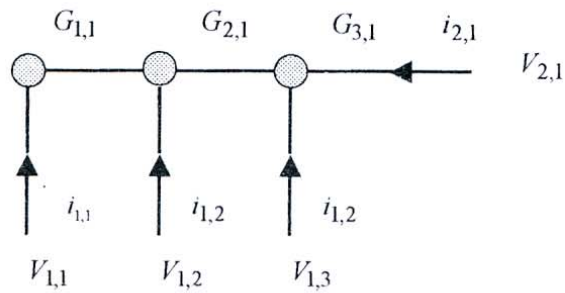
4. UNIVERSALITY OF THE MATRIX CONVERTER

Having the $N \times M$ matrix converter, any sub-converter with the phase numbers less than N and M can be created by changing the conductance area $G_{1,1}$ only. For the 3×3 matrix converter, considered in Chapter 3, the converters: 3×1 , 3×2 , 2×3 and 1×3 can be realized. Those topologies and the con-

ductance area $G_{1,1}$ belonging to them, are given in the following figures: Fig.14 through Fig.17. All conducting areas in these figures correspond to the basic conducting area $G_{1,1}$ shown in Fig.3. Then, each of them can be modified as it has been done for the 3×3 matrix converter in Chapter 3.

The matrix converter shown in the Fig.14 can be used as a one-way rectifier ($\omega_2 = 0$). The matrix converter in Fig.15 can work as a two-way rectifier but also as an AC-AC inverter, which changes the number of phases from 3 to 1 and, at the end as a symmetrizer of a one-phase load to a 3-phase system.

a)



b)

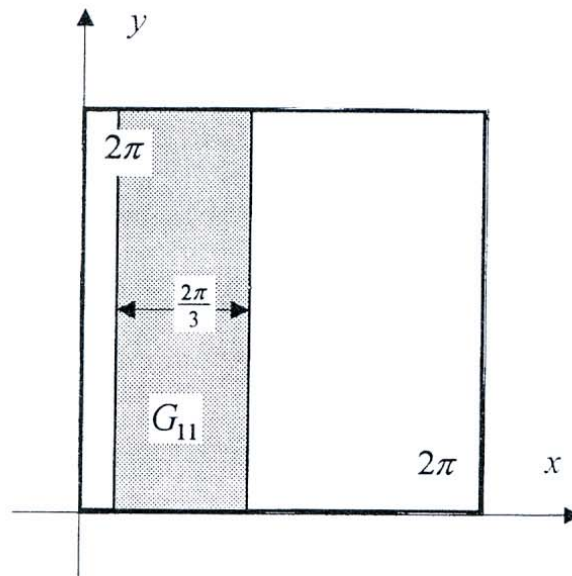
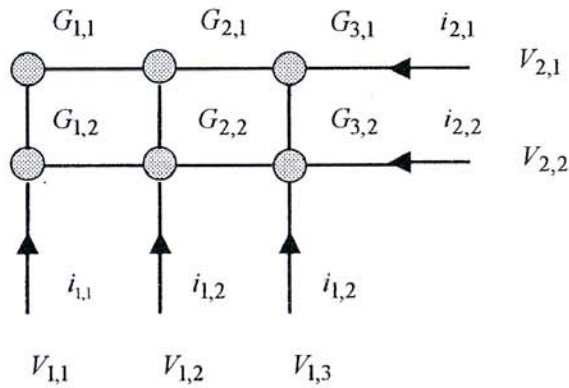


Fig.14. The 3×1 matrix converter and a basic conductance area $G_{1,1}$.

a)



b)

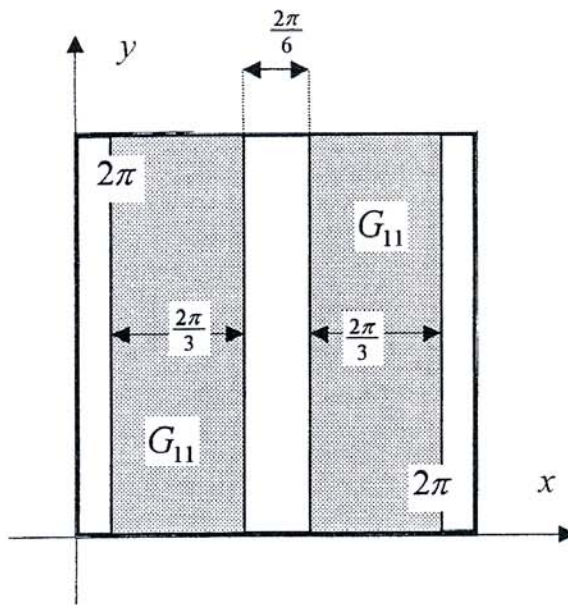


Fig.15. The 3×2 matrix converter and a basic conductance area $G_{1,1}$.

The matrix converter in Fig.16 represents a typical DC-AC inverter but it can also be used as an AC-AC converter from a one-phase to a three-phase system. The topology in Fig.17 can be used to distribute the DC signal into three phases. These are only exemplary applications.

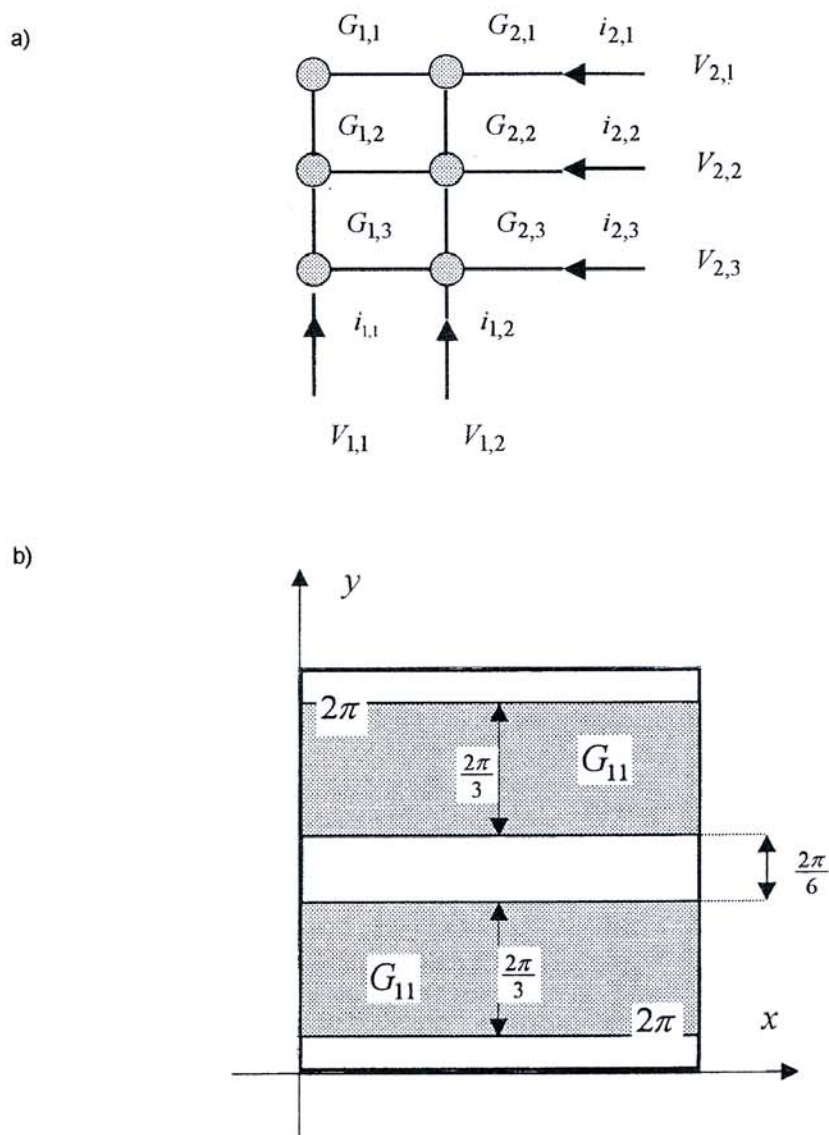
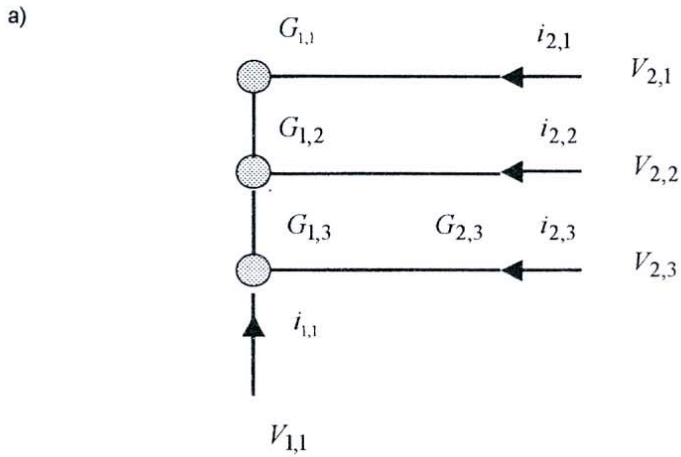


Fig.16. The 2×3 matrix converter and a basic conductance area $G_{1,1}$.

Then, physically the same unit can be used for quite different applications. Assuming that the matrix converter is controlled digitally by a DSP module it can be obtained by changing only the software, which realizes an universal control strategy described in this paper.

It should be recalled that the proposed strategy requires, generally, ideal switches conducting current in both directions and switched on and off in an

arbitrary time instant. It is expected that such semiconductor elements should be available in next few years.



b)

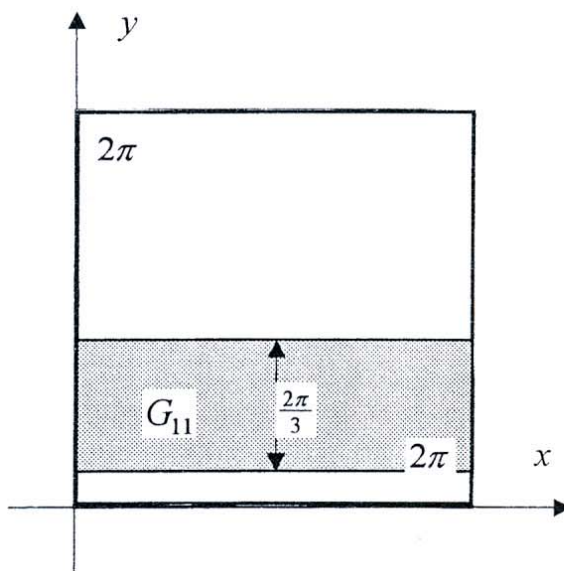


Fig.17. The 1×3 matrix converter and a basic conductance area $G_{1,1}$.

5. CONCLUSIONS

In the paper a universal control strategy for the class of the $N \times M$ matrix converters is presented, which allows to foresee the transformation of voltages and currents independently of the input and output frequencies. The geometrical interpretation leads to a rather simply recognition of the states of all switching elements in the matrix converter and constitutes a base for creating a digital algorithm for a matrix converter control.

By an example of the 3×3 matrix converter it has been explained how this strategy works and that the matrix converter can be a universal power electronic unit of the future.

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PRZEKSZTAŁTNIK MACIERZOWY – – UNIWERSALNY UKŁAD ENERGOELEKTRONICZNY

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STRESZCZENIE *Głównym celem pracy jest wskazanie uniwersalności przekształtników macierzowych sterowanych według zaproponowanej strategii. Strategia ta, ma swoje źródło w matematycznym opisie przekształtnika macierzowego. Pozwala ona jednocześnie rozwiązywać problemy przetwarzania N fazowego układu napięć i prądów o częstotliwości f_1 w M fazowy układ o częstotliwości f_2 , zachowując ich symetrię. W pracy, na przykładzie przekształtnika 3×3 , omówiono zasady wyznaczania tzw. obszarów przewodzenia poszczególnych łączników przekształtnika oraz wskazano na możliwości wykorzystania przekształtnika jako uniwersalnego układu energoelektronicznego, którego zadania mogą być kształtowane jedynie w wyniku zmiany elementarnego obszaru przewodzenia.*



Prof. Tadeusz J. Sobczyk was born (1944) and educated in Poland. He received M.Sc., Ph.D. and Dr.Habil. (D.Sc.) degrees in electrical engineering from the Department of Electrical Engineering, Automatics and Electronics at the University of Mining and Metallurgy, Cracow, in 1967, 1974, and 1977 respectively and a Professor scientific title in 1991 from President of Poland

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From 1991 cooperate with the Division of Basic Research in Power Electrical Engineering of Russian Academy of Science in St. Petersburg. In 2000 was awarded by honouree title Doctor Honoris Causa of Russian Academy of Science.

His main research fields are: electrical machines and drives, electromechanical systems, electrical energy conversion and transformation by power electronic systems. He has published more than 150 scientific papers in Polish and international journals and proceedings of conferences.



