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The Study of Implementation of Multiphase Matrix Converter in Power Systems

Streszczenie. *Artykuł przedstawia właściwości wielofazowego (6,12,...faz) Przekształtnika Matrycowego w zastosowaniach sieciowych. Rolą Przekształtnika Matrycowego w systemie jest kontrola rozpływu mocy czynnej (urządzenia FACTS, kontrola faz napięć węzłowych) oraz konwersja częstotliwości dla przyłączania źródeł o zmiennej prędkości obrotowej oraz turbin szybkoobrotowych. W pracy zaproponowano układ sterowania oparty na metodzie polowej oraz określono właściwości konwertera (w tym rzeczywistego modelu) pracującego w tym systemie sterowania.*
Studium Zastosowania Wielofazowego Przekształtnika Matrycowego w Sieciach Elektroenergetycznych

Abstract. *The article shows the properties of the multiphase (6,12,...phases) Matrix Converter (MC) developed for power system applications. The MC is used to control active power flow (FACTS devices, node voltage control)as well as to interconnection variable frequency energy sources to the grid. The work included the development of the control technique based on area control approach as well as real life drive models and the research of their properties under proposed control.*

Słowa kluczowe: Przekształtnik Matrycowy, Sterowanie obszarowe, Układy wielofazowe, Transfer mocy czynnej i biernej.
Keywords: Matrix Converter, Area based control, Multiphase power systems, Active and reactive power transfer.

Introduction

A NxM multi-phase matrix converter (MC) is an array of NxM bi-directional switches (fig.1), able to convert N-phase input voltages into M-phase output voltages of different amplitude, phase and frequency than the input ones.

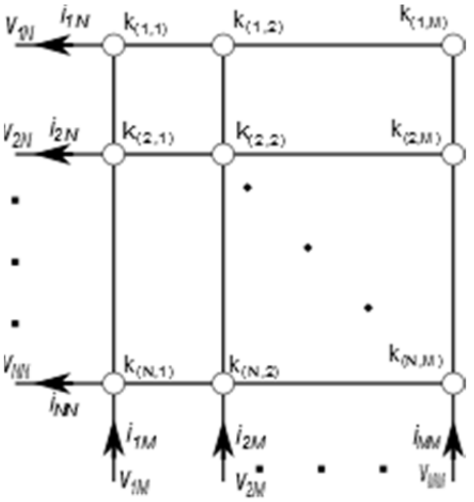


Figure.1. The structure of NxM matrix converter

This conversion is done without the use of a DC current circuit or any energy storage elements between the converter input and the output. Recently, due to its simplicity, the matrix converter (MC) has received a lot of attention. The main problems in large scale industry application are complexity of control schemes, large amount of low order harmonics in converter currents and their non-continuity [1],[2],[3],[4],[5],[6].

The proposed application field of the MC considered in this research is a power system, especially FACTS [7],[8],[9] phase shifting devices with fast response times. The MC is sought as a part of those devices responsible for phase shift (active power flow control) and frequency converter (connection of variable frequency sources to the grid). The voltage amplitude control (however is possible) is not an issue at this research, since in the proposed configuration two multiphase transformers are used (Fig. 2). These transformers are necessary to convert energy to lower voltage acceptable by power electronic switches and are usually equipped with taps to control voltage level

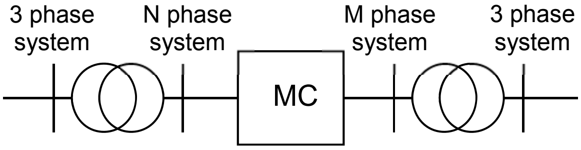


Figure.2. The structure MC based phase shifter device (FACTS device type)

The requirements for the proposed application are quite different then for typical motor drives since not only sinusoidal output currents are required but also sinusoidal input currents and sinusoidal voltages at both sides. Of course MC as power electronic device will produce some disturbances, but the goal is to build such structure and such control system to minimize these disturbances. Previous research on MC was mainly leaded for three to three phase structures utilizing vector based PWM control and drive applications. Since in power systems PWM applications are not used and three to three phase structures of the MC are producing heavy and difficult to filter disturbances, the research concentrates on multiphase (6, 12, 18...) structures [10],[11],[12]. The other advantage of the proposed structures is that single phase current in multiphase MC for the same power flow is much smaller than for three phase one what creates much smaller stress to the switching elements. This paper presents and analyze the conditions with have to be fulfilled by MC control system to satisfy proposed application requirements.

The relationships between input and output currents and voltages in Matrix Converter

For the proposed structure any output phase can be connected at a certain instant to any input phase what creates ties not only for voltages but also for currents. Analyzing the MC structure one can notice that if one output phase is connected to more than one input phases or one input phase is connected to more than one output phases (Fig.1) it will create short circuits at the input or output respectively. When MC structure is not square (number of inputs is equal to number of outputs) the currents at the side with larger number of phases are including zero current periods. It can be also stated that in order to maximize MC power transfer and to minimize produced disturbances it is necessary to switch on at a certain instant all possible switches without the creation of the short circuits. Matrix converter under proposed control is a device which creates the output voltage as a combination of the input voltages.

In general the output voltage for m-th output phase can be written as:

$$V_{mM}(t) = k_{(1,m)}(t)\cdot V_{1N}(t) + k_{(2,m)}(t)\cdot V_{2N}(t) + \dots + k_{(N,m)}(t)\cdot V_{NN}(t) \tag{1}$$

where: $k_{(n,m)}(t)$- membership function of n-th input phase in m-th output phase, $V_{nN}(t)$ - voltage for the n-th input phase

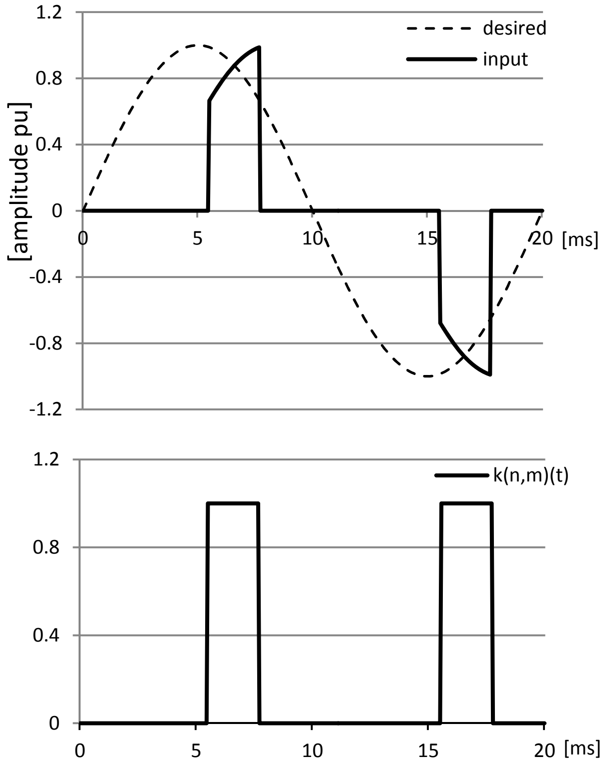


Figure.3. The fragments of the input phase used to build desired waveform and corresponding to them membership function $k_{(n,m)}(\vartheta)$

In general the MC can be described using the relationships between its input and output quantities (currents and voltages). Such description can be easy constructed when MC switch is modeled using “high-low” conductance models (Fig.4)

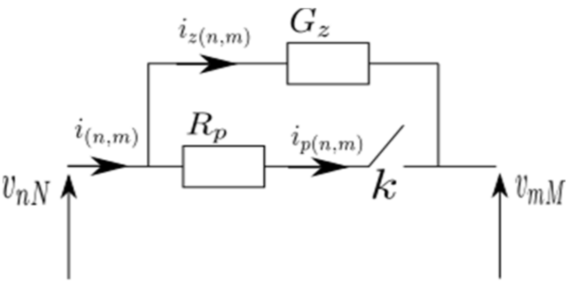


Figure.4. The structure of switch model

For such model the (n,m) switch (switch connecting any input phase to any output phase) current is the sum of “on” (high conductance) and “off” (low conductance) currents of the switches connected to this phase.

$$i_{k(n,m)} = G_z\cdot\left(V_{nN} - V_{mM}\right) + k_{(m,n)}(t)\cdot\left(V_{nN} - V_{mM}\right)/R_p \tag{2}$$

Where $k_{(n,m)}(t)$ is a function describing the state of a switch

Proposed approach enables to separate model to two models - for “on” and “off” states of the switches.

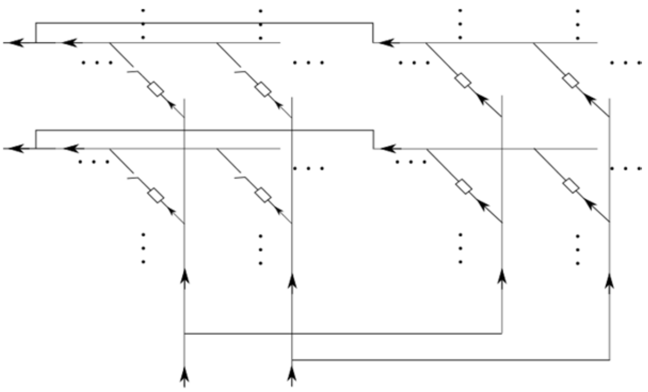


Figure. 5. The split of the MC model into two structures for “on” and “off” switch states

In real life applications the “off” currents of the switches can be neglected, thus the final model consists only of relationships between “on” currents and voltages, and the membership functions become functions of switch states. In matrix form for m-output and n-input MC the relationships between input and output voltages and currents can be written in a matrix form as:

$$\begin{aligned} |V_m| &= |K(t)| * |V_n| \\ |I_n| &= |K(t)|^T * |I_m| \end{aligned} \tag{3}$$

Where |K(t)| is a function describing the state of all switches in matrix – so called state function of matrix (4).

$$|K(t)| = \begin{bmatrix} k_{(1,1)}(t) & \cdots & k_{(1,M)}(t) \\ \vdots & \ddots & \vdots \\ k_{(N,1)}(t) & \cdots & k_{(N,M)}(t) \end{bmatrix} \tag{4}$$

The above formula clearly states that MC is a device which introduces ties not only to voltages but also to currents. The description of the MC using external currents and voltages enables in further work the incorporation additional external elements into MC simulation.

MC Control algorithm

Let’s assume that all input and output side waveforms are sinusoidal functions of time. Thus the required output waveform (of the same amplitude as input but different initial phase shift) can be built only as the superposition of fragments of input waveforms. The function $k_{(n,m)}(t)$, called membership function, for the proposed scheme achieves value „1” for time intervals for witch n-th input phase is a part of m-th output phase and zero for any other case.

Thus the control algorithm should be based on the comparison of instant values of input phases voltages and the desired output. Thus it is visible that in analog control these limits can be derived from series of logic conditions. However, the analog control scheme is not feasible since it does not include the conditions enabling short circuit avoidance and is voltage shape dependent.

The value of the function $k_{(n,m)}(t)$ depends on the position of a certain input phase with respect to the desired waveform. This dependence can be described using running phases (arguments) of input and output functions. Since in theory the running phases of the input functions are independent from the running phases of the outputs thus the control algorithm can be viewed as two dimensional problem. In such approach on the X axle is the running phase of a certain input and on Y axle is the running phase of a certain output. If the input and output functions are periodical, only $(0,2\pi)\times(0,2\pi)$ space have to be considered when developing control algorithm. The proposed method is thus similar to the “area” based control strategy derived in [13],[14].

For two sinusoidal waveforms: the given one and the desired one, both with the same amplitude, the determination of waveform crossing points can be done by solving a simple equation:

(5) $$\sin\tau_N = \sin\tau_M$$

where: τ_N and τ_M - running phases of the input and output waveforms.
The solution is:

(6) $$\tau_M = \tau_N + 2c\pi \;\; or \;\; \tau_M = \pi - \tau_N + 2c\pi$$

Where c is an integer.
In the proposed control space the graphic interpretation of the solutions of the above equations create following diagram [15] (Fig. 6)

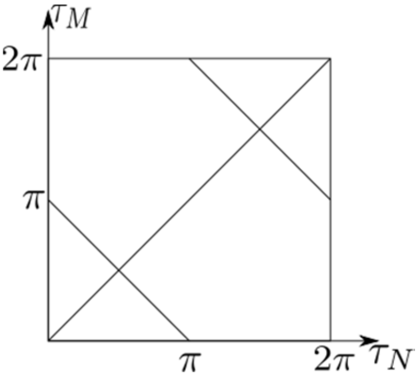


Figure.6. Diagram corresponding to the solution of the equation (2)

If the sinusoidal voltage waveform is to be created from sinusoidal input phases, the points in which function $k_{(n,m)}(t)$ achieves value "1" (switch connecting two considered phases is in "on" position) have to lay in the vicinity of the drawn lines. These points will create areas on the $(0,2\pi)\times(0,2\pi)$ space called conduction areas.

These divagations can be repeated for all N input phases. What changes for the n-th input is the argument (running phase) of the first sinusoidal function in the formula (5) what results in following statement:

(7) $$\sin(\tau_N - {}^{2\pi n}\!/_{N}) = \sin\tau_M$$

Its solution is similar as in the case of the first phase (formula 5) and it is shifted along X axis by $2\pi n/N$.
Since MC is described using two-dimensional space every set of the conduction areas for input phases can be shifted by $2\pi m/M$ (where M is a number of output phases) to create $M\times N$ control spaces for all converter switches. For the same input and output frequencies, the control algorithm of the MC has to determine actual input and desired output running phase to establish unique point at $(0,2\pi)\times(0,2\pi)$ space and check at which control space this point lays inside conduction area. If the point lays within control area at certain space, the switch corresponding to this space is in "on" state.

The control strategy should also include certain restrictions derived from the required conditions of converter work. The control in the proposed application should be able to eliminate short circuits at the both sides of the converter and assure the elimination of zero flow periods from current flow in each phase. First condition (short circuit) occurs when two or more input phases are connected to one output phase or two or more output phases are connected to one input phase. If the short circuits at the input are to be avoided, the conduction areas corresponding to the switches connected to a certain input phase should be disjoint sets and accordingly if the short circuits at the output are to be avoided, the areas corresponding to the switches connected to a certain output phase should be disjoint sets, thus the conduction areas for a certain input or output phase do not have any common points .

The second stated condition can be satisfied at the output if a certain output phase is always connected to one from the input phases. It takes place when the sum of the conduction areas for all switches connected to this output phase fully covers the $(0,2\pi)\times(0,2\pi)$ control space. Similar statement is valid for any input phase

For any MC structure the control space should be covered by the conduction areas at every point minimum two times what corresponds to minimum two switches turned "on". This condition is necessary to allow current flow through MC when structure without neutral conductor is used.

According to the proposed control, for every switch (valve) in the MC structure the state of this switch can be determined at any instant on the plane where the value of the coordinate on X axis is the value of the running phase of the input at this instant, and similarly the Y axis represents the running phase at the output. Since time is a parameter determining the values of the running phases, any time instant during input/output periods is represented by a unique point on the plane. If the running phases are continuous functions of time, the points determined on the plane are forming a continuous curve as time elapses. This curve is called the trajectory. When input and output frequencies are constant and running phases are linear functions of time, then the trajectory is a linear function. If input and output waveforms are periodical then the plane, as assumed before can be limited to the rectangle of the size one period by one period. In such space when any one of input or output running phases reaches the border of this space the trajectory is shifted to 0.

In proposed approach the position and the shape of the area in control space determines when and how long the switch will be open, thus determine the switch control strategy. The change of the control strategy require the change of the conduction area sets. The advantage of the proposed approach is that the shape of the conduction area is independent of frequency and initial phase shifts of input and output waveforms.

The examples of conduction areas

Before the development of real life models, several shapes of the conduction areas were created and applied to the proposed control strategy using simulation tools.

The shape of the output voltage depends on the control strategy what is equivalent to the shape of the conduction areas and their localization with respect to the solution of the equation 5 shown in Fig. 7 – Fig.9.

If the conduction areas are situated in the vicinity of both of the lines representing the solution of the equation 5, the output voltage consists of fragments of the input waveforms with the same sign of derivatives as the desired one and of fragments of input waveforms with the opposite signs of derivatives crossing desired one (Fig.9). When conduction areas are situated along only one of the solutions of the equation 5 (one of the diagonals in Fig.6), the output waveform is built only from input waveforms with the same signs of the derivatives

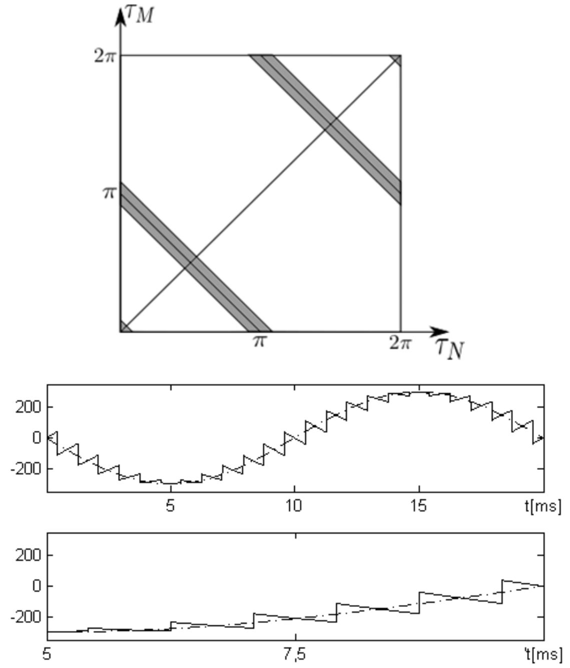


Figure.7. The conduction areas located along one of the solution of the equation 5 for a 12×12 MC and corresponding to them output waveform

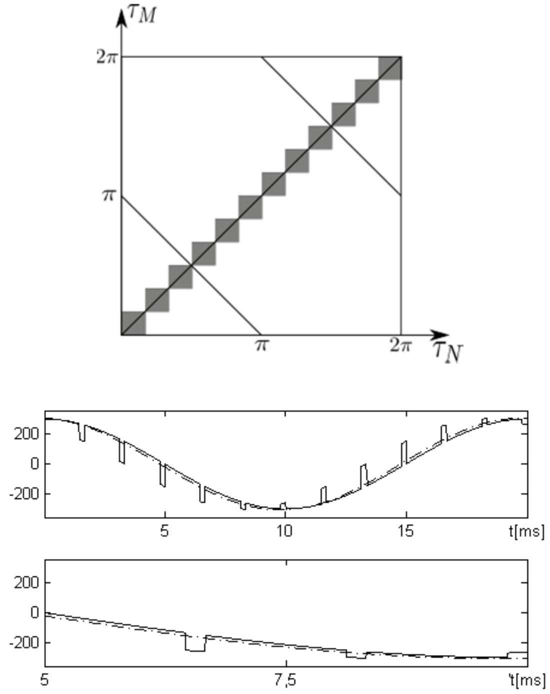
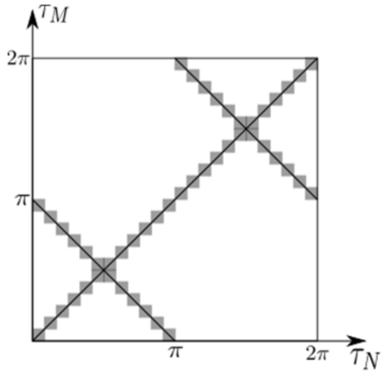


Figure.8. The conduction areas located along one of the solution of the equation 5 for a 12×12 MC and corresponding to them output waveform



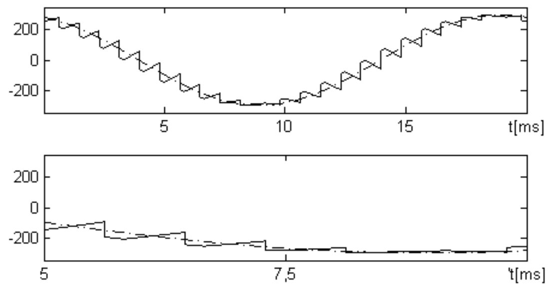


Figure.9. The conduction areas located along both of the solutions of the equation 5 for 12×12 MC and corresponding to them output waveform

Current waveforms for the proposed control algorithms

All the proposed algorithms were developed to obtain close to sinusoidal output voltage from sinusoidal input voltages. Next step of the verification of those procedures is the analysis of the input and output current waveforms. To analyze this problem simulations have to be lead for different control strategy and for different MC load condition. For resistive loads with the supply from voltage source, output current waveforms shape follows the shape of output voltage and input current waveforms are sinusoidal.

However, when load was changed to the inductive or capacitive one, it influenced the shapes of input or output currents waveforms.

For inductive loads MC output current tends to become sinusoidal and of course its first harmonic is delayed with respect to first harmonic of output voltage.

The load inductance acts in this case as current source and input currents are built from fragments of the output currents according to the control strategy.

For the control strategies based on areas situated along only one diagonal of the control plane (corresponding only to one solution of the equation 5) input current waveform are close to sinusoidal one. If the conduction areas are located along the first solution of the equation 5, the phase shift between first harmonic of input current and first harmonic of input voltage is the same as for output. However if the conduction areas are situated along second solution of the equation 5, the phase shift between first harmonic of input current and first harmonic of input voltage is opposite as for output. Thus for this case output inductance is visible from the input as a capacitance

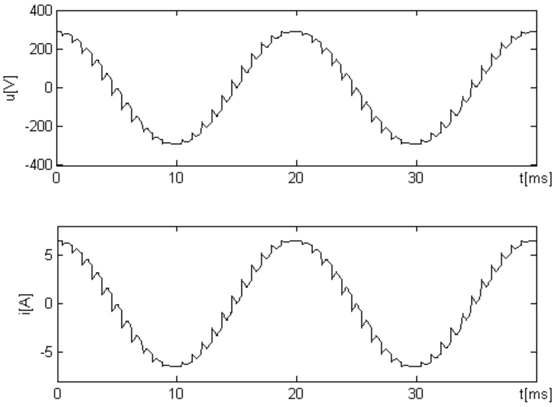


Figure.10. Output voltage and current for the conduction areas from fig.7 and resistive load

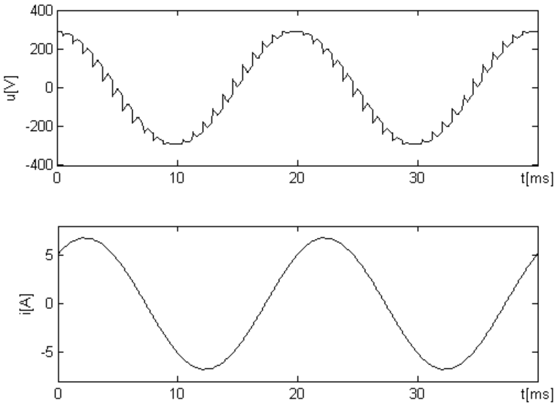


Figure.11. Output voltage and phase current for the control area from fig.8 and for inductive load

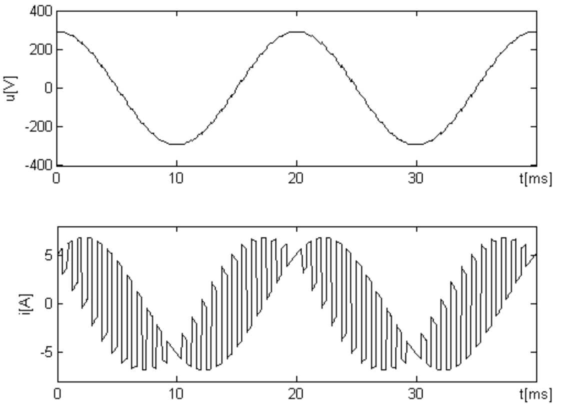


Figure.12. Input voltage and phase current for the control area from fig.8 and for inductive load

For the conduction areas located along both solutions of the equation (5) and the inductive load, the shape of the input current is not always sinusoidal. In this case, for inductive load the input current waveform is a sum of two runs symmetrical with respect to the input voltages. One run lays along the sinusoid delayed with respect to the input voltage and is built from the parts of the output currents with derivatives of the same sign as the derivative of this sinusoid. The second run lays along the sinusoid preceding input voltage and is built from the parts of the output currents with derivatives of opposite sign as the derivative of this sinusoid (Fig.12). The width of pulses of the input current belonging to each sinusoid depends on the angle shift between input and output voltages, thus power factor of the input current changes from the maximum inductive (the same as the load power factor) to maximum capacitive with the absolute value equal to the load power factor.

The real life model of the MC working under proposed control scheme

The proposed control scheme was applied using custom build digital controller. The controller can handle up to 12×12 matrix structures. The idea of the controller was based on digitalization of the control space with the resolution of one degree and storage of the two dimensional (360×360) maps of the conduction areas corresponding to every switch. The trajectory (curve created by points representing running phases) was created as straight line where on X axle was the running phase of the input waveform and on Y axle the running phase of the desired sinusoidal output waveform. Thus such system requires synchronization with input voltage waveform and correction of the delays caused by synchronization equipment and procedures.

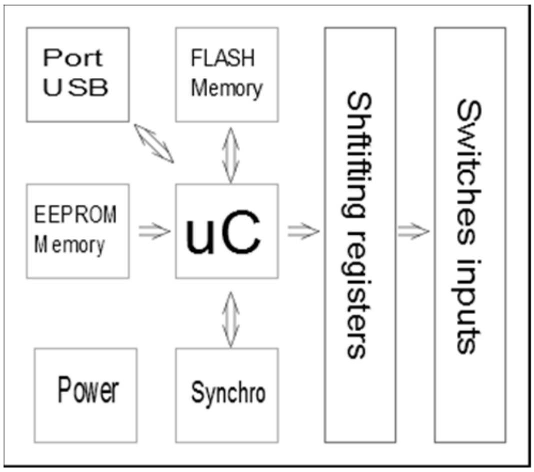


Figure.13. The block diagram of the controller

The controller can be programmed (maps of the conduction areas, relative angle shift, output or input frequency) from PC via USB connection. The map of the conduction areas has to be programmed before the initiation of the converter work but other parameters can be changed “on line”. The crucial part of the controller program is memory searching procedure able to deliver to up to 144 outputs 18000 times per second vector of actual states of the switches. To achieve this, the three dimensional array of switch states $(360\times360\times144)$ created in Matlab software for simulation purposes was decomposed, organized to minimize memory space and converted into binary form. The memory structure is crucial to create unique address string corresponding to sole point at 360×360 control space.

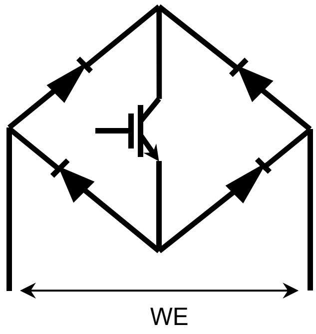


Figure.14. The setup of a bidirectional switch

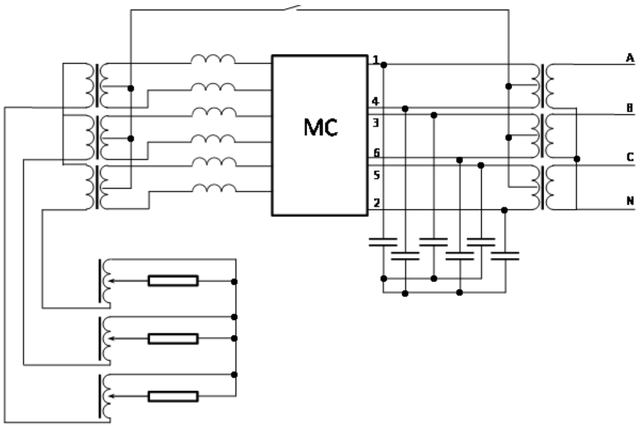


Figure.15. The laboratory setup MC external circuitry

For test purposes, the matrix hardware was build using 36 bi-directional switches (Fig.14) to form 6×6 phases MC. The construction of the switch allows to control current flow in both directions using pulse with the same polarity, what is crucial for the proposed control system where “0” corresponds to switch “off” state and “1” to “on” state, regardless of the direction of power flow. The measurement were taken using the setup shown in Fig. 15 with the 6 phases MC working from voltage source and driving inductive load.

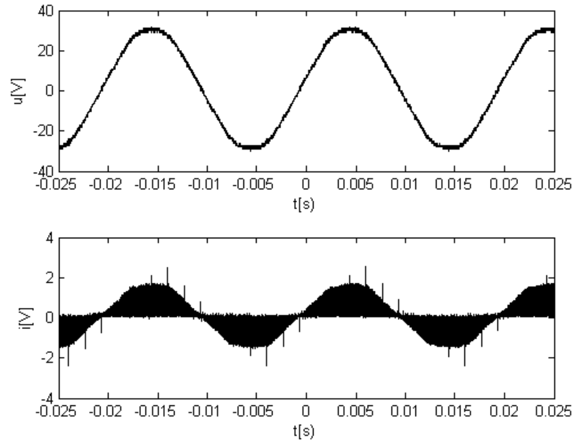


Figure.16. The input voltage and current (one phase of the converter) for a capacitive source and the inductive load

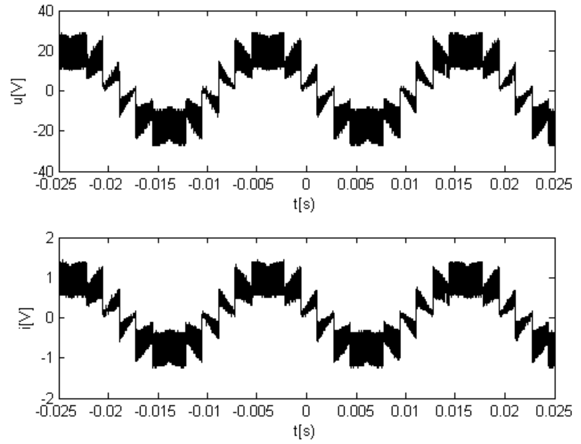


Figure.17. The output voltage and current (one phase of the converter) for a capacitive source and small inductive load

The input and the output 6 phase systems were converted to the 3 phase systems using 3 to 6 phase transformers. The MC model has been tested in the laboratory to check its characteristics under proposed control schemes and under different load conditions (Fig.16, Fig.17).

Conclusions

The article shows the possibility of the practical application of the multiphase matrix converter into power system. Multiphase structures (6,12 or more phases) show much better performance than three phase ones. For those structures output waveforms are built from fragments of input quantities, thus, more input phases enables multiphase structure to build output waveforms closer to the desired ones. Similar, if input frequency is higher than output one, during the period of the output there is more possibilities to build the desired waveforms. Moreover, if the number of phases increases, the single phase current decreases compare to the three phase system during the transfer of the same power what results in smaller stresses of switching elements. Further work (not included in this dissertation) includes the research of MC properties (harmonic distortion, voltage transfer) witch respect to the number of phases and control strategy (shapes of control areas)

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