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Integration of matrix converters into mechatronics systems

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ABSTRACT

Use of 3×3 matrix converters (MCs) in AC drive is discussed. Main advantages of the MCs that facilitate integration of such converters and mechanical systems (AC drives) are listed in the beginning. More detailed analysis of these aspects is given in the next sections of the article. The final conclusions and recommendation for further work are made in the final part of the paper.

INTRODUCTION

Matrix converters (MCs) are a rather new class of power electronic converters that nowadays can practically be used in electrical AC drive. Although these converters have been investigated in a large number of scientific projects during the last 30 years (one of the first publications about MCs probably was [1]), but quite successful implementations of such converters was done in the last 10 years that can be explained by a completely different level of modern power semiconductor devices. MC is basically a matrix of power semiconductor switches that connect input and output phases of the converter. Input of the matrix is usually connected via a low-pass filter to a supply network, but its output – to the load. Since the motor load usually has three phases, but the supply network has three lines, the most useful MC has a 3×3 matrix structure that contains 9 electronic switches. An electrical drive based on such power matrix is given in Fig.1.

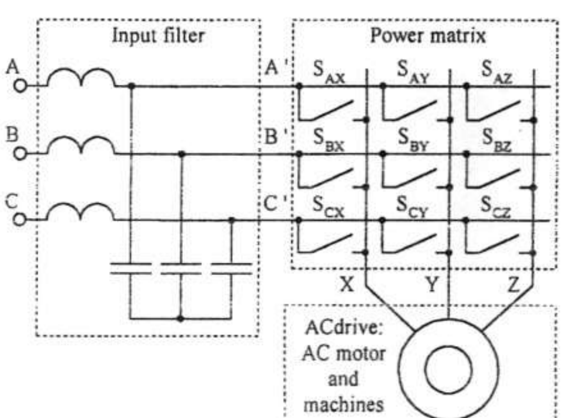


Fig.1 Electrical diagram of an MC based electrical drive with a 3-phase network and a 3-phase load

As it can be seen in Fig.1 the MC by itself has no bulky reactive components, unlike a DC-link frequency converter. Thus MC can be performed as an all-in-silicon converter that can be easy integrated into AC motor. This feature facilitates incorporation of the power converter, filter (whose elements are rather small), asynchronous motor and control system into a single monolithic drive system. In order to make such integration more effective the MC must have a simple control algorithm that can be performed by a simple control board as well as it must have space saving commutation technique that eliminates use of additional reactive elements. As it will be shown in the further sections it is possible to perform these conditions in the MC. From the other hand the described unification of the drive gives additional advantages to MC, such like a better performance from the point of view of thermal design and EMI.

REACTIVE COMPONENTS

The MC has reactive components in its snubber circuits and in the input filter. It must be noted, that the reactive components in the filter of the MC are much smaller than in the DC-link frequency converter. Let us to estimate these values.

Allowed voltage pulsations in the DC-link are assumed to be 2.5% of its value. If the phase voltage is V_f, then the pulsations can be expressed as follows:

$$\Delta V_{DC} = 2.5\% \cdot V_f \cdot \sqrt{3}\sqrt{2} \qquad (1)$$

These pulsations can be expressed also based on the output power. The DC-link capacitor is charged 6 times per 20ms. Between the charge intervals load current discharge the capacitor. Since charge time is rather small it may be assumed that the discharge interval is 1/6 of the 20ms. If the output frequency of the converter is 50Hz, then within $\omega t = 0 \ldots 60^0$:

$$i_{DC} = I_{OMAX}[\sin\omega t + \sin(\omega t + 120^0) -$$
$$- \sin(\omega t - 120^0)] = 2I_{OMAX}\sin(\omega t + 60^0)$$

Taking into account:

$$P = 3V_f \cdot I_f \cdot \cos\varphi \cdot \eta$$

gives:

$$i_{DC} = \frac{2\sqrt{2} \cdot P}{3V_f \cdot \cos\varphi \cdot \eta} \cdot \sin(\omega t + 60^0).$$

Then the voltage pulsations are:

$$\Delta V_{DC} = \frac{1}{C_{DC}} \cdot \int_0^{20ms/6} i_{DC} dt = \frac{1}{\omega C_{DC}} \cdot \frac{2\sqrt{2} \cdot P}{3V_f \cdot \cos\varphi \cdot \eta}$$

(2)

Solving together (1) and (2) gives:

$$\Delta V_{DC} = \frac{\frac{1}{\omega C_{DC}} \cdot \frac{2\sqrt{2} \cdot P}{3V_f \cdot \cos\varphi \cdot \eta}}{2.5\% \cdot V_f \cdot \sqrt{3}\sqrt{2}}$$

If V_f=220V and $\cos\varphi \cdot \eta$=0.76 (at the motor load), then:

$$C_{DC} \approx 1.3 \cdot 10^{-6} \cdot P \qquad (3).$$

In the other word each kW of the output power asks for approximately 1000□F in the DC-link.

In the case of MC numerical values of the filter elements can be found on the basis of the maximal input current of the power matrix. Output voltage of the converter if defined by its voltage transfer ratio. The maximal value of this ratio can be expressed as follows:

$$V_O = K_V \cdot V_f \le 0.87 \cdot V_f$$

Then the output power is:

$$P = 3V_O \cdot I_O \cdot \cos\varphi \cdot \eta = 3 \cdot K_{V\max} \cdot V_f \cdot I_O \cdot \cos\varphi \cdot \eta,$$

from where:

$$I_O = \frac{P}{3 \cdot K_V \cdot V_f \cdot \cos\varphi \cdot \eta} \text{ or}$$

$$I_{O\max} = \frac{\sqrt{2} \cdot P}{3 \cdot K_V \cdot V_f \cdot \cos\varphi \cdot \eta} \qquad (4)$$

This also is the maximal current that can flow in the converter input. The input phase voltage pulsations on the filter are defined by the formula:

$$\Delta V_{Ff} = \frac{1}{C_F} \cdot \int_0^{T_{sw}} I_{Ff\max} dt = \frac{I_{Ff\max} \cdot T_{SW}}{C_F}$$

or, taking into account (4):

$$\Delta V_{Ff} = \frac{\sqrt{2} \cdot P \cdot T_{SW}}{C_F \cdot 3 \cdot K_V \cdot V_f \cdot \cos\varphi \cdot \eta}.$$

These pulsations can also be expressed as a 2.5% of the phase voltage that gives:

$$\frac{\sqrt{2} \cdot P \cdot T_{SW}}{C_F \cdot 3 \cdot K_V \cdot V_f \cdot \cos\varphi \cdot \eta} = \sqrt{2} \cdot V_f \cdot 2.5\%.$$

Hence

$$C_F = \frac{P \cdot T_{SW}}{2.5\% \cdot 3 \cdot K_V \cdot V_f^2 \cdot \cos\varphi \cdot \eta}.$$

At $K_V = K_{V\max}$=0.87, V_f=220V, T_{SW}=100μs (f_{SW}=10kHz) and $\cos\varphi \cdot \eta$=0.76 (motor load) filter capacitance is expressed as follows:

$$C_F = \frac{P \cdot 100 \cdot 10^{-6}}{2.5\% \cdot 3 \cdot 0.87 \cdot 220^2 \cdot 0.76} = 42 \cdot 10^{-9}$$

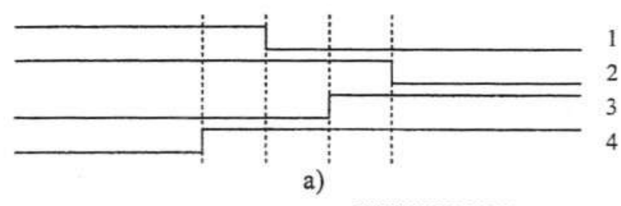
It means that each kW of the output power asks for approximately 40nF of the filter capacitance. The similar approach can be used for inductance estimation and it gives approximately the same results. At the same power filter inductance is many times smaller than inductance required in the DC-link. These calculations can be confirmed also by other estimation techniques, fro example in [2].

The obtained data evidence that reactive components in the MC filter have rater small values and smaller size. Hence it is easy to implement such filter into a monolithic system.

COMMUTATION TECHNIQUE

Reactive components are also used to improve commutation transients in the power matrix. However these elements can be significantly reduced or eliminated if proper commutation technique is used.

If there is no stray inductance on the input of MC, then all the switchings are of the same type: current in the output phase is being disconnected from one input voltage source and connected to another. Similar process takes place in a single leg of the voltage source inverter (VSI), where "dead" time (when both transistors of the same leg are off) is used in order to avoid a short-circuit. The path for the output current during the "dead" time is ensured by back action diodes. The main difference between VSI and MC is that both, forward and back action devices of the MC are controlled by a signal. If back-action IGBT goes on and off (Fig.2) like diodes of VSI, switching is safe (no short-circuit on the input and no interruption of current on the output). Such control of switching is called "four-step commutation strategy" and was described, for example, in [4]. No reactive component is required at such commutation type.



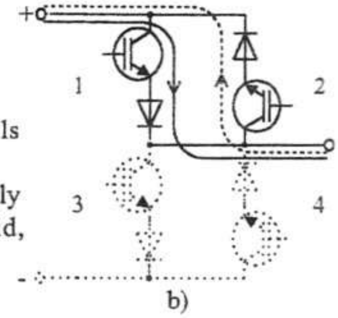


Fig.2 Four-step commutation in MC:
a) control sequence (signals from processor unit);
b) equivalent circuit (initially activated devices are solid, incoming - dotted)

If there is stray inductance on the input, then overvoltage always happens during commutations and snubber circuits have to be placed across power switches. However, it possible not to use them if specific commutation technique is used. The proposed algorithm (Fig.3) assumes that the gate current is reduced as soon as collector-emitter voltage achieves a certain value of $V_{CEclamp}$. Thus, there are at least 2 levels of I_G. During the time $t_1 \ldots t_{21}$ and $t_4 \ldots t_5$ there are no changes in the collector current and voltage. The actual switching starts at t_{21} and stops at t_4. At time t_3 collector voltage $v_{CE}(t)$ is maximal. If there is controllable I_G, then at t_{22} it goes down to a low level and slows down the falling of $i_C(t)$. Hence, a lower slope of $v_{CE}(t)$ can be achieved and the overvoltage is restricted by control.

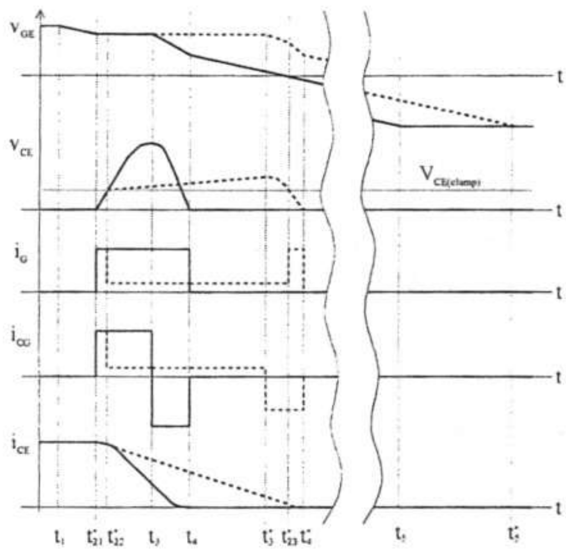


Fig.3 Turn-off of an IGBT at zero-voltage and 2-level gate current

Experimental results that confirm the method can be found in [4]. From the all mentioned above it is seen that bulky reactive circuits are not obligatory for safe commutation.

CONTROL METHODS OF MC

In order to obtain qualitative input current 2 input voltages (Fig.4) must be involved into modulation process. There are 5 switching times in that case.

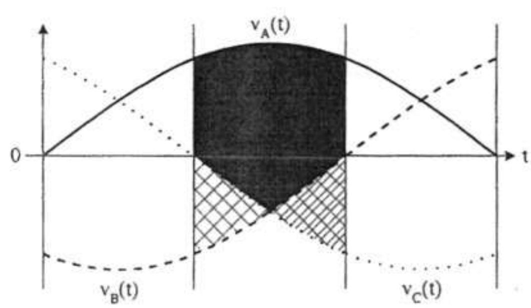


Fig.4 Modulation voltages of MC at the two-level control mode

Although number of switching times is rather high, but equation for its calculation is quite simple (complete form can be found in [4]):

$$\gamma = K \cdot \sin(\omega_{in} t + \varphi_1) \cdot \sin(\omega_{out} t + \varphi_2) \quad (5)$$

It contains in fact 2 multiplications and 2 sinusoidal functions that can be performed in a table form. The algorithm requires no measurements and can be done by even very simple control unit.

CONCLUSIONS

As it was shown in the paper the MC based AC electrical drive contains (besides AC motor) silicon power matrix, high frequency filter and simple control board with no measurement circuits. No bulky components are needed. That is why all mentioned units could be easily combined in a single unit. Very obvious technological solution assumes that power matrix, filter and control board are placed inside of extended terminal box of the motor. In that case system has common thermal design where heat sinking is ensured by a motor fan. Motor body is also good screen against EMI noise. An example of such system, which is made in Alaborg University, is given in Fig.5.

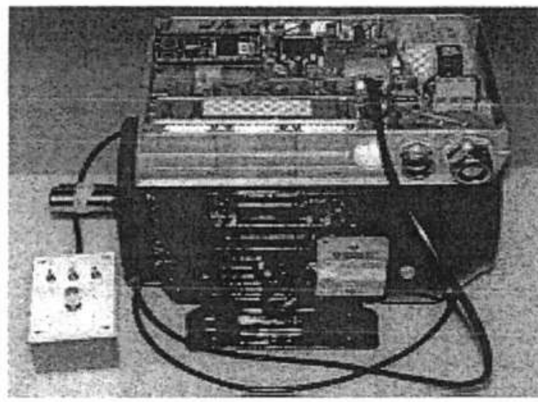


Fig.5 An example of integrated electrical AC drive with power MC and corresponding environment assembled in Alaborg University.

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