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Design and Dimensioning of Essential Passive Components for the Matrix Converter Prototype

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The continuous popularity of the research in the area of the matrix converter control theory has been supported by steady technological improvements. It is still common to use discrete semiconductor switches in an anti-serial connection, even though some integrated solutions have been presented by various vendors already. Furthermore, recently experimental all-in-one matrix converter power modules based on reverse blocking transistors were introduced. However, this development has not eliminated the need of the protection circuit and other passive components in the converter's power part. This article strives to describe design procedure for one kind of the matrix converter protection circuits and the design of the input filter for the 3×3 matrix converter prototype.

Key words: Matrix converter, Input filter, Protection circuit, Direct frequency converter

Dizajn i dimenzioniranje ključnih pasivnih komponenata prototipnog matričnog pretvarača. Dugotrajna popularnost istraživanja u području upravljanja matričnim pretvaračima podržana je trajnim tehnološkim napretkom. Još se uvijek učestalo koriste diskretne poluvodičke sklopke u antiserijskom spoju, iako postoje integrirana rješenja. Unatoč nedavno predstavljenim prototipnim *sve-u-jednom* matričnim pretvaračima zasnovanim na reverzno blokirajućim tranzistorima, još nije eliminirana potreba za zaštitnim krugom i drugim pasivnim komponentama u energetskom dijelu pretvarača. Upravo je cilj ovoga članka opisati korake u sintezi jedne vrste zaštitnog kruga matričnih pretvarača i ulaznog filtra za prototip matričnog pretvarača dimenzije 3×3.

Ključne riječi: matrični pretvarači, ulazni filter, zaštitini krug, direktni frekvencijski pretvarači

1 INTRODUCTION

The area of the regulated AC drives is very wide. But most of them are based on the induction machines and frequency converters. Till now indirect frequency converters are the spread ones, but they have several disadvantages. In order to push the limits of the IM drives and reach maximal efficiency the research in this field focuses also to other converter topologies like multilevel inverters or so called all silicon solutions [1-3]. One of them is matrix converter [4].

The matrix converter does not include passive accumulation element in DC-link, thus uses 9 bidirectional switches to transfer voltage from its input to the output. Compared to the indirect frequency converters it has some attractive features:

- The output frequency is nearly without limits. The only limit is the maximal switching frequency of the used devices.
- It has relative simple power circuit, indirect frequency converters comprises of rectifier part, inverter part and DC-link with passive accumulation element.
- Matrix converter has only 9 bidirectional switches. They are mostly realized from discreet semiconductor modules, but several manufactures already offers integrated compact IGBT modules.
- The features of the matrix converter are same as VSI with active front end on its input. But the drawback is, that because of the DC-link absence, the output voltage amplitude is limited to 86.6% of the input voltage amplitude when we wish to maintain sinusoidal input currents.
- Sinusoidal input and output currents.
- Power factor regulation.
- Work in all four quadrants.

The matrix converter got the name because of its switches can be formed into two dimensional matrix [1],

[5]. Alternatively, this topology, consisting of nine bidirectional switches, is re-depicted in Fig. 1 to underscore what the important characteristics of the input and output are or perhaps more appropriately, should be.

Generally, it is silently assumed if we talk about the transfer functions of matrix converters that ideal voltage sources and ideal current sources are attached to the input and output. Each current source is connected to a single voltage source. It means a voltage source might be left unconnected and hence must not be connected to any other voltage source.

From another point of view, equivalent to the previous paragraph, an inductive load and a capacitive source have to be connected. Then, as in any other power converter the inductor's ends are switched among capacitor ends or shorted in turn again and again.

Since the mains behaves typically as an ideal voltage source with an inductor and a resistor serially connected together, it is necessary to plug capacitors, in a star or delta arrangement, to the mains. However, by adding these capacitors an oscillating circuit is created with a natural frequency of oscillations that depends on mains inductance. That is why it is justifiable to put a whole 3 phase LC-input filter before a matrix converter [1], [5-7]. Naturally, the inductance of the inductor in the input filter has to be significantly larger than the mains inductance in order to keep its natural frequency under control.

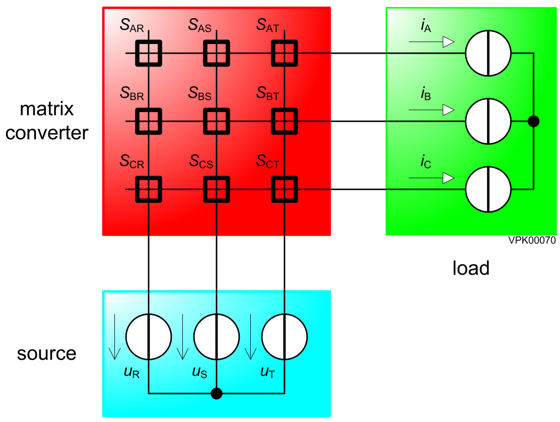

Fig. 1. Matrix converter – character of source and load

On the load side, there is normally no additional circuit required. Common representatives of load, asynchronous or synchronous motor, fulfil above mentioned condition thanks to their leakage inductance.

When the switching proceeds correctly, no other additional components are needed. However, any failure could then leads to converter harm - i.e. due to over voltage caused by cutting of the induction motor current. For this

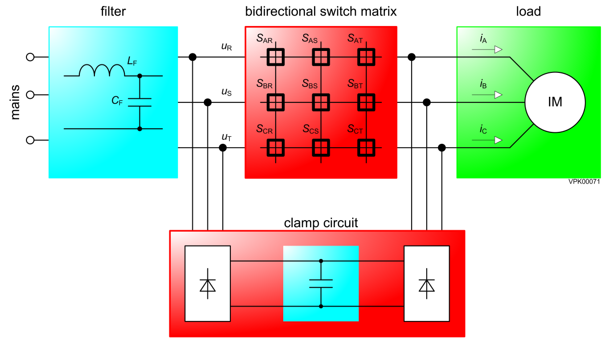

Fig. 2. Matrix converter induction motor drive

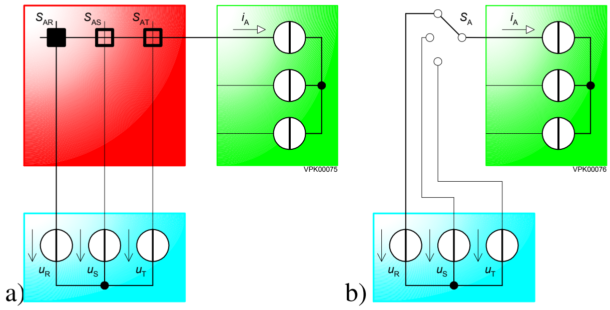

Fig. 3. The three-position switch analogy and its implementation

reason a clamp circuit is typically added. Such a clamp device can be made up of two three phase rectifiers and a capacitor. A typical configuration of both filter and clamp circuit is depicted in Fig. 2.

2 SWITCHING

Independence of the choice of modulation method, correct switching is characterized by two basic rules [5-6]:

- the output circuit (currents) must not be interrupted
- the input circuit (voltage) must not be shorted

This can be represented by an infinitely quick three-position switch (Fig. 3.b) where the joint outlet is connected to the load and the three separated outlets are connected to the particular source (or filter) phases.

Of course, real semiconductor switches do not offer infinitely short switching over. When using a diode embedded transistor, no control of the current direction is possible. This means that whenever this bidirectional AC switch is turned on, it will operate in all four quadrants all the time. When the current changes its sign, it will automatically be commutated to the opposite conduction device. Since the current cannot be changed instantaneously

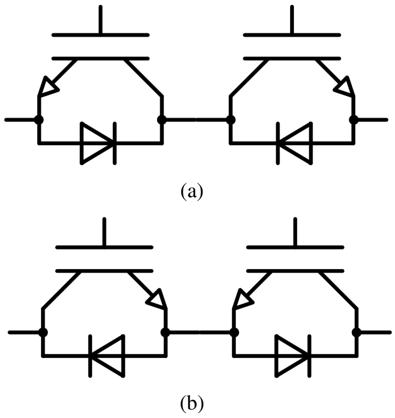

Fig. 4. Bidirectional switch topologies

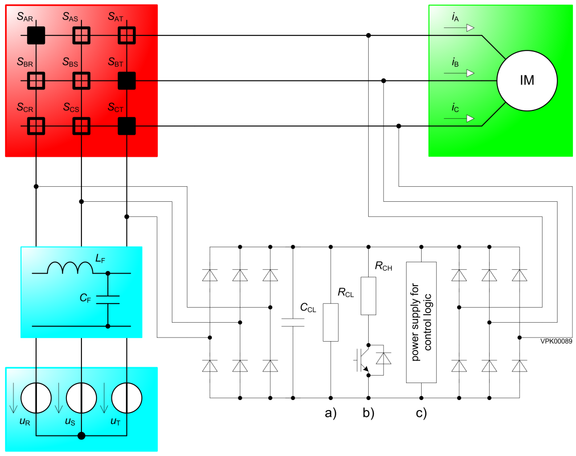

Fig. 5. Floating protection of a matrix converter

through semiconductor devices either a short gap or a short overlap in the gating signals for two sequential switching signals would have to be introduced. Both are not desired as described above. Only solutions offering the control of current direction are acceptable.

This can be achieved by employing of alternative bidirectional switch configurations. As example how to realize this switch, let us mention the most wide spread implementations consisting in anti-serial connection of two transistors with common emitter (Fig. 4.b) or with common collector (Fig. 4.a).

3 CLAMP CIRCUIT

A part of the matrix converter not mentioned often is a protection circuit [8-10]. On one hand, such circuit is used to avoid destroying the converter in fault situations. On the other hand, even in normal operation the protection circuits are used to reduce the overvoltages caused by the quick dI/dt in the leakage inductance of the power switch matrix during commutation. This phenomenon occurs in any semiconductor converter. However, for mass produced products a whole scale of plug and play components are already on the market, e.g. in middle power voltage source inverters this is typically solved by adding dedicated fast snubber capacitors directly onto the one leg that includes the module.

Another reason for adding protection is the necessity of a circuit able to accept the energy accumulated in load inductance (e.g. leakage inductance of the induction motor) when a wrong switching appears or the mains falls down [11]. In the case of a voltage source inverter, this energy can always be carried by means of free-wheeling diodes, even should all transistors be turned off. Unfortunately for the matrix converter an additional circuit is needed (Fig. 2).

A typical solution of a hardware protection circuit [10] consists of by two diode rectifier bridges connected to the input and output of the direct converter switch matrix, respectively, whose outputs have to be connected together. By placement of a capacitor to the new DC link obtained in this way, the construction of a floating protection is finished (Fig. 5).

After connecting the matrix converter system to the mains of the capacitor C_{CL} in the clamp circuit is charged to a voltage according to the amplitude of the line voltage. Moreover, as was mentioned above, this voltage level is continuously boosted due to the converter's leakage inductances. This is why the discharging of the capacitor must always be ensured. Some of the existing solutions are shown in the Fig. 4. The first possibility a) is to put a resistor R_{CL} in parallel and to set its resistance according to the requested time constant of the clamp circuit. This is connected with additional power-losses in the converter and it decreases its efficiency. Also too small resistance value can excite filter oscillations.

The power losses in the clamp circuit can be decreased by increasing the resistance of R_{CL} or by its complete elimination. In this case a proper discharging must then be supported by adding a chopper b). Some authors suggested using the dissipated power in a profitable way. The control logic of the converter has to be supplied anyway, so its consumption could be covered by the clamp circuit. Such solution could be a good idea for example on a machine's rotor carried converter.

Turning back to the main protection function of the clamp circuit, which is the draining the energy accumulated in leakage inductances of the connected machine. In Fig. 6 a switching combination is shown, where the switches S_{AR}, S_{BT} and S_{CT} are closed and others are open. Next, assume a case when $u_R > u_T, i_A > 0, i_B < 0$ and $i_C < 0$. Furthermore, suppose there is a defect in the switch S_{BT} or in generating its control signal. The cut load

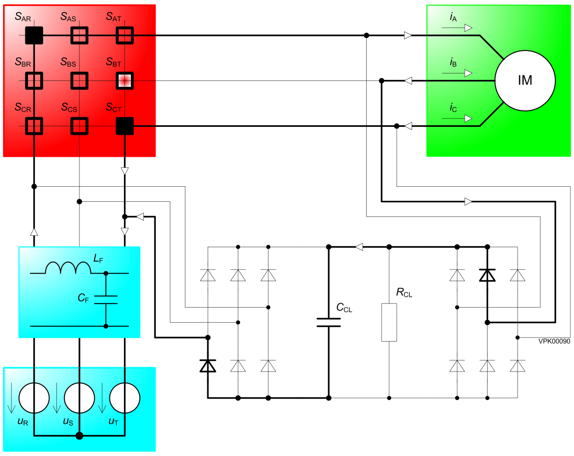

Fig. 6. Intervention of the floating protection in case of a switch error

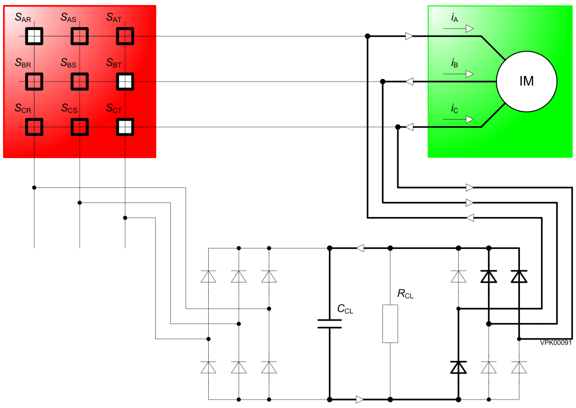

Fig. 7. Floating protection after immediate and complete turn off

current i_B will be then automatically adopted by diode bridges in the protection (Fig. 6).

When the fault is detected and the converter is switched off, the currents i_A and i_C are undertaken by the diode bridge as well (Fig. 7). The same would happen if we break the circuit between the filter and converter. And similar, the energy accumulated in inductances of the line filter has to be partially dissipated in the clamp circuit for the case of a sudden converter turn-off or mains outage as well, which is not shown in the picture for clarity. If a power cut lasting a few periods is quite a common event in mains, it would be good to equip the matrix converter with a "ride-through"" faculty to work for the short term during the mains shut down break in order to not loose survey of the load and speed up the return to normal operation.

An alternative protection method has been recently mentioned in [9], [11]. It replaces the clamp with varistors between each of the input phases and separate varis-

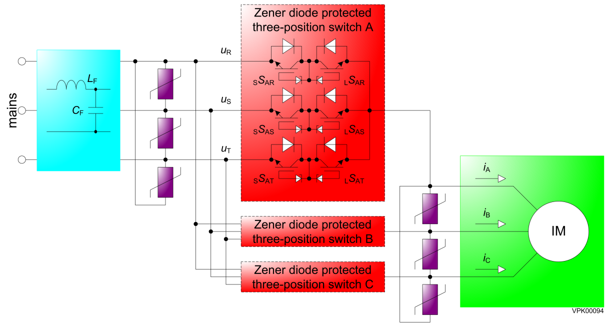

Fig. 8. Collector gate clamp and varistor protection

tors connected between each of the output phases, together with a zener diode added to each gate driver circuit in order to automatically bring into operation the IGBT in its linear region if the voltage across the device exceeds a maximum limit. With this method all of the switching devices are protected and the energy is quickly dissipated by the varistors and IGBTs (Fig. 8).

4 THE DESIGN PROCEDURE

The design procedure of any kind protection circuit must include information about effect of how large the accumulated energy in the load can be and what kind of energy it will be transferred. In general, energy accumulated in a coil is given by its inductance and the appropriate current flowing through it.

$$E_{\mathrm{L}} = \frac{1}{2} \cdot \mathrm{L} \cdot i_{\mathrm{L}}^2. \tag{1}$$

When the current carried by the coil is forced to be zero, the energy has to be converted to another type. Here we restrict the choice to the energy of a magnetic field in a capacitor or heat produced in any kind of resistor. Additional energy transferred to a capacitor is connected with an increase in voltage given by

$$\Delta E_{\mathrm{C}} = \frac{1}{2} \cdot \mathrm{C} \cdot \left(u_{\mathrm{C2}}^2 - u_{\mathrm{C1}}^2\right). \tag{2}$$

The power, ΔPR, dissipated in any kind of resistor is given by its resistance R and carried current i_R. This power is partly transferred away (in a manner corresponding to the value of its thermal resistance between the case and the ambient $R_{TH,CA,R}$) and partly accumulated in its thermal capacity $C_{TH,R}$, which is connected with an increase in temperature, ΔT_R.

$$\begin{aligned} \Delta T_{\mathrm{R}} &= \frac{1}{\mathrm{C_{TH,R}}} \int \left(\Delta P_{\mathrm{R}} - \frac{\Delta T_{\mathrm{R}}(t)}{\mathrm{R_{TH,CA,R}}}\right) \mathrm{d}t \\ &= \frac{1}{\mathrm{C_{TH,R}}} \int \left(\mathrm{R} \cdot i_{\mathrm{R}}^2 - \frac{\Delta T_{\mathrm{R}}}{\mathrm{R_{TH,CA,R}}}\right) \mathrm{d}t \end{aligned} . \tag{3}$$

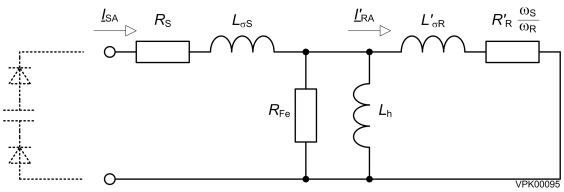

Fig. 9. Induction machine load shutdown

In short processes the influence of the thermal resistance can be neglected and we obtain

$$\Delta T_{\mathrm{R}} = \frac{\Delta E_{\mathrm{R}}}{\mathrm{C}_{\mathrm{TH,R}}}. \tag{4}$$

Thus, the used clamp devices have to comply with a voltage increase $u_{\mathrm{C2}} - u_{\mathrm{C1}}$ and a temperature increase ΔT_R.

Analogously for a general symmetrical three phase load:

$$E_{3\mathrm{L}} = \frac{1}{2} \cdot \mathrm{L} \cdot \left(i_{\mathrm{A}}^2 + i_{\mathrm{B}}^2 + i_{\mathrm{C}}^2 \right). \tag{5}$$

The fundamental currents are bundled together in the symmetrical system. The instantaneous values can be derived from the time complex vectors. Even thought different authors present different equations [7], [12] the derivation is as follows:

$$E_{3\mathrm{L}} = \tfrac{1}{2}\mathrm{L} \left(\begin{array}{l} \left(\Re\left\{\sqrt{2}\underline{I}_{\mathrm{A}} e^{j\omega t}\right\}\right)^2 + \\ \left(\Re\left\{\sqrt{2}\underline{I}_{\mathrm{B}} e^{j\omega t}\right\}\right)^2 + \left(\Re\left\{\sqrt{2}\underline{I}_{\mathrm{C}} e^{j\omega t}\right\}\right)^2 \end{array} \right), \tag{6}$$

and finally

$$E_{3\mathrm{L}} = \frac{1}{2} \cdot \mathrm{L} \cdot 3 \cdot I_{\mathrm{A}}^2 = \frac{1}{2} \cdot \mathrm{L} \cdot 3 \cdot \underline{I}_{\mathrm{A}} \underline{I}_{\mathrm{A}}^*. \tag{7}$$

where the I_A is the RMS value of the of the output phase A. Similarly we would get for instantaneous processes

$$E_{3\mathrm{L}} = \frac{1}{2} \cdot \mathrm{L} \cdot \frac{3}{2} \cdot \underset{\rightarrow}{i}_{\mathrm{ABC}} \underset{\rightarrow}{i}_{\mathrm{ABC}}^* = \frac{1}{2} \cdot \mathrm{L} \cdot \frac{3}{2} \cdot \left| \underset{\rightarrow}{i}_{\mathrm{ABC}} \right|^2, \tag{8}$$

where $\underset{\rightarrow}{i}_{\mathrm{ABC}}$ is the space vector of the output current.

As far as an asynchronous machine is concerned, the relevant energy is accumulated in its leakage inductances. In Fig. 9, this situation is depicted symbolically with the help of one of the typical induction motor equivalent circuits.

It is evident that not all stator current flows through the motor leakage inductance. Moreover, after the stator is disconnected only the stator current I_{SA} is forced to decrease

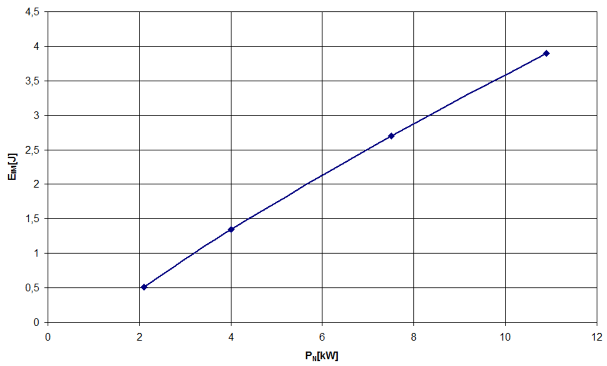

Fig. 10. Accumulated energy in leakage inductances for an nominal loaded induction motor

to zero, whereas the rotor current I'_{RA} will partially continue to flow through the main inductance L_h. If we write

$$\Delta E_{\mathrm{IM}} = \frac{3}{2} \cdot I_{\mathrm{A}}^2 \cdot \left(\mathrm{L}_{\sigma\mathrm{S}} + \mathrm{L}_{\sigma\mathrm{R}}\right) \tag{9}$$

an additional margin of safety that depends on the motor's current operating regime is included. Based on motor examples in [12] a relation between the machine's rated power and accumulated energy under nominal motor usage is constructed here in Fig. 10.

The nominal accumulated energy seems to be linear-depend on the machine's rated power. When leakage inductances are not parameters that are present in common motor datasheets, it would be useful for clamp design to estimate them from other available parameters. This can be done with the ratio i_K of the inrush current to its nominal value. From (9)

$$\begin{aligned} \Delta E_{\mathrm{IM}} &= \frac{3}{2} I_{\mathrm{AN}}^2 \left(\mathrm{L}_{\sigma\mathrm{S}} + \mathrm{L}_{\sigma\mathrm{R}}\right) \\ &= \frac{3}{2} I_{\mathrm{AN}}^2 \frac{U_{\mathrm{AN}}}{\omega_{\mathrm{S}} I_{\mathrm{inrush}}} \\ &= \frac{3}{2} I_{\mathrm{AN}} \frac{U_{\mathrm{AN}}}{\omega_{\mathrm{S}} \frac{I_{\mathrm{inrush}}}{I_{\mathrm{AN}}}} \\ &= \frac{3}{2} I_{\mathrm{AN}} \frac{U_{\mathrm{AN}}}{\omega_{\mathrm{S}} \mathrm{i}_{\mathrm{K}}}. \end{aligned} \tag{10}$$

Based on the relation for the nominal current

$$I_{\mathrm{AN}} = \frac{P_{\mathrm{N}}}{3 \cdot U_{\mathrm{AN}} \cos\varphi_{\mathrm{N}} \eta_{\mathrm{N}}} \tag{11}$$

we obtain

$$\Delta E_{\mathrm{IM}} = \frac{1}{2} \cdot \frac{P_{\mathrm{N}}}{\mathrm{i}_{\mathrm{K}} \omega_{\mathrm{S}} \cos\varphi_{\mathrm{N}} \eta_{\mathrm{N}}}. \tag{12}$$

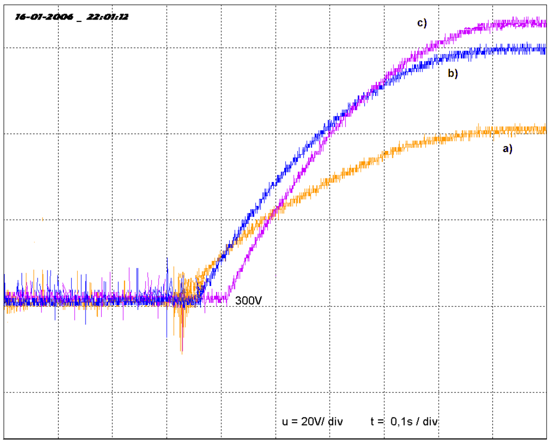

Fig. 11. Measured voltage in the clamp circuit while 0.75 *kW motor shutdown*

Table 1. Measurement of 0.75 *kW induction motor leakage inductance energy*

Experiments			**Results**		
	C_{CL} [mF]	I_A [A]	U_{CL1} [V]	U_{CL2} [V]	ΔE_{IM} [J]
a)	9.9	1.2	300	340	0.127
b)	9.9	1.8	300	360	0.196
c)	5.2	1.1	300	366	0.103

If we consider a power region from about 1 kW up to 100 kW the inrush coefficient is between 3.5 and 7.5, the power factor is 0.7 to 0.85 and the efficiency moves from 0.7 to 0.95, thus after substitution of these values we can estimate the leakage energy by

$$\frac{P_{\mathrm{N}}}{3803} \leq \Delta E_{\mathrm{IM}} \leq \frac{P_{\mathrm{N}}}{1077}. \tag{13}$$

For the 11 kW motor from Fig. 11 we obtain a coefficient of 2858 which matches derived value. This value has been also measured for a 0.75 kW induction motor.

The experiment has been repeated for three different conditions, which are evaluated in detail according to (2) in the following table. All the bidirectional switches in the matrix converter were turned off at the same time. The given capacity is the nominal value of used components and it is silently assumed that ΔE_{IM} is approximately equal to ΔE_C.

In order to be able to compare the obtained values with (13), the nominal current must be recounted for:

$$\Delta E_{\mathrm{IMN}} = \Delta E_{\mathrm{IM}} \left(\frac{I_{\mathrm{AN}}}{I_{\mathrm{A}}}\right)^2 \tag{14}$$

As an average we obtain 320 mJ which corresponds with a coefficient of 2340 according to (13). This match derived interval.

Table 2. Recounted values of induction motor leakage inductance energy

Experiments			**Results accounting for $I_{AN} = 2\,A$**	
	C_{CL} [F]	I_A [A]	Ratio $(I_{AN}/I_A)^2$	ΔE_{IM} [J]
a)	9.9	1.2	2.77	0.351
b)	9.9	1.7	1.38	0.270
c)	5.2	1.1	3.31	0.340

It can be generalized as a design pattern. The over voltage protection must meet the requirement of absorbing maximal available energy stored in the connected electric machine.

5 INPUT FILTER

Now let us move on to the next part of the converter, which is made of passive elements and therefore must be designed properly, is input filter. The input filter is very important part of each converter because especially power converters belong to the category of worse supply network polluters [13]. Therefore were defined limits of interferences that can not be exceeded during the operation of the converter. That is why the devices, that contain electronic, are also equipped with filters. Its place in an induction motor drive system topology was shown in the system overview in Fig. 2.

As was mentioned above the input of the matrix converter is being considered as a voltage source [14]. Because the mains behave typically as an ideal voltage source with and resistor and inductor connected in series together it is necessary to plug the capacitors in star or delta arrangement to the input of the converter. However, this creates an oscillation circuit with resonance frequency dependent on the inductance of the mains. That is why, it is advantageous to connect whole LC filter to the input of the converter. The inductance of the filter must be greater than the inductance of the mains in order to hold the resonant frequency of the filter under control.

The typical, oft-presented solution for such a filter is made up of a serial combination of an inductor set and a star or delta configuration of capacitors (Fig. 12)[15]. This configuration is often introduced as definitive and without problems. A design procedure for a simple second order LC star filter can be found in [16-17] or [18-21]. In a slightly modified and simplified way, it is described in the following paragraphs as well.

The simple second order LC filter can be considered from two points of view:

- LC combination as 50 Hz (mains frequency) load

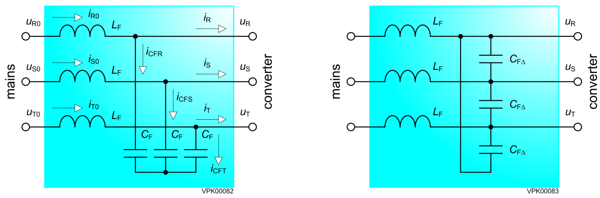

Fig. 12. Two possibilities of LC filter configuration

- LC combination behaviour in the frequency domain (transfer function)

As far as the mains frequency is concerned, the filter can be described in a harmonic three-phase quasi-steady state by means of time complex vectors. For a non-loaded filter's input current we can write

$$\underline{I}_{\mathrm{CFR}} = \frac{\underline{U}_{\mathrm{R0}}}{\underline{X}_{\mathrm{F,mains}}} = \frac{\underline{U}_{\mathrm{R0}}}{j \cdot \left(\mathrm{L_F}\omega_{\mathrm{mains}} - \frac{1}{\mathrm{C_F}\omega_{\mathrm{mains}}}\right)}. \quad (15)$$

Assuming that the power factor of the converter itself (given by i_R and u_R) is equal to one and the efficiency is 100%, its current can be derived from its rated apparent power

$$\underline{I}_{\mathrm{Rn}} = \frac{\underline{S}_{\mathrm{MCn}}}{3 \cdot (\underline{U}_{\mathrm{R0}} - j\mathrm{L_F}\omega_{\mathrm{mains}}\underline{I}_{\mathrm{R0n}})*}. \quad (16)$$

If we fix our requirements for the filter by defining a maximum angle between mains voltage and current for a certain relative utilization of the converter rated power, we get

$$k_{\mathrm{S}} = \frac{S_{\mathrm{MC}}}{S_{\mathrm{MCn}}}. \quad (17)$$

Then the maximum value of the filter capacitor is

$$\mathrm{C_F} < \frac{k_{\mathrm{S}} \cdot S_{\mathrm{MCn}} tg\varphi_{\mathrm{mains,max}}}{3U_{\mathrm{R0}}\omega_{\mathrm{mains}}}. \quad (18)$$

The next characteristic property of the LC filter is its cut-off frequency (called also resonance frequency)

$$f_0 = \frac{1}{2\pi\sqrt{\mathrm{L_F C_F}}}. \quad (19)$$

This cut-off frequency *f0* should have a sufficient distance from the switching frequency of the converter *fSW*. This can be defined by a safety frequency ratio

$$k_{\mathrm{F}} = \frac{f_{\mathrm{SW}}}{f_0}, \quad (20)$$

from which we obtain

$$\mathrm{L_F} > \frac{k_{\mathrm{F}}^2}{2\pi^2 f_0^2 \mathrm{C_F}}. \quad (21)$$

The filter design is a compromise between capacitor and inductor size. A small capacitor assures a high power factor $\cos(\varphi_{mains})$ is available but requires a large inductor to secure an appropriate cut-off frequency. The size of the inductor is limited by the voltage drop across it.

Some authors prefer the delta variation instead of the star capacitor configuration. This is surely reminiscent of motor starting by interchange of the star and delta connections. As an induction motor in delta connection can produce a three times higher torque when it has sufficient winding insulation and appropriate magnetic circuits, analogously, a capacitor of the same value with a sufficient isolation level produces in delta connection a three times larger reactive power than in the star connection.

Thus a factor of thrice smaller capacity value for the same cut-off frequency in the delta configuration is necessary. However the behavior with respect to some components (3^{rd} order and its multiples) of the frequency spectrum is not the same.

The simple LC filter introduced in, is often called undamped since its damping depends on the load resistance only otherwise and its gain is limited by just internal resistance of the real components. Its transfer function can be written

$$F_{\mathrm{LC}}(\omega) = \frac{\underline{U}_{\mathrm{LC,out}}}{\underline{U}_{\mathrm{LC,in}}} = \frac{1}{1 + j\omega\frac{\mathrm{L_F}}{\mathrm{R_{load}}} + \mathrm{L_F C_F}\,(j\omega)^2}. \quad (22)$$

If we define the cutoff frequency in radians

$$\omega_0 = \frac{1}{\sqrt{\mathrm{L_F C_F}}} \quad (23)$$

and the damping factor (zeta)

$$\zeta = \frac{\mathrm{L_F}}{2 \cdot \mathrm{R_{load}}\sqrt{\mathrm{L_F C_F}}} \quad (24)$$

the transfer function can be arranged again

$$F_{\mathrm{LC}}(\omega) = \frac{1}{1 + j\omega\frac{\mathrm{L_F}}{\mathrm{R_{load}}} - \mathrm{L_F C_F}\omega^2} = \frac{1}{1 + j2\zeta\frac{\omega}{\omega_0} - \frac{\omega^2}{\omega_0^2}}. \quad (25)$$

The influence of the damping factor to the filter transfer function can be seen in Fig. 13. In order to avoid uncertainty in damping, different damping circuit solutions have been developed for use with power converters. Some of these are found below.

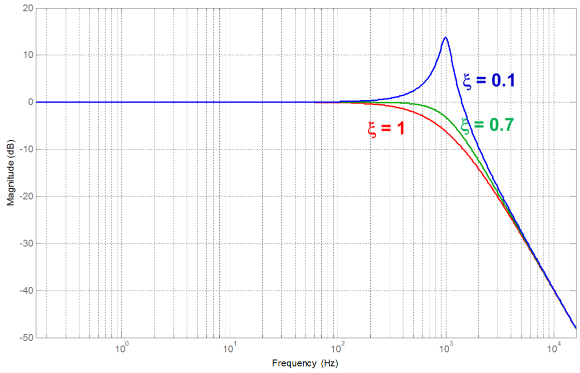

Fig. 13. LC filter transfer functions for different damping factors

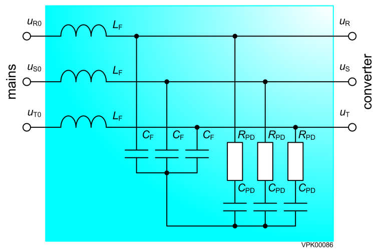

Fig. 14. LC filter topology with parallel damping

A parallel damping circuit is depicted in Fig. 14. The purpose of resistor R_{PD} is to reduce the output peak impedance of the filter at the cut-off frequency. The capacitor C_{PD} blocks the DC component of the input voltage, and avoids power dissipation on R_{PD}. The capacitor CPD should have a lower impedance than R_{PD} at the resonant frequency and be a larger value than the filter capacitor so as not to effect the cut-off point of the main LC filter.

$$\mathrm{R_{PD}} = \sqrt{\frac{\mathrm{L_F}}{\mathrm{C_F}}}, \mathrm{C_{PD}} = 4\mathrm{C_F} \tag{26}$$

The transfer function of the parallel damped LC filter is

$$\frac{1+sR_{PD}C_{PD}}{1+sR_{PD}C_{PD}+s^2L_F(C_F+C_{PD})+s^3L_FC_FR_{PD}C_{PD}}. \tag{27}$$

Effects of the damping circuit on the LC filter's transfer function are in Fig. 16(blue).

A series damping circuit with a resistance R_{SD} in series with an inductor L_{SD}, all connected in parallel with the filter inductor L_F is shown in Fig. 15. At the cut-off frequency, the resistance R_{SD} must be a higher value than the L_{SD} impedance.

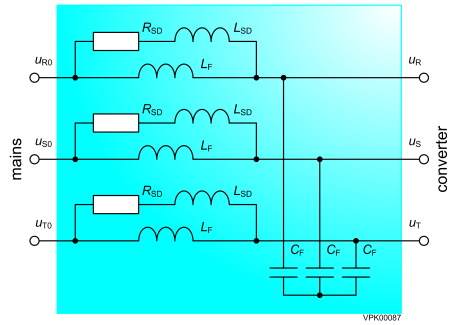

Fig. 15. LC filter with serial damping

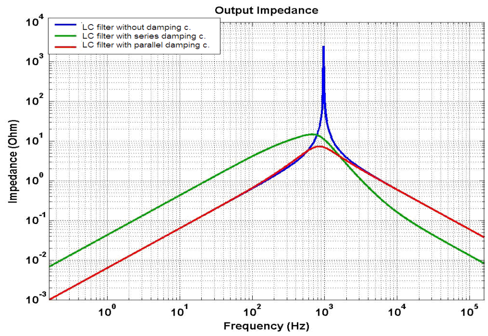

Fig. 16. LC filter output impedance

An optimum damping can be obtained with the following parameter choice

$$\mathrm{R_{SD}} = \sqrt{\frac{\mathrm{L_F}}{\mathrm{C_F}}}, \mathrm{L_{SD}} = \frac{2}{15}\cdot\mathrm{L_F}. \tag{28}$$

The transfer function of the series damped LC filter is

$$\frac{R_{SD}+s\left(L_F+L_{SD}\right)}{R_{SD}+s\left(L_F+L_{SD}\right)+s^2L_FC_FR_{SD}+s^3L_FC_FL_{SD}}. \tag{29}$$

The disadvantage of this damped filter is that the high frequency attenuation is degraded (see Fig. 16 green).

The transfer functions of the filters are in Fig. 16. Red waveform represents the filter without damping. The peek in the area of the cutoff frequency is clear. The blue waveform corresponds with the filter with parallel damping. The parallel damped filter has better attenuation compared to with the green waveform, which belongs to the series damped filter. Output impedances of proposed filter variants are in Fig. 17.

It was also mentioned that a diode clamp circuit can cause oscillations in the input filter. This undesirable interaction will be shown for an operation when the converter is not active but connected to the mains. In order to

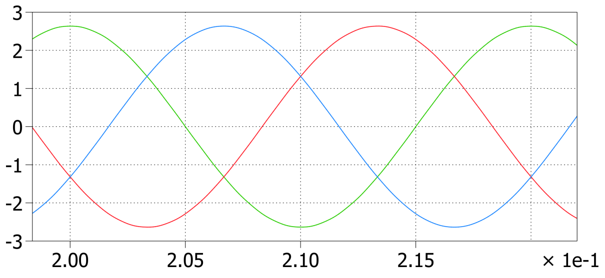

Fig. 17. Current on the input of the filer – no damping, $R_{CL} = 0$

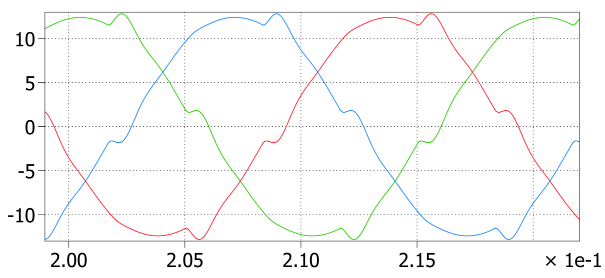

Fig. 19. Current on the input of the filer – parallel damping, $R_{CL} = 10\,k\Omega$

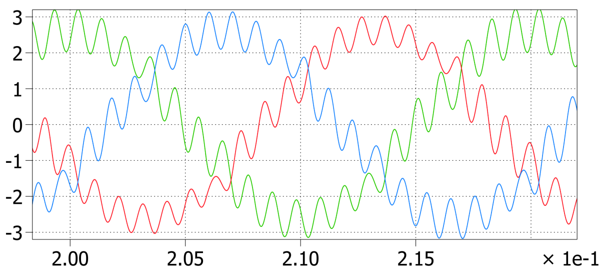

Fig. 18. Current on the input of the filer – no damping, $R_{CL} = 10\,k\Omega$

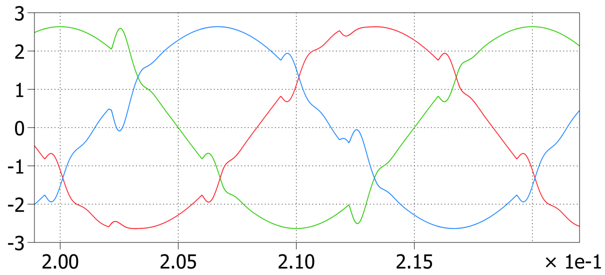

Fig. 20. Current on the input of the filer – series damping, $R_{CL} = 10\,k\Omega$

avoid these oscillations and test the behaviors of the filter Matlab/Simulink models were created. The following values of parameters have been taken: $U_{A0} = 230$ V / 50 Hz, $L_F = 1$ mH, $C_F = 27$ mF, $C_{CL} = 10$ mF. The cut-off frequency of the filter is then equal to 937 Hz. This parameter choice matches with those that should be realized. The following figures show the results of the simulations. Following variants have been investigated:

- LC filter without damping, no discharging resistor R_{CL}
- LC filter without damping, resistor R_{CL} = 10 kΩ
- LC filter with series damping, resistor R_{CL} = 10 kΩ
- LC filter with parallel damping, resistor R_{CL} = 10 kΩ

Figures 18 - 21 shows the simulation results of the interaction between input filter of the matrix converter and components in the clamp circuit C_{CL} and R_{CL}. It is obvious, that the connection of the clamp circuit causes oscillations of the input filter. Therefore the damping of the filter must be included. However the addition of the damping circuit is connected with the increase of the filter losses. The results in Fig. 16 and 19 show, that parallel damping has better influence on the filter and it also does not deteriorate attenuation of the filter. On the other hand better behavior of the filter is obtained by increased current consumption. That is why the serial damped filter seems to be better solution of this problem.

6 CONCLUSION

A clamp circuit and input filter are essential components of any kind of the classical matrix converter. This article presents a derivation of design formulas for their key components. For a rapid design, also formulas based on rated power are included. Formulas and simulation results, presented in this paper, were used for a design of the filter and clamp circuit for the matrix converter prototype, which is now being assembled. The real impact of the design will be evaluated after the whole prototype construction.

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