Modulation and Realization of a Novel Two-Stage Matrix Converter

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***Abstract* - Topology and equations of a novel 2-stage matrix converter are presented. The circuit is consisting of an ac voltage source rectifier (AC-VSR) and a dc voltage source inverter (AC-VSI). The operation principle of the converter is discussed in comparison to the conventional 1-stage matrix converter. This helps in understanding the voltage conversion and the opposite current conversion path through the circuit. Space vector modulation is applied to control the switches. Thereby, sinusoidal short term mean values for output voltages and input currents are obtained. Measurements confirm the expectations.**

***Keywords:* 2-stage MC (matrix converter), VS (voltage source), CS (current source), SVM (space vector modulation), modulation index, short term mean value (stm-value)**

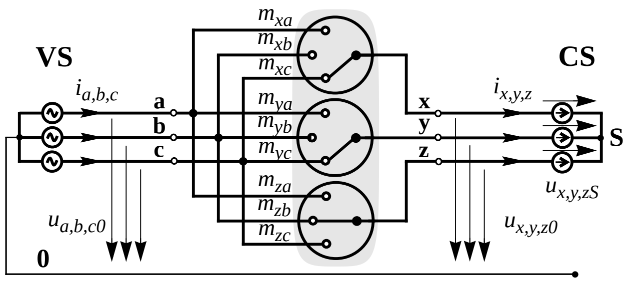

Fig. 1. 1-stage matrix converter with three change-over switches

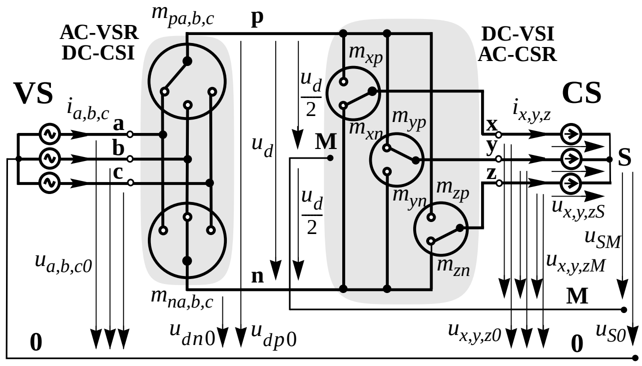

Fig. 2. 2-stage matrix converter with five change-over switches and with existing dc link *p*,*n*

I. Introduction

"Full"-silicon design with a minimum of reactive components is a new trend based on the following idea:
Power semiconductor elements become better and cheaper every year, since they strongly benefit from technological progresses. Reactive components, however, like inductances and capacitances have limited development potentials and remain bulky and expensive.

Matrix **c**onverters (MCs) [1] are a step ahead towards "full"-silicon circuits. They avoid dc link inductances and capacitances by performing direct ac to ac conversion. Only at the mains side they need capacitive filters which, however, are small, when the switching frequency is high.

MCs, however, are waiting for new monolithic bi-directional turn-off devices before they are really ready for commercial applications. Monolithic bi-directional turn-off elements are in an early stage of research efforts [2] with promising ideas but still far away from becoming a commercial product. Today's MCs use two anti-series connected, existing IGBTs, each with an anti-parallel diode, instead of one single, future monolithic bi-directional turn-off device (Fig. 3).

This paper deals with matrix converters (MCs), especially with a novel 2-stage MC. In chapter II the basic mode of operation is explained. The system equations are derived in chapter III. Chapter IV presents and illustrates the modulation method, whereas Chapter V shows a hardware set-up with sophisticated low inductance design and measurement results.

II. Topology - Basic Mode of Operation

MCs are direct linked type ac-ac converters without intermediate energy storage components. Two versions are shown: The 1-stage MC in Fig. 1 and the 2-stage MC in Fig. 2. The 1-stage MC is a full matrix converter, whereas the 2-stage MC has slightly reduced matrix functions, because just two input phases can be connected to the output phases. This fact, however, does not limit the application.

The circuits in Fig. 1 and Fig. 2 are represented in a way which makes the functions clearly visible: with idealized inertia-free change-over switches. The positions of the change-over switches are determined by the modulator. The pivot points of the change-over switches are always placed at the **c**urrent **s**ource side (CS) of the converter stages. There, they never can interrupt the CS side and always leave a current path to the **v**oltage **s**ource side (VS) open, avoiding in this way high turn-off over-voltages. The moving ends of the change-over switches are always at the VS side. At this place, they can never short-circuit the VS side which would cause short-circuit currents. The circuit realization with power semiconductor devices is described below.

The focus in this paper is on the 2-stage MC. In Fig. 2 it is represented with change-over switches. Fig. 3 shows a today's realization of a 2-stage MC. The basic mode of operation of the 2-stage MC is easy to understand when going through the converter from the left to the right along the voltage conversion path and then the way back along the current conversion path:

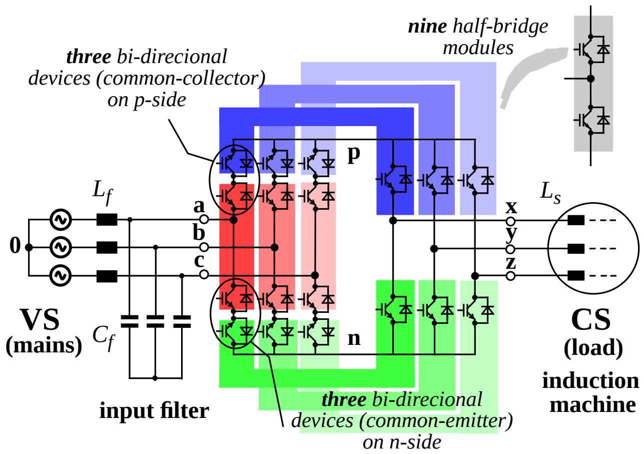

Fig. 3. Realization of the 2-stage matrix converter circuit with today's semiconductor devices

• The **ac** **v**oltage **s**ource **r**ectifier (AC-VSR) rectifies the line-to-line ac input voltages $\pm u_{ab,\,bc,\,ca}$ ($\pm u_{ab,\,bc,\,ca} = \pm(u_{a,\,b,\,c0} - u_{b,\,c,\,a0})$) (Fig. 4a left), impressed from the 3-phase mains side, and generates a switched dc voltage u_d (Fig. 4d left), which is directly the input voltage for the **dc** **v**oltage **s**ource **i**nverter (DC-VSI).

• The DC-VSI "inverts" this impressed dc voltage u_d and generates a switched 3-phase ac voltage $u_{x,\,y,\,zM}$ (Fig. f left) with sinusoidal **s**hort **t**erm **m**ean (stm) values $u_{x,\,y,\,zS}$ at the motor windings. This voltage $u_{x,\,y,\,zS}$ (Fig. f right) gives rise to a sinusoidal 3-phase ac current $i_{x,\,y,\,z}$ (Fig. 4f right), the ripple of which is limited by the serial leakage inductance L_s of the load motor.

• This 3-phase ac current $i_{x,\,y,\,z}$ can be regarded as an impressed current for the DC-VSI. The DC-VSI, which is at the same time also an **ac** **c**urrent **s**ource **r**ectifier (AC-CSR), rectifies this impressed 3-phase ac current $i_{x,\,y,\,z}$ and generates a switched dc current i_d (Fig. 4d right), which is directly fed into the AC-VSR.

• The AC-VSR — being at the same time also a **dc** **c**urrent **s**ource **i**nverter (DC-CSI) — "inverts" this impressed dc current i_d and generates a switched 3-phase ac current $i_{a,\,b,\,c}$ (Fig. 4a right) with sinusoidal short term mean values. It is fed into the mains side 3-phase ac voltage source $u_{a,\,b,\,c0}$ (Fig. a right and left), which is backed by the shunt capacitors C_f of a CL-filter. This filter keeps the voltage and current ripples low.

Fig. 3 shows the realization of the 2-stage MC circuit with today's power semiconductor devices. The current i_d, impressed to the AC-VSR, has two polarities. Even in cases with energy transfer from the supply side to the load, i_d has negative pulses at low load. For this reason each position of the change-over switch leg needs two existing IGBTs in anti-series connection, each with antiparallel diode (Fig. 3). In future, these four devices will be replaced by one single, monolithic bi-directional turn-off device. The DC-VSI, however, needs only one single, existing IGBT with antiparallel diode for each switch leg position — because the switched dc voltage u_d can always be kept positive: that means the DC-VSI remains conventional also for the future. Bi-directional energy transfer is easy to perform with this circuit.

III. System Equations

This Chapter starts with the definition of the modulation indices before writing the system equations (chapter *III. A*). In this way it is possible to compare mathematically the modulation indices of 1- and 2-stage MCs on condition that the input-output behaviour of both topologies is presumed to be the same (chapter *III. B*).

III. A. Equations of the 2-Stage MC

The AC Voltage Source Rectifier (AC-VSR)

The change-over switches of the AC-VSR in Fig. 2 connect the dc terminals *p*, resp. *n* of their pivot points with the ac terminals *a*, *b* or *c*. The allocated modulation indices m_{pa}, m_{pb}, m_{pc}, respectively m_{na}, m_{nb}, m_{nc} indicate with their actual values the percentage of time in which the terminals *pa*, *pb*, *pc*, resp. *na*, *nb*, *nc* are connected during a short term period. The sum of all modulation indices of the same pivot point must always be 100%, i.e.

$$m_{pa} + m_{pb} + m_{pc} = 100\% \qquad \text{(1 stm)}$$

$$m_{na} + m_{nb} + m_{nc} = 100\% \qquad \text{(2 stm)}$$

By introducing modulation indices ($0 \le m_{ij} \le 1$), **s**hort **t**erm **m**ean (stm) values for voltage and current are used. In this section, the succeeding equations always refer to the calculation with stm-values of the system, indicated by the index "stm". The generated pulsed momentary values, however, can be described by the same equations. Based on the consideration made above in (1) and (2), the AC-VSR system equations can be established:

The dc voltages u_{dp0} and u_{dn0} (Fig. 2) are generated from all three impressed ac voltages $u_{a,\,b,\,c0}$. Each of them is used with a percentage of time, which is given by the allocated AC-VSR modulation indices m_{pa}, m_{pb}, m_{pc}, resp. m_{na}, m_{nb}, m_{nc}.

$$u_{dp0} = m_{pa} \cdot u_{a0} + m_{pb} \cdot u_{b0} + m_{pc} \cdot u_{c0} \qquad \text{(3 stm)}$$

$$u_{dn0} = m_{na} \cdot u_{a0} + m_{nb} \cdot u_{b0} + m_{nc} \cdot u_{c0} \qquad \text{(4 stm)}$$

The difference of (3) and (4) between u_{dp0} and u_{dn0} constitutes the dc link voltage u_d in (5) being independent of the neutral "0":

$$u_d = u_{dp0} - u_{dn0} \qquad \text{(5 stm)}$$

Consequently, (6) represents the combined modulation indices $m_{a,\,b,\,c}$ of the AC-VSR switch settings.

$$m_{a,\,b,\,c} = m_{pa,\,b,\,c} - m_{na,\,b,\,c} \qquad \text{(6 stm)}$$

Current conversion goes right in the opposite direction: converting the given, impressed dc current i_d to a generated input ac-current $i_{a,\,b,\,c}$, the AC-VSR simultaneously operates as a *dc current source inverter (DC-CSI)*. This is demonstrated in (7) for each phase:

$$i_{a,\,b,\,c} = m_{a,\,b,\,c} \cdot i_d \qquad \text{(7 stm)}$$

The DC Voltage Source Inverter (DC-VSI)

The change-over switches of the DC-VSI in Fig. 2 connect the ac terminals *x*, *y*, resp. *z* of their pivot points with the dc terminals *p* or *n*. The sum of all modulation indices of the same pivot point must equal 100%, i.e.:

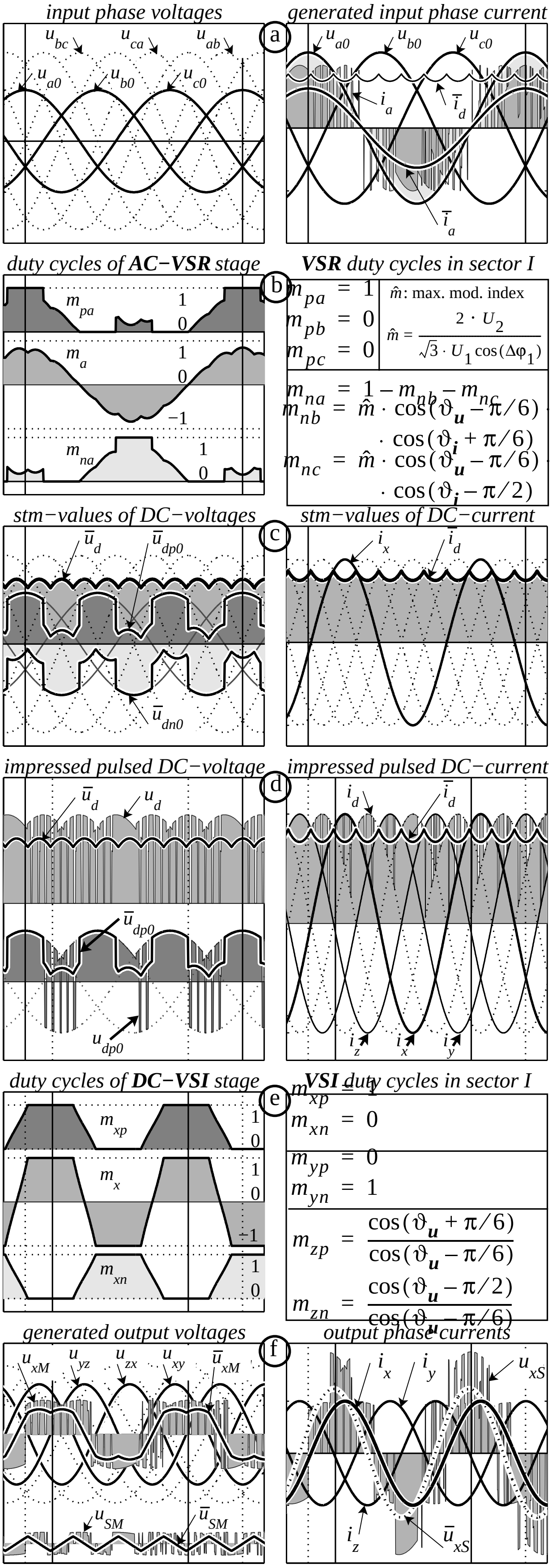

Fig. 4. Output voltage generation (left), input current generation (right), with modulation method impressing the *minimal* dc voltage; maximal modulation index $\hat{m} = 0.85$, output frequency $f_2 = 80\,\mathrm{Hz}$.

$$m_{xp} + m_{xn} = 100\% \tag{8 stm}$$

$$m_{yp} + m_{yn} = 100\% \tag{9 stm}$$

$$m_{zp} + m_{zn} = 100\% \tag{10 stm}$$

Based on this consideration the DC-VSI system equations can be established:
The ac output voltages $u_{x,\,y,\,z0}$, resp. $u_{x,\,y,\,zM}$, (Fig. 2) are generated from the impressed dc voltages $u_{dp,\,n0}$, resp. $u_{dp,\,nM}$. Each of them is used with a percentage of time, which is given by the allocated DC-VSI modulation indices m_{xp}, m_{xn}, resp. m_{yp}, m_{yn}, resp. m_{zp}, m_{zn}.

$$u_{x,\,y,\,z0} = m_{x,\,y,\,zp} \cdot u_{dp0} + m_{x,\,y,\,zn} \cdot u_{dn0} \tag{11 stm}$$

$$\begin{aligned} u_{x,\,y,\,zM} &= m_{x,\,y,\,zp} \cdot u_{dpM} + m_{x,\,y,\,zn} \cdot u_{dnM} = \\ &= (m_{x,\,y,\,zp} - m_{x,\,y,\,zn}) \cdot u_d/2 \end{aligned} \tag{12 stm}$$

Regarding current impression, the dc current i_d is created from the impressed three load phase currents $i_{x,\,y,\,z}$ according to (13). Thus, the DC-VSI can also be named as a *ac-current source rectifier (AC-CSR)* by analogy.

$$\begin{aligned} i_d &= m_{xp} \cdot i_x + m_{yp} \cdot i_y + m_{zp} \cdot i_z = \\ &= -m_{xn} \cdot i_x - m_{yn} \cdot i_y - m_{zn} \cdot i_z \end{aligned} \tag{13 stm}$$

Introducing the combined modulation indices $m_{x,\,y,\,z}$ of the DC-VSI, another calculation of the dc current made in (15) can be derived from (14):

$$m_{x,\,y,\,z} = m_{x,\,y,\,zp} - m_{x,\,y,\,zn} = \tag{14 stm}$$

$$i_d = 1/2 \cdot (m_x \cdot i_x + m_y \cdot i_y + m_z \cdot i_z) \tag{15 stm}$$

The load

An asynchronous machine is fed by the converter output voltages (Fig. 3). The load phase voltages $u_{x,\,y,\,zS}$ over the three windings of the stator are related to the star-point S of the machine. The three-phase output voltages $u_{x,\,y,\,zS}$ do not contain the zero-sequence voltage u_{S0} or u_{SM}. This component must be considered separately (16).

$$u_{x,\,y,\,zS} = u_{x,\,y,\,z0} - u_{S0} = u_{x,\,y,\,zM} - u_{M0} \tag{16}$$

Further, the sum of the load currents equals zero as for the mains currents, i.e.

$$i_x + i_y + i_z = 0 \tag{17}$$

III. B. Mathematical Equivalence of 1- and 2-Stage MC

Both kinds of circuit topologies can be depicted using matrices. The modulation matrix $\boldsymbol{M}$ contains the converter modulation indices m_{ij}. It must be transposed for the description of current relations compared to voltage relations. The input source voltages $u_{a,\,b,\,c0}$ and the output load currents $i_{x,\,y,\,z}$ are transformed into the desired output phase voltages $\bar{u}_{x,\,y,\,zS}$ and the resulting input phase currents $\bar{i}_{a,\,b,\,c}$, respectively, with user-defined phase shift angle φ_{i10} for the input current, where:

input voltage vector $\boldsymbol{u}_1 = \left[u_{a0}\ u_{b0}\ u_{c0}\right]^T$,

desired output voltage vector $\bar{\boldsymbol{u}}_2 = \left[\bar{u}_{xS}\ \bar{u}_{yS}\ \bar{u}_{zS}\right]^T$,

output current vector $\boldsymbol{i}_2 = \left[i_x\ i_y\ i_z\right]^T$ and resulting stm-values of input current vector

$$\bar{\boldsymbol{i}}_1 = \begin{bmatrix} \bar{i}_a & \bar{i}_b & \bar{i}_c \end{bmatrix}^T$$

1-Stage Matrix Converter

The 3×3-matrix $\boldsymbol{M}_{\text{1-stage MC}}$ represents the 1-stage MC with its *nine* modulation indices. So, the relations (18), (19) between the impressed and the generated variables are as follows [3]:

$$\bar{\boldsymbol{u}}_2 = \begin{bmatrix} U_2 \cdot \cos(\omega_2 t + \varphi_{u20}) \\ U_2 \cdot \cos(\omega_2 t + \varphi_{u20} - 2/3 \cdot \pi) \\ U_2 \cdot \cos(\omega_2 t + \varphi_{u20} + 2/3 \cdot \pi) \end{bmatrix} =$$

$$= \begin{bmatrix} m_{xa} & m_{xb} & m_{xc} \\ m_{ya} & m_{yb} & m_{yc} \\ m_{za} & m_{zb} & m_{zc} \end{bmatrix} \cdot \begin{bmatrix} U_1 \cdot \cos(\omega_2 t) \\ U_1 \cdot \cos(\omega_2 t - 2/3 \cdot \pi) \\ U_1 \cdot \cos(\omega_2 t + 2/3 \cdot \pi) \end{bmatrix} =$$

$$= \boldsymbol{M}_{\text{1-stage MC}} \cdot \boldsymbol{u}_1 \qquad (18)$$

and

$$\bar{\boldsymbol{i}}_1 = \begin{bmatrix} I_1 \cdot \cos(\omega_1 t + \varphi_{i10}) \\ I_1 \cdot \cos(\omega_1 t + \varphi_{i10} - 2/3 \cdot \pi) \\ I_1 \cdot \cos(\omega_1 t + \varphi_{i10} + 2/3 \cdot \pi) \end{bmatrix} =$$

$$= \begin{bmatrix} m_{xa} & m_{ya} & m_{za} \\ m_{xb} & m_{yb} & m_{zb} \\ m_{xz} & m_{yc} & m_{zc} \end{bmatrix} \cdot \begin{bmatrix} I_2 \cdot \cos(\omega_2 t + \varphi_{i20}) \\ I_2 \cdot \cos(\omega_2 t + \varphi_{i20} - 2/3 \cdot \pi) \\ I_2 \cdot \cos(\omega_2 t + \varphi_{i20} + 2/3 \cdot \pi) \end{bmatrix} =$$

$$= \boldsymbol{M}^T{}_{\text{1-stage MC}} \cdot \boldsymbol{i}_2 \qquad (19)$$

2-Stage Matrix Converter

Substitution of (3)$\div$(4) in (11) leads to the following composed 3×3-matrix $\boldsymbol{M}_{\text{2-stage MC}}$ of the 2-stage MC with its *twelve* modulation indices:

$$\boldsymbol{M}_{\text{2-stage MC}} = \begin{bmatrix} m_{xp} \\ m_{yp} \\ m_{zp} \end{bmatrix} \cdot \begin{bmatrix} m_{pa} & m_{pb} & m_{pc} \end{bmatrix} + \begin{bmatrix} m_{xn} \\ m_{yn} \\ m_{zn} \end{bmatrix} \cdot \begin{bmatrix} m_{na} & m_{nb} & m_{nc} \end{bmatrix} \qquad (20)$$

Multiplication of the two products in (20) and equating both modulation matrices ($\boldsymbol{M}_{\text{1-stage MC}} = \boldsymbol{M}_{\text{2-stage MC}}$) yields:

$$m_{ij} = m_{ip} \cdot m_{pj} + m_{in} \cdot m_{nj}, \quad (i = x, y, z, \; i = x, y, z) \qquad (21)$$

According to (21) the 1-stage and 2-stage MC can be obviously controlled in the way that their input-output behaviour is exactly identical. However, the sum in (21) comes from the existing dc link with its two connection terminals *p* and *n*, whereas the products show the two stages AC-VSR and DC-VSI. It indicates the possibility that generally each modulation index $m_{ip,n}$, $m_{p,nj}$ of the 2-stage MC can be generated differently in order to produce the same m_{ij} of the 1- stage MC. There are more degrees of freedom to control the 2-stage MC.

IV. Space Vector Modulation

The 2-stage MC circuit favours the idea of space vector modulation, which is also applied to 1-stage MCs [4]. In this paper, the space vector modulation method gives a good idea of how pulse generation works without explaining particularly defined pulse sequences. This chapter helps in understanding how the space vector modulation index $\tau_{U,I}$ of a specific space vector position $\boldsymbol{U}_i$ or $\boldsymbol{I}_i$ ($i = 1 \ldots 6$) can be expressed, in general, with the known modulation indices m_{ij} of the switch connection *i-j*. The m_{ij} themselves depend on the chosen modulation strategy and have to be calculated in advance. There exist a lot of different strategies, but just one of them is demonstrated in this paper (Fig. 4), namely a method creating the *minimal* dc voltage u_d which is necessary at all to feed the load with sufficient output voltages $u_{x,y,zS}$. Actually, it is possible to impress any kind of dc voltage u_d. Compared to existing realizations [5], all these modulation strategies do not require the measurement of any dc link variables u_d, $u_{dp,n0}$ or i_d.

IV. A. Output Voltage and Input Current Generation

By taking the impressed pulsed dc voltages $u_{dp,n0}$, the DC-VSI generates a pulsed ac output voltage space vector $\bar{\boldsymbol{u}}_{xyzS}$ (Fig. 5a) consisting of maximal six space vectors $\boldsymbol{U}_i$ and two combinations yielding the zero voltage vectors $\boldsymbol{U}_{0p,n}$.

By taking the impressed pulsed dc current i_d, the AC-VSR generates a pulsed ac input current space vector $\bar{\boldsymbol{i}}_{abc}$ (Fig. 5b) consisting of maximal six space vectors $\boldsymbol{I}_i$ and three combinations yielding the zero current vectors $\boldsymbol{I}_{0a,b,c}$.

Let the voltage space vector $\bar{\boldsymbol{u}}_{xyzS}$ of the desired output voltages $\bar{u}_{x,y,zS}$ and the current space vector $\bar{\boldsymbol{i}}_{abc}$ of the arising stm-input currents values $\bar{i}_{a,b,c}$ be as defined in (22) and (23):

$$\bar{\boldsymbol{u}}_{xyzS} = (u_{xS} \cdot e^{j0°} + u_{yS} \cdot e^{j120°} + u_{zS} \cdot e^{-j120°}) \quad (22)$$

$$\bar{\boldsymbol{i}}_{abc} = (\bar{i}_a \cdot e^{j0°} + \bar{i}_b \cdot e^{j120°} + \bar{i}_c \cdot e^{-j120°}) \quad (23)$$

Both space vectors, $\bar{\boldsymbol{u}}_{xyzS}$ and $\bar{\boldsymbol{i}}_{abc}$, are visible in the complex plane in Fig. 5 and Fig. 6.

IV. B. Computation of modulation indices for Space Vector Generation

As an example, in Fig. 7 the desired output voltage space vector $\bar{\boldsymbol{u}}_{xyzS}$ is assumed to be composed of the four space vectors $\boldsymbol{U}_1$, $\boldsymbol{U}_2$, $\boldsymbol{U}_6$ and $\boldsymbol{U}_{0p}$, which is apparent in the first equation in (24). The space vector modulation indices τ_{U_i} ($i = 0p, 1, 2, 6$) indicate the raltive duration of one single voltage space vector $\boldsymbol{U}_i$. Of course, the example can also be shown by means of the arising input current space vector $\bar{\boldsymbol{i}}_{abc}$ using the current space vectors $\boldsymbol{I}_i$. Regarding the

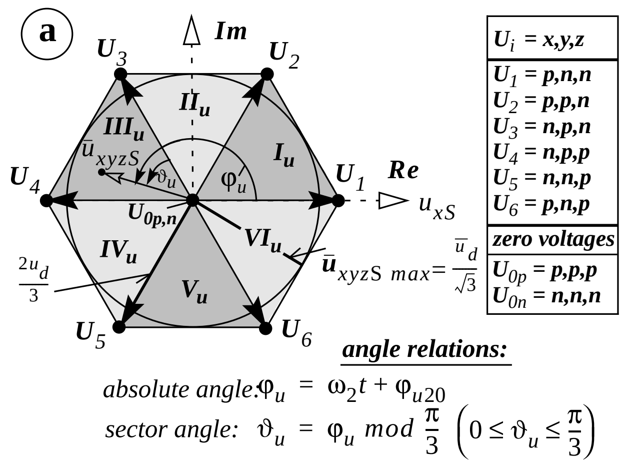

Fig. 5. Voltage hexagon with generated output voltage space vectors with 6 sectors, absolute angles and sector angles

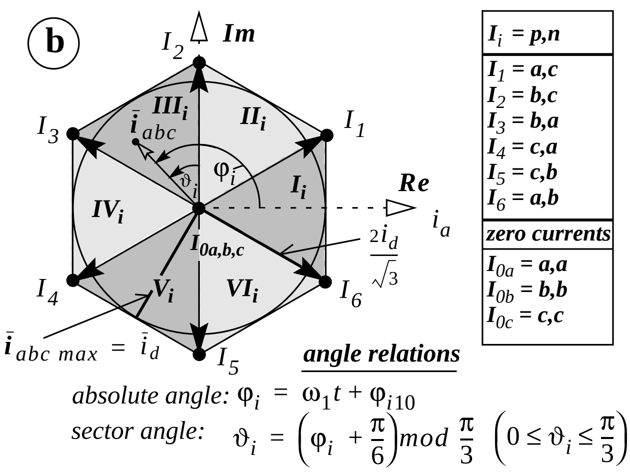

Fig. 6. Current hexagon with generated input current space vectors with 6 sectors, absolute angles and sector angles

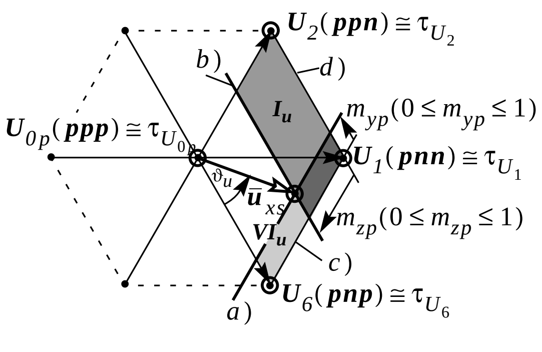

Fig. 7. Graphical representation of DC-VSI modulation indices m_{ij} in tetragon $\boldsymbol{U_6}$-$\boldsymbol{U_1}$-$\boldsymbol{U_2}$-$\boldsymbol{U_{0p}}$ consisting of voltage sectors $\boldsymbol{I_u}$ and $\boldsymbol{VI_u}$

switch settings *xyz*, it is usual to decide on one appropriate space vector of the zero voltage vectors $\boldsymbol{U}_{0p,n}$ or zero current vectors $\boldsymbol{I}_{0a,b,c}$, respectively. In order to minimize the switching operations, it is reasonable to choose $\boldsymbol{U}_{0p}$ by setting $\tau_{U_{0n}} = 0$.

The space vector modulation indices τ_{U_i} must satisfy the set of equation (24) stated below for the case shown in Fig. 7. The auxiliary straight lines *a* and *b* (Fig. 7) exactly cross the intersection in the middle of the desired output voltage space vector $\bar{\boldsymbol{u}}_{xyzS}$. In addition, there are the hexagonal margin lines *c* and *d* being in parallel to the lines *a* and *b*. The distance between line *a* and *c* (*b* and *d*, respectively) directly depends on the modulation index m_{yp} (m_{zp}, respectively) for the sector VI_u. Considering that on the one hand, the switch position *y=p* is created by the vectors $\boldsymbol{U}_2$ and $\boldsymbol{U}_{0p}$, and on the other hand, the switch position *y=n* is created by the vectors $\boldsymbol{U}_1$ and $\boldsymbol{U}_6$, the rule of proportion for m_{yp} and m_{yn} in the second equation in (24) is derived from the given position for line *a*. The third equation in (24) is created analogously.

$$\left|\begin{array}{l} \tau_{U_6} + \tau_{U_1} + \tau_{U_2} + \tau_{U_{0p}} = 1 \\ m_{yp} \cdot (\tau_{U_6} + \tau_{U_1}) = m_{yn} \cdot (\tau_{U_2} + \tau_{U_{0p}}) \\ m_{zp} \cdot (\tau_{U_1} + \tau_{U_2}) = m_{zn} \cdot (\tau_{U_6} + \tau_{U_{0p}}) \end{array}\right| \quad (24)$$

Obviously, the solution of the three equations in (24) with its four variables τ_{U_i} is not well-defined. Therefore, it seems to be clear that one further modulation index can be eliminated, i.e. by choosing $\tau_{U_2} = 0$, because space vector $\boldsymbol{U}_2$ does not touch the current sector VI_u. Consequently, the solution of (24) gets unequivocal (25), where $m_{xp} = 1$, $m_{xn} = 0$.

$$\begin{aligned} \tau_{U_6} &= 1 - m_{yp} - m_{zn}, \\ \tau_{U_1} &= m_{zn}, \\ \tau_{U_{0p}} &= m_{yp}. \end{aligned} \quad (25)$$

Related to the input current (Fig. 6), the modulation indices τ_{I_i} of sector I_i for the current space vectors are similarly determined as in (25) under the assumption that the upper change-over switch *p* of the AC-VSR is held on the input phase *a* ($\tau_{I_{0b}} = \tau_{I_{0c}} = 0$), where $m_{pa} = 1$, $m_{pb} = m_{pc} = 0$, i.e.

$$\begin{aligned} \tau_{I_6} &= m_{pb}, \\ \tau_{I_1} &= m_{pc}, \\ \tau_{I_{0p}} &= m_{pa}. \end{aligned} \quad (26)$$

The solutions for the modulation indices in (25) and (26) refer to the specific sectors VI_u and I_i. They can be cyclically exchanged with a correct permutation of all modulation indices m_{ij} for AC-VSR and DC-VSI.

IV. C. Unique Determination of a Modulation Method

There are many different, highly sophisticated modulation methods to control this converter. In this paper, just one method is employed by demanding a *minimal* dc voltage (Fig. 4) as an example. For this case, the DC-VSI must be always in full conduction (Fig. 4e), which leads to $\tau_{U0p} = \tau_{U0n} = 0$. Thus, the desired output voltage space vector $\boldsymbol{\bar{u}}_{xyzS}$ moves along the hexagonal margins but is never inside the voltage hexagon so that the stm-value $\bar{u}_d$ of the dc voltage u_d itself must be modulated during one period of the output voltages to create a sinusoidal stm-value for the output voltages $u_{x,y,zS}$.

Generally, in order to determine the modulation indices m_{ij}, it is necessary, at first, to fix enough variables in the equations (1) ÷ (17) before solving the system equations. So, the calculation of the modulation indices m_{ij} gives a powerful instrument for a correct space vector modulation for desired u_d-values.

V. Realization and Measurements

The realization of a hardware circuit (Fig. 8 left) is presented by using a clever wiring technique. Since monolithic bi-directional turn-off devices are not available yet, purchasable half-bridge modules in one single element are a good substitution to realize the novel 2-stage MC (Fig. 3). Finally, measurements are the proof for correct operation (Fig. 8 right). The shown output frequency is f_2 = 80 Hz. The output frequency is just limited by the switching ferquency f_s.

VI. Conclusions

A 2-stage matrix converter for combining two different three-phase systems without any energy storage elements in the existing dc-link has been developed and tested. It can be controlled in the same way like a 1-stage matrix converter but has an existing dc-link, using conventional semiconductor devices (half bridge modules), which is useful for higher power applications. The presented circuit has been built up for a 3kW asynchronous motor with a switching frequency of about f_s = 9.1 kHz and a control frequency of about f_s = 9.1/4 = 2.3 kHz.

VII. References

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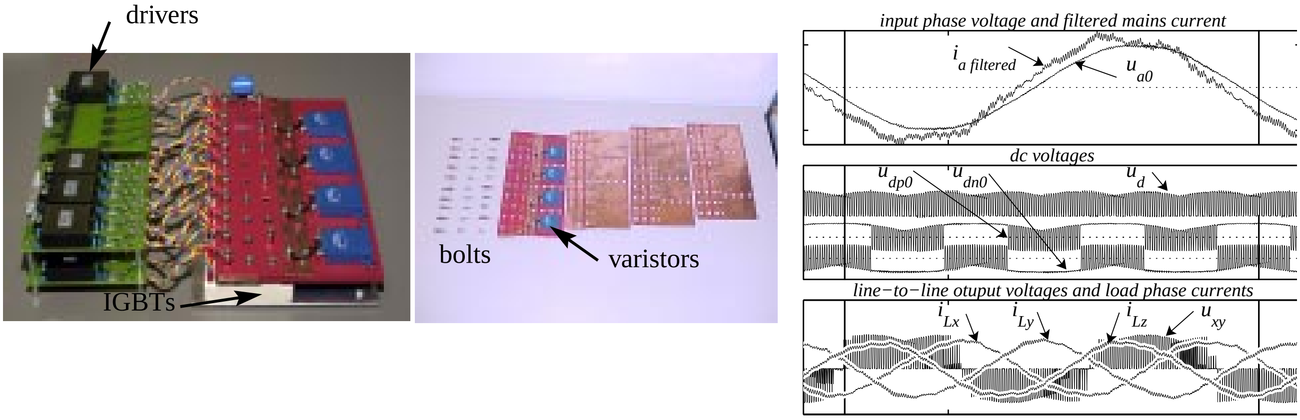

Fig. 8. Realization of a 2-stage matrix converter with five sandwich copper-layers gate-drivers and varistors.
Measurements of input current phase a, dc-voltages and output voltages and currents confirm the technical feasibility