Control Algorithms for Traction Drive with High Voltage Matrix Converters and Medium Frequency Transformer

Martin Pittermann, Pavel Drabek, Bedrich Bednar
Dept. of Electromechanics and Power Electronics
University of West Bohemia
Pilsen, Czech Republic
pitterma@kev.zcu.cz, drabek@kev.zcu.cz, bead@kev.zcu.cz

***Abstract* – This paper describes the control algorithms for electric drive with single phase matrix converters supplied medium frequency converter for traction purpose. Described control algorithms realize the control of active and reactive power, output voltage, reduce harmonic disturbance in input current and oscillation of voltage on input filter etc. These control algorithms were implemented into multiprocessor control system with DSP for small-scale prototype as physical model in laboratory.**

Keywords - Single phase matrix converter; Control algorithms; Traction drive; Medium frequency transformer

I. INTRODUCTION

Figure 1 shows principle of modern concept for traction drive for electric vehicles for AC-high voltage input. Drive consists from input high voltage matrix converters (MC), medium frequency transformer (MFT) and indirect frequency converter on secondary side of MFT. Secondary side frequency converter consist from active rectifier (VSAR) and voltage sourced inverter (VSI) supplied traction motor. Using of high voltage converter brings the possibility of using of MFT with reduced weight (in compare with low frequency transformer). This drive has a high number of elements with many versions of control algorithms. This paper presents useful control algorithms, which bring the best properties during previous long-term simulation and measurement in physical model of this drive in laboratory in our department.

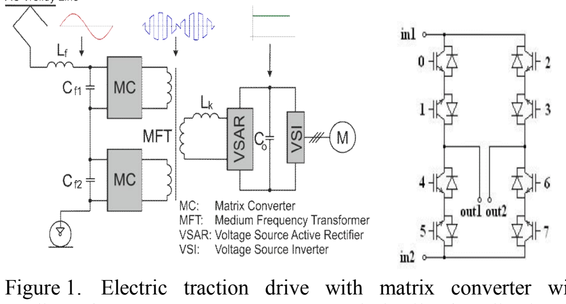

Figure 1. Electric traction drive with matrix converter with medium frequency converter MFT and detail of realization of matrix converter with classical IGBT transistors.

II. CONTROL ALGORITHMS FOR MATRIX CONVERTER

High power and high voltage applications (for example traction drives) bring the requirement for minimization of switching frequency. Control algorithms with minimal switching frequency bring two basic types of control strategies:

- control algorithms with use so called zero vectors (“NULL-vectors”)
- control algorithms without zero vectors

Zero vectors are switching combinations, when input terminal of matrix converter is open and output terminals are closed (i.e. input current is zero value and output voltage is zero). Matrix converter (according to Figure 1) brings zero vectors by switching combination 0123 or 4567 (i.e. during simultaneously closed top elements or bottom elements). Zero vectors bring many disadvantages, because during disconnection of input terminals the input filter can generate uncontrolled oscillation and increasing of voltage ripple (by current flow in input inductances). Using of zero-vectors brings higher values of passive components of input filter (namely higher value of capacitances C_f in input filter) and problems with this time response and frequency response (resonant frequencies, influence of actual parameters on trolley-line etc.). Control algorithms with zero vectors are described for example in [2], [3].

Described control algorithm use cooperation between converters in primary side of MFT and converters in secondary side of MFT – i.e. basic idea of this control algorithm is using the most simple control algorithm for matrix converter (i.e. without zero vectors etc.) – for example only switching with constant frequency and rest functions are realized by converter on secondary side of MFT.

Input voltage (from trolley-line) is AC – it brings modification of actual value of switching frequency for optimal magnetic saturation of MFT – during zero crossing of input voltage actual switching frequency has minimal value and during magnitude of input voltage the switching frequency has maximal value.

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III. CONTROL ALGORITHMS FOR SECONDARY CONVERTER

Control algorithms for secondary converter realize control of output voltage source inverter (VSI) and control of input voltage source active rectifier (VSAR). VSI supplied induction motor and it has standard control algorithm (i.e. vector control, resp. scalar control or direct torque control DTC). VSAR cooperate with high voltage matrix converter in primary side of MFT and its control algorithm brings these functions:

- control of voltage on capacitance C_o in DC-link in secondary converter
- control of optimal phase shift between input current and input current (i.e. minimization of input wattles power)
- control for purpose to obtain optimal sinusoidal waveform of input current (i.e. minimization of unwanted higher harmonics)
- optimization of voltage in input filter capacitances C_f (i.e. minimization of oscillation of voltage on these capacitances, potential equalization of voltage on these input capacitances C_f)
- possibility of recuperation mode of drive (i.e. active rectifier VSAR works as inverter)

Figure 2 shows the basic principle of control algorithm for matrix converter in primary side of MFT and active rectifier on secondary side of MFT.

First line shows power circuits and position for current sensors and for voltage sensors.

Second line shows position of control blocks for switching logic. Switching logic for active rectifier is standard. Switching logic for matrix converter is complicated (synchronization with actual values from sensors and 4-step commutation switching algorithms according to actual input voltage or actual output current) and it is described in other literature (these details it is not importance for this basic description). The most illuminated situation brings constant switching frequency (for example 400Hz) for semiconductor elements in matrix converter.

Third line shows blocks for measurement of actual value of phase shift φ between input current and input voltage and synchronization with input voltage (value of actual phase-shift ϑ of input voltage).

Next line (number 4) shows phase controller Rφ for previous signals φ and ϑ.

Last line (number 5) shows position of voltage controller R_{Uc} (as master controller) and current controller R_i (as slave controller). Voltage controller R_{Uc} realize voltage control loop for purpose to obtain approximately constant voltage U_c (on capacitance C_0 in DC-link in secondary converter) by secondary current. Output power (realized by VSI supplied traction motor – see Figure 1) brings the decreasing of voltage in DC-link (in motor-mode of induction machine and rectifier-mode of VSAR in secondary side) or increasing of voltage in DC-link (in generator braking-mode of induction machine and inverter-mode of VSAR in secondary side). It is possible upgrade this effect by attachment between control algorithm for traction motor and this voltage controller R_{Uc} (i.e. current reference as output from voltage controller R_{Uc} is add with signal from actual output power for minimization of negative influence on output power to regulation error in voltage controller R_{Uc}).

Sinusoidal input current (i.e. input current from AC trolley-line) and switching of semiconductor elements in matrix converter bring situation, that optimal waveform for secondary current (flow from matrix converter thru MFT to rectifier on secondary side of MFT) is waveform shown in Figure 2 (i.e. product from multiplication between actual value of switching combination of matrix converter and sinusoidal waveform with magnitude from voltage controller R_{Uc} and phase-shift from phase controller Rφ). Last block is current controller R_i (i.e. hysteresis 2-stage current controller or PI-controller with block with pulse-width modulation).

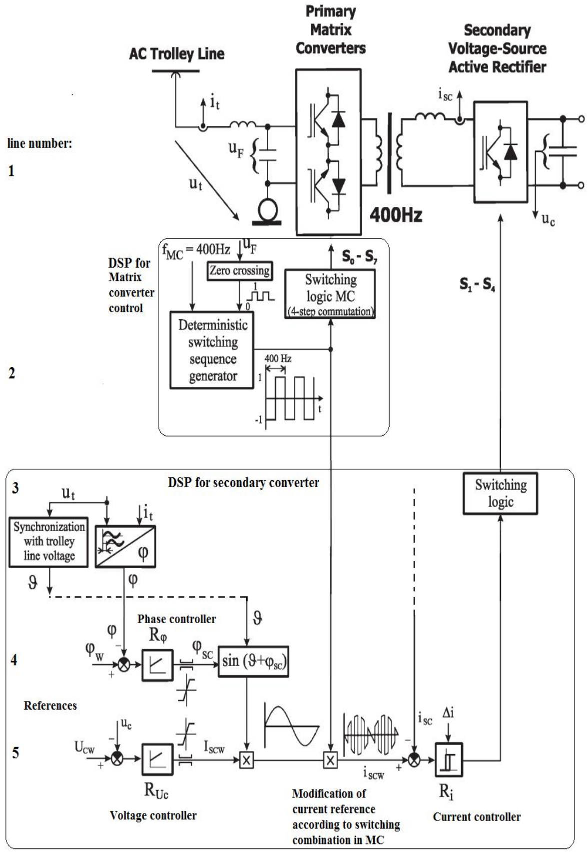

Figure 2. Basic principle of control algorithm for matrix converter and for active rectifier on secondary side of MFT

This basic control algorithm is possible to complement by many other modification - for example:

- by additional controllers for possibility of realization of regulation of actual value of wattles power (this basic control algorithm realize regulation of wattles power by reference of phase-shift φ),
- by additional controllers for purpose to control high-order harmonics components (this basic control algorithm according to Figure 2 minimize these high-order harmonics),

- by additional controllers for purpose damping of oscillation of voltage on capacitances C_f on input filter and for potential balancing of voltage on these input capacitances C_f (for modular configuration with separately MFTs and individually secondary converters for each matrix converter)
- by modification of actual value of switching frequency of matrix converter for purpose to obtain optimal magnetic saturation on MFT.

IV. Realization of Physical Models in Laboratory

Described power circuits was simulated in PC and realized in laboratory in three physical models (small-scale prototypes with rated power circa 3 kW and with only 2 levels with only two input "high voltage" matrix converters).

Control algorithms were implemented into microprocessor system with two DSP (older versions) resp. into microprocessor system with only one DSP with FPGA (new version).

Older versions (first and second versions) of physical models use two independently microprocessors DSP (Texas Instruments TMS320F2812 with fixed point). One DSP realize switching logic for matrix converters (i.e. commutation 4-step algorithms according to actual value of input voltage or according to output current – see line 2 in Figure 2). Second DSP realize other algorithms according to Figure 2 (i.e. voltage control, current control, switching logic for active rectifier, pulse width modulation for output VSI, speed control for induction motor etc.). Communication between these DSPs is reduced to only one signal (i.e. only information of actual switching combination of matrix converter). This solution brings the possibility of easy cooperation between these independently DSPs.

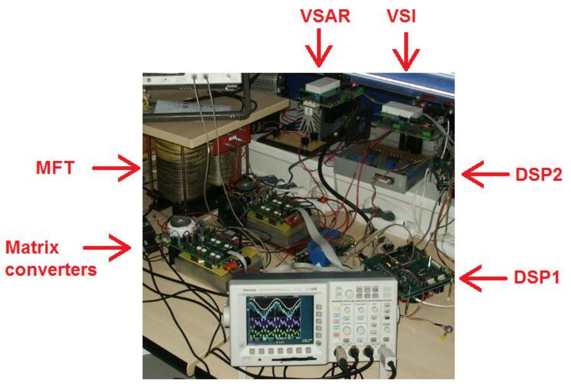

Figure 3. First physical model in laboratory with medium frequency transformer (MFT), two matrix converters (on primary side of MFT), voltage sourced active rectifier (VSAR) and voltage sourced inverter (VSI) on secondary side of MFT controlled by two DSPs (DSP1 for matrix converters and DSP2 for secondary side indirect frequency converter).

New version (i.e. third physical model) use modern DSP (Texas Instruments TMS320F28335 with floating point) for all control algorithms. Standard DSP do not has enough number of outputs for all IGBT. The number of this output signals are increased by FPGA.

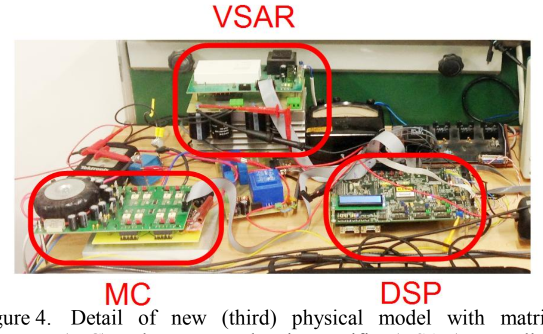

Figure 4. Detail of new (third) physical model with matrix converter (MC), voltage sourced active rectifier (VSAR) controlled by one DSP (on the join PCB with FPGA).

V. Measurement Results

Figure 5 shows steady state (motor mode 2 kW) of physical model with power circuit physical model according to Figure 1.

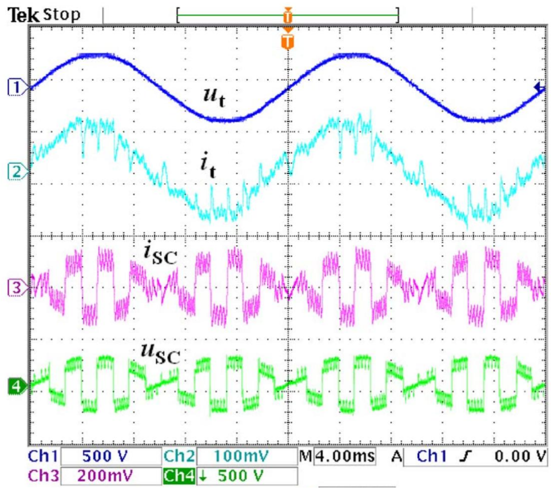

Figure 5. Steady state 2kW, basic control algorithm. Ch1=input voltage u_t (on "trolley line"), Ch2= input current i_t (from "trolley line") 10A/100mV, Ch3= secondary current i_{SC} (in MFT) 10A/100mV, Ch4= secondary voltage u_{SC} (in MFT).

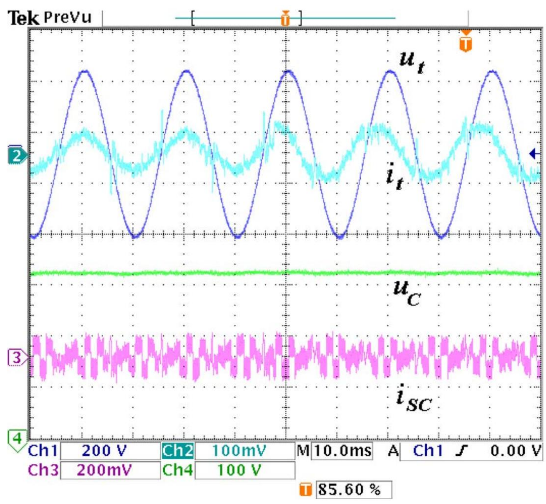

Figure 6. Transient phenomena (change of phase-shift reference), basic control algorithm. Ch1=input voltage u_t (on "trolley line"), Ch2= input current i_t (from "trolley line") 10A/100mV, Ch3= secondary current i_{SC} (in MFT) 10A/100mV, Ch4= output voltage u_C (in capacitance C_0 in DC-link).

Figure 6 shows transient phenomena – change phase-shift reference from $\varphi_w=0°$ (i.e. from zero watt-less power) to $\varphi_w=-45°$ (i.e. to leading power factor). Output power and voltage u_C on capacitance C_0 in DC-link is constant – it brings the increasing of input current i_t (i.e. constant active power and increasing of reactive power and its component of current).

Figure 7 shows transient phenomena – decreasing of voltage reference u_{Cw} for voltage on output capacitance C_0 in DC-link. Rapidly decreasing of voltage (discharge of capacitance) brings short-time for recuperation mode for VSAR and matrix converter - during this transient phenomena (see phase shift between input current i_t and input voltage u_t).

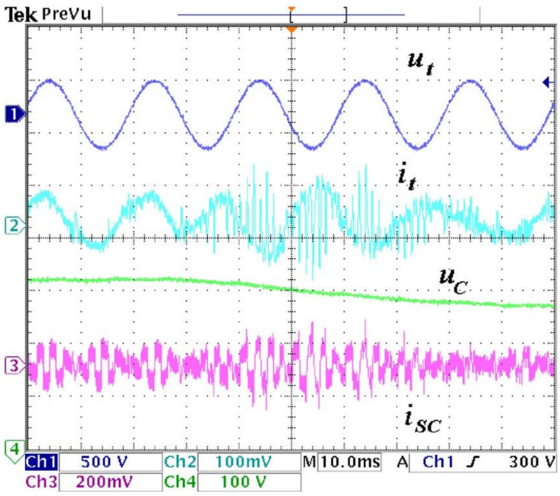

Figure 7. Transient phenomena (change of output voltage reference). Ch1=input voltage u_t (on "trolley line"), Ch2= input current i_t (from "trolley line") 10A/100mV, Ch3= secondary current i_{SC} (in MFT) 10A/100mV, Ch4= output voltage u_C (in capacitance C_0 in DC-link).

Figure 8 shows steady state in generator regime (recuperation power 1.5 kW).

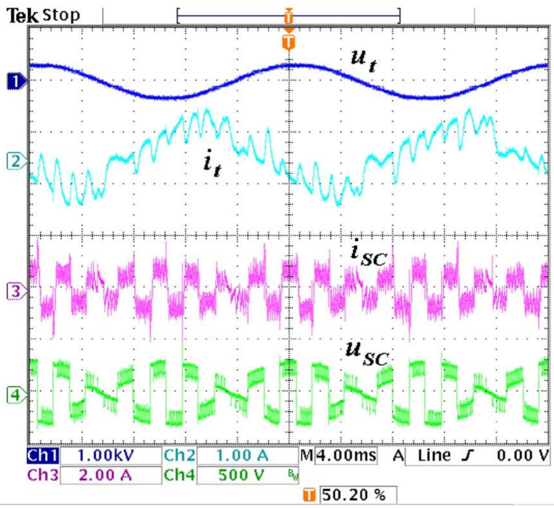

Figure 8. Steady state -1.5kW (recuperation) basic control algorithm. Ch1=input voltage u_t (on "trolley line"), Ch2= input current i_t (from "trolley line") 10A/100mV, Ch3= secondary current i_{SC} (in MFT) 10A/100mV, Ch4= secondary voltage u_{SC}.

Figure 9 shows very importance transient phenomena – rapidly increasing of actual value of input voltage (because real trolley-line has not constant voltage – for example other vehicles generate big overvoltage on long trolley-wire).

Figure 9 shows high immunity of this drive according this step change of input voltage (input current has is the same waveform as during steady state – only input capacitances in input filter generate short charge current pulse). Actual values of voltage on both input capacitances C_{f1} and C_{f2} have the same values (i.e. the voltages are balanced for purpose to reduce voltage stress in all IGBT transistors in input "high-voltage" matrix converters).

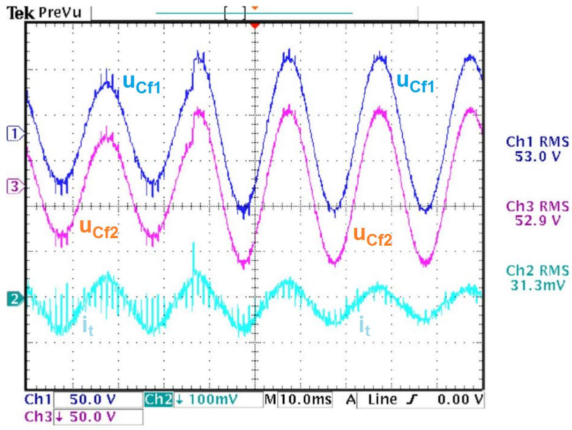

Figure 9. Transient phenomena (step change of input voltage u_t (on "trolley line"). Ch1=input voltage u_{Cf1} on first input capacitance C_{f1} (top capacitance C_{f1}), Ch2= input current i_t (from "trolley line") 10A/100mV, Ch3= input voltage u_{Cf1} on second input capacitance C_{f2} (bottom capacitance C_{f2})

VI. Conclusion

This paper presents the control algorithms for traction drive with medium frequency transformer (MFT), high voltage matrix converters in primary side on MFT and secondary side on MFT. These control algorithms were implemented into multiprocessor system with DSP for physical model in laboratory (small-scale prototype of traction drive). Simulation on PC and experimental results on physical model brings positive results for steady state and for transient phenomena.

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