Single-Phase Induction Motor Supplied from Direct Converter with Minimum Switching Devices and Variable Capacitor

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Abstract: - The paper deals with a single-leg direct (matrix) converter with minimum switching devices and enhancements for improving current THD and phase advancing with the use of variable (switched) capacitors. This converter is supplying single-phase induction motor (SPIM). Due to strongly non-harmonic phase voltages, an additional circuit should be used, so that phase-currents can be nearly harmonic. Simulations are done under both resistive-inductive load and motoric load. Speed control was realized using vector control with current controlled pulse-width-modulation (hysteresis regulator). Verification of such a drive system was done using dSpace environment. Preliminary results are given in the paper.

Key-Words: - One-leg matrix converter, bi-directional switch, single-phase induction motor - SPIM, speed control, pulse width modulation, switched capacitor.

1 Introduction

The Single-phase induction motor - SPIM is widely used in a r ange of applications such as r esidential blowers, pumps, and compressors operated under fixed frequency. Using variable speed operation, this drive brings possible energy and money saving for consumers [1]-[3]. The motor can be supplied either from two single-phase or one three-phase VSI inverter [2], [4]. The matrix converter (MxC) topology has become well known after substitution of thyristor-devices in cyclo-converters by switched-off elements acting in the high-frequency range, in 70-80-years [5]-[6]. The MxC replaces two energy conversion by one energy conversion only because within converter is not an energy storage element. Since classical electric conversion uses DC-link converters with somewhat large smoothing capacitors, direct MxC operates without a D C-link circuit. One of the main advantages of that is unity power factor on its input side. Another advantage is that this converter generally offers sinusoidal input and output harmonics quantity and bi-directional energy flow. To save the number of power switching elements, it is possible to use the one-leg connection of the converters. The basic configuration of single-leg MxC was derived from single-leg voltage source inverter [1], [4], and the first time was published in 2015, [5] with analysis and modeling of that in [8]. Preliminary comparison of a SPIM Drive Fed by VSI and MxC with Option

of Speed Reduction has been made in [9]. The proposed system, in relation to the conventional system currently used, reduces the number of power switching elements of the converter.

2 Single Leg Matrix Converter

There are basically two different topologies of single-leg matrix converter derived from topologies of single-leg voltage source inverter [5], [9], Fig. 1, 3. Similarly to single-leg voltage source inverter, single-leg matrix converter also works with two operation modes.

2.1 Topology of a s ingle leg MxC fed single phase induction motor for full speed operation

Basis connection is given in Fig. 1. Denotes R1, L1 and R2, L2 represents the phase windings of the motor.

In full speed regime of operation, the main phase of IM is supplied by one half of the main voltage directly; therefore, the motor should be designed for that voltage. The auxiliary phase is supplied by one-leg matrix converter creating voltage with phase shift by 90 degrees against voltage of the main phase.

First operation mode can be called "Full speed

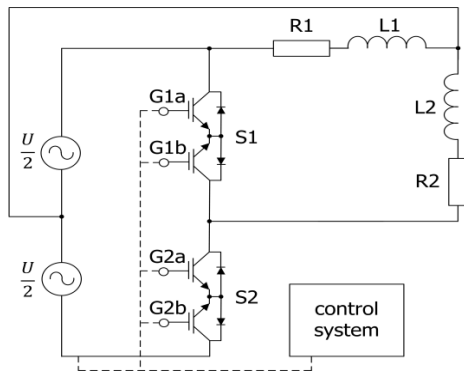operation." Voltage source feeds the main phase $U_{AC}/2$ and auxiliary phase is fed by single leg MxC.

Fig. 1 Single leg matrix converter topology for full speed operation.

As in single leg, VSI using MxC is also necessary to sense phase of AC voltage source and ensure 90° phase shift for auxiliary phase.

It is necessary to aware that supply voltage for the auxiliary phase is strongly non-harmonic, Fig. 2.

As the magnitude of fundamental harmonic is equal one half of network magnitude, so induction motor should be designed to that value of supply network voltage.
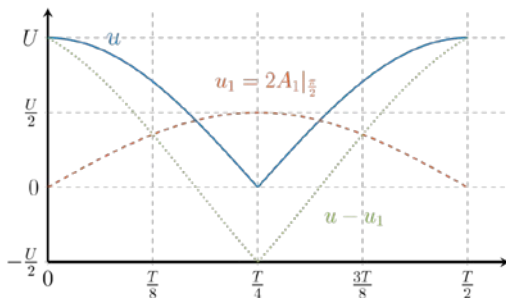
Fig. 2 Supply voltage for auxiliary phase and its fundamental harmonic [8].

Besides, it is also important, that total harmonic distortion of the auxiliary phase voltage reaches up to 86 %, so the torque of the sum of higher harmonics will permanently brake, and start-up of the motor is practically impossible. Using some control method (e.g., hysteresis CC_PWM) the current shape will be good, but anyway, the value of the auxiliary phase voltage will be always smaller as nominal one.

2.2 Topology of a single leg MXC fed single phase induction motor for reduce speed operation

The second operation mode is also called "Reduced speed operation." Main and auxiliary phase is fed by single leg MxC, Fig. 3. The frequency of voltage gives the speed of induction machine. The phase shift is ensured by a capacitor connected in series with auxiliary phase.
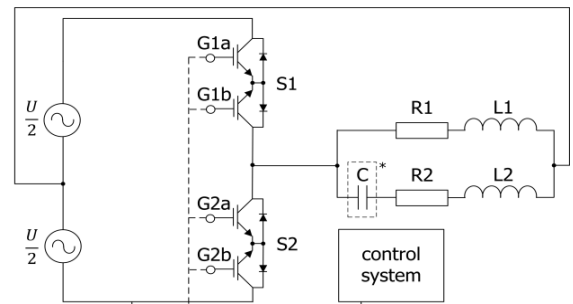

Fig. 3 Single leg matrix converter topology for reduced operation.

Similarly, as in the previous case, waveforms of supply voltages are still strongly non-harmonic ones, Fig. 4.
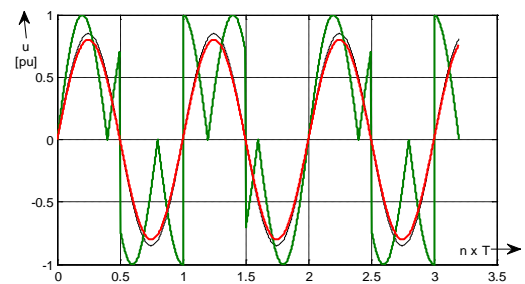

Fig. 4 Supply voltage of both phases with its fundamental harmonics in reduced speed regime at 33.33 Hz.

So, it is necessary to accept some measures for improving the voltage and current, respectively, waveforms.

2.3 Using LC filters and switched capacitors for improvement of converter waveforms

Using resonant $L_{res}C_{res}$ filter in main and/or auxiliary phase and designed, e.g., by [10] the current waveform will be acceptable Fig. 5, and Fig. 6. The problem, maybe, could be regarding a higher voltage of the resonant capacitor and/or bigger dimensions of the filter element due to relatively smaller resonant frequency.
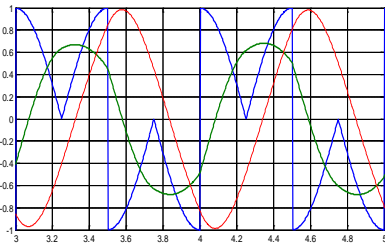
Fig. 5 Supply voltage (blue) and current (green) of auxiliary phase, and capacitor voltage (red) at nominal speed, 50 Hz – without PWM.
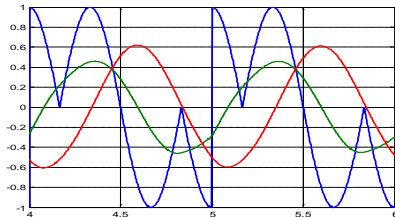

Fig. 6 Supply voltage (blue) and current (green) of main and auxiliary phases, and capacitor voltage (red) at reduced speed, 33.33 Hz – without PWM.

Another possibility is to use the non-resonant low-pass filter on the output of the converter. Results, as regarding to phase currents, are similar to those of resonant filter, Fig. 7 and Fig. 8.
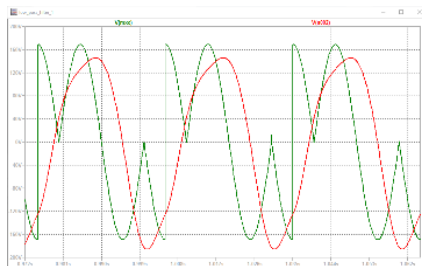

Fig. 7 Supply voltage (blue) and current (green) of main and auxiliary phases, and capacitor voltage (red) at reduced speed, 33.33 Hz – without PWM.
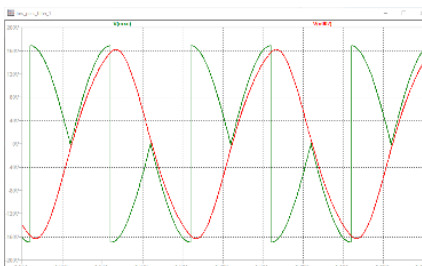

Fig. 8 Supply voltage (blue) and current (green) of main and auxiliary phases, and capacitor voltage (red) at full speed, 50 Hz – without PWM.

Another problem is that under variable frequency the value of both capacitors, for phase shift and for resonance, should also be variable one. One of the solutions, how to provide this problem, is to use switching capacitors [11]-[13]. Anyway, the number

of electronic switches will be higher. There is shown acting of switching capacitance for controlled phase shift 90 deg., in Fig. 9 and 10.
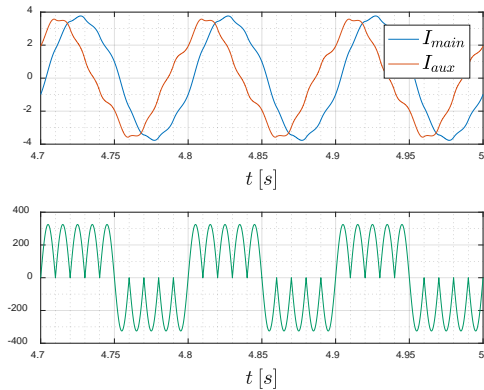

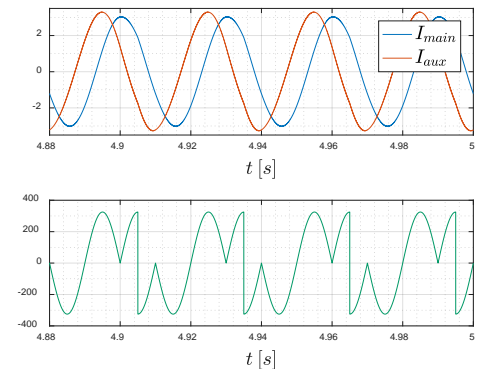**Fig. 9** Quadrature currents of single-phase induction motor at 10 Hz.

Fig. 10 Quadrature currents of single-phase induction motor at 33.33 Hz.

3 Single Phase Induction Machine

3.1 Model of single phase induction motor

Model of such a motor is well known [1]-[4], [11]. So, the electric machine being considered may be described by the following set of ordinary differential equations in the stator reference coordinate frame under the commonly used simplifying assumptions:

$$u_{s\alpha} = R_{s\alpha}.i_{s\alpha} + L_{s\alpha}.\frac{di_{s\alpha}}{dt} + L_{M\alpha}.\frac{di_{r\alpha}}{dt}, \quad (1)$$

$$u_{s\beta} = R_{s\beta}.i_{s\beta} + L_{s\beta}.\frac{di_{s\beta}}{dt} + L_{M\beta}.\frac{di_{r\beta}}{dt}, \quad (2)$$

$$0 = R_{r\alpha} \cdot i_{r\alpha} + L_{s\alpha} \cdot \frac{di_{r\alpha}}{dt} + L_{M\alpha} \cdot \frac{di_{s\alpha}}{dt} \qquad (3)$$
$$+ \frac{1}{N} \cdot \omega_m \cdot (L_{r\beta} \cdot i_{r\beta} + L_{M\beta} \cdot i_{s\beta}),$$

$$0 = R_{r\beta} \cdot i_{r\beta} + L_{r\beta} \cdot \frac{di_{r\beta}}{dt} + L_{M\beta} \cdot \frac{di_{s\beta}}{dt} \qquad (4)$$
$$- N \cdot \omega_m \cdot (L_{r\alpha} \cdot i_{r\alpha} + L_{M\alpha} \cdot i_{s\alpha}),$$

$$T_e = pp \cdot \left[N \cdot (L_{r\alpha} \cdot i_{r\alpha} + L_{M\alpha} \cdot i_{s\alpha}) \cdot i_{r\beta} \right.$$
$$\left. - \frac{1}{N} \cdot (L_{r\beta} \cdot i_{r\beta} + L_{M\beta} \cdot i_{s\beta}) \cdot i_{r\alpha} \right], \qquad (5)$$

$$T_e = T_{load} + J \cdot \frac{d\omega_m}{dt}. \qquad (6)$$

where N is the ratio between the effective numbers of turns in the auxiliary and the main stator windings; ω_m - mechanical angular speed, and pp - is the number of pole pairs.

3.2 Speed control of a single-phase induction motor fed by single leg MXC

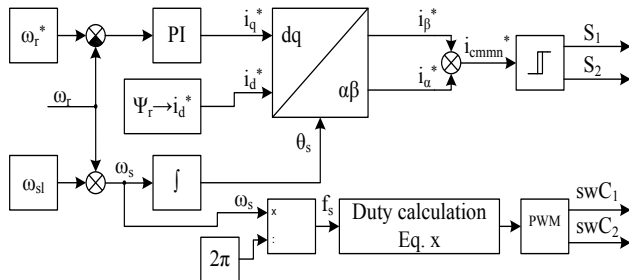The basic control schematic is shown in Fig. 11.

Fig. 11 Block scheme of speed control of the drive with single-phase induction motor and single-leg matrix converter.

It deals with common vector control. Moreover, phase-shift of auxiliary phase is controlled by computation of duty cycle for the needed value of the running capacitor.

Current of common phase is controlled by CC_PWM (hysteresis) controller [14]-[15], Fig. 12.
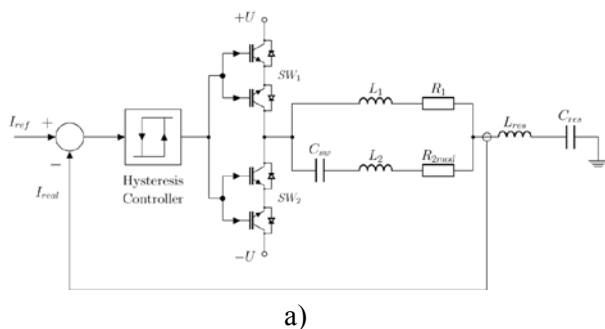
a)
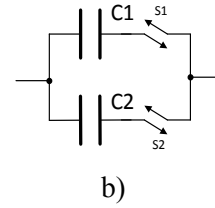
b)

Fig. 12 Block scheme: a) CC_PWM (hysteresis) control of the drive, b) switched capacitor circuit.

4 Modelling and Simulations

All simulations were calculated using the Matlab-Simulink package for source voltage 230 V_{RMS}, 50 Hz at full speed operation, a calculation step of $1e^{-5}$ sec.

Parameters of the single-phase motor:
Stator voltage 230 V
Stator resistance $R_{s\alpha}$ = 58.85 Ω; $R_{s\beta}$ = 66.1 Ω;
R_r = 80 Ω
Stator inductance L_{sd} = 1.835 H; L_{sq} = 1.64 H
Mutual inductance between rotor and stator
M_{srd} = 1.74 H; M_{srq} = 1.52 H
Moment of inertia J = 0.0000488 kg.m2
Number of pole pairs pp = 1;
The capacitance of the capacitor in auxiliary phase C = 14.6 μF.

4.1 Simulations of a Single-Phase Induction Motor Fed by Single Leg MxC with PWM only

Single-phase induction motor was fed by voltage waveform depicted in Fig. 5 or Fig. 6, respectively. Simulation result of phase currents waveforms are shown in Fig. 13.
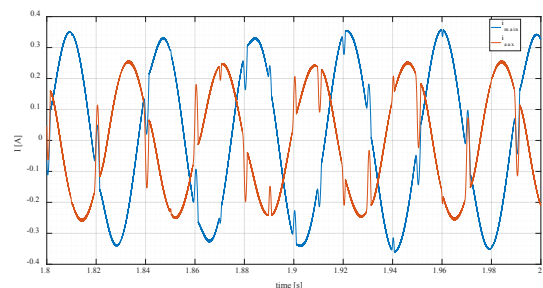

Fig. 13 Quadrature currents of main and auxiliary phases main (blue) and auxiliary (red) at reduced speed, 33.33 Hz – with PWM.

The current of common phase, i.e., current taking from the network is given in Fig. 14.
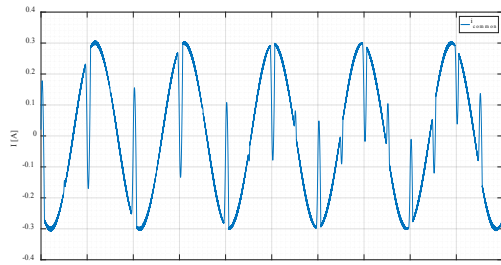
Fig. 14 The current of both phases-common phase at reduced speed, 33.33 Hz – with PWM.

4.2 Simulations of a Single-Phase Induction Motor Fed by Single Leg MxC with PWM and resonant LC filter

Single-phase induction motor was fed by voltage as above, and the simulation result of both phase currents and common phase current are depicted in Fig. 15 and Fig. 16 are nearly harmonic ones
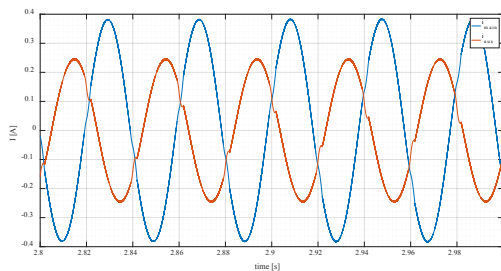

Fig. 15 The current of both phases-common phase at reduced speed, 33.33 Hz – with PWM and resonant LC filter.
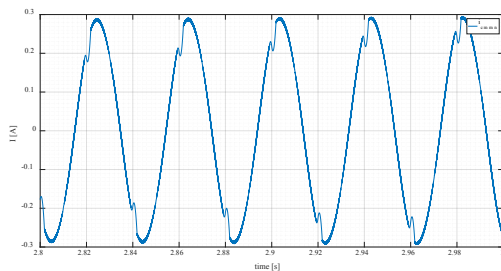

Fig. 16 The common current of both phases reduced speed, 33.33 Hz – with PWM and resonant LC filter.

4.3 Simulations of a Single-Phase Induction Motor Fed by Single Leg MxC at full speed without PWM

Single-phase induction motor was fed by the voltage from the network, therefore, waveforms of both voltage and currents depicted in Fig. 17 are
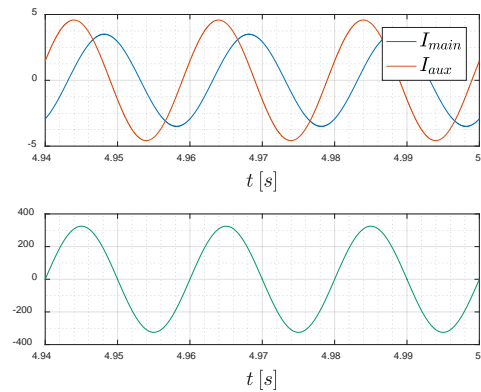
harmonic ones.

Fig. 17 Quadrature currents of main and auxiliary phases main (blue) and auxiliary (red) at full speed, 50 Hz – without PWM.

5 Verification using two-phase induction motor and controlled using dSpace

Single-phase induction motor, with parameters given in Chap. 4, w as controlled through dSpace control system.

Speed control of single-phase induction motor fed by single leg MxC, including start-up, was realized by the setting of requested angular speed to 100 rad/sec, consequently after start-up 150 rad/sec, and then 200 and 250 rad/sec, respectively. Time dependence of measured angular speed is shown in Fig. 18. C orresponding currents of main and auxiliary phases are given in Fig. 19.
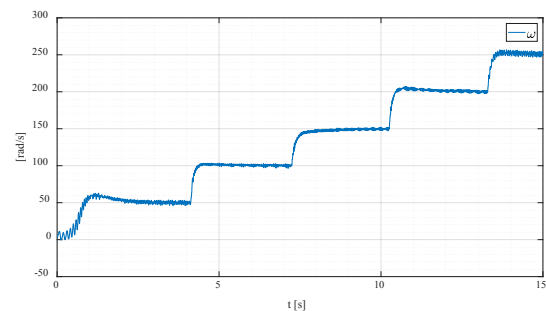

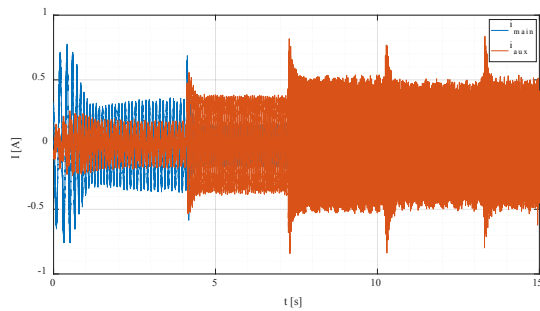**Fig. 18** Step changes of angular speed.

Fig. 19 Quadrature currents of main and auxiliary phases main (blue) and auxiliary (red) at step changes of angular speed.

The corresponding common current of both phases of the single-phase induction motor is depicted in Fig. 20.
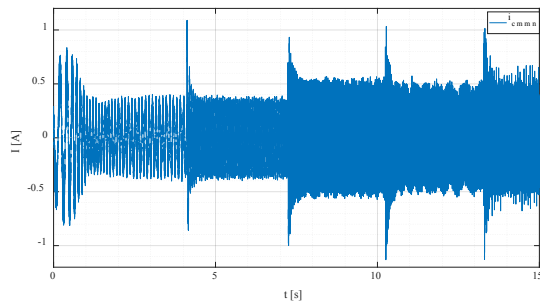

Fig. 20 The common current of main and auxiliary phases at step changes of angular speed.

The voltage waveforms of switched capacitors under step response of angular speed are depicted in Fig. 21. As we can see from the waveforms of the switched capacitors, the value of the voltage for each capacitor depends on the duty cycle.
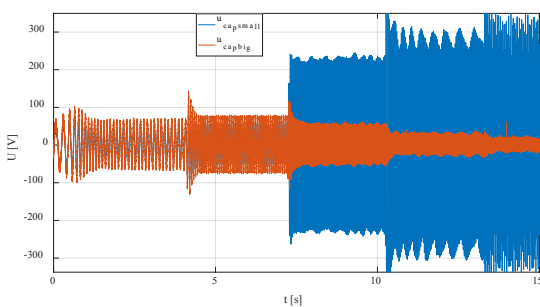

Fig. 21 Voltages on the switched capacitors: a small capacitor (blue) and a large capacitor (red) at step changes of angular speed.

On Fig 22. and Fig 23. are depicted details of switched capacitors voltages, at different switching frequencies (500Hz and 5kHz). As we can see from the figures, the capacitor voltage ripple decreases with the increase of switching frequency.
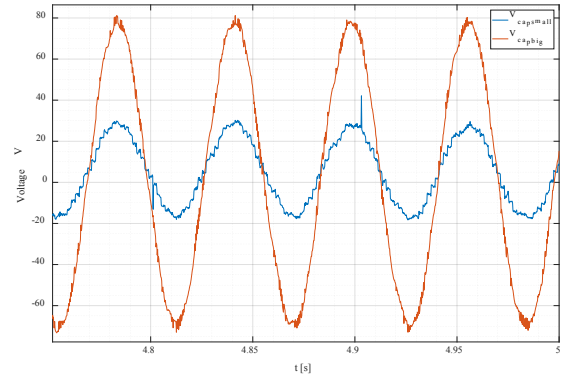

Fig. 22 Detail of capacitor voltages: a small capacitor (blue) and a large capacitor (red) at capacitor switching frequency of 500Hz.
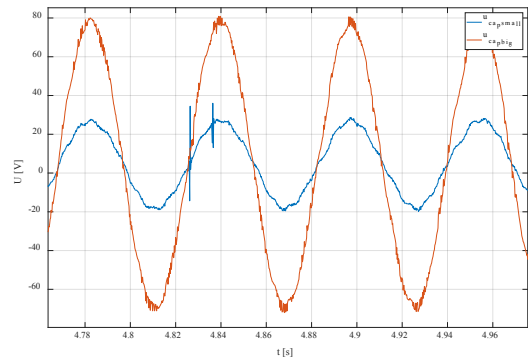

Fig. 23 Detail of capacitor voltages: a small capacitor (blue) and a large capacitor (red) at capacitor switching frequency of 5kHz.

On Fig 24. and Fig 25. are depicted details of every current of single phase induction machine. It can be seen from the figures that the currents are almost harmonic.
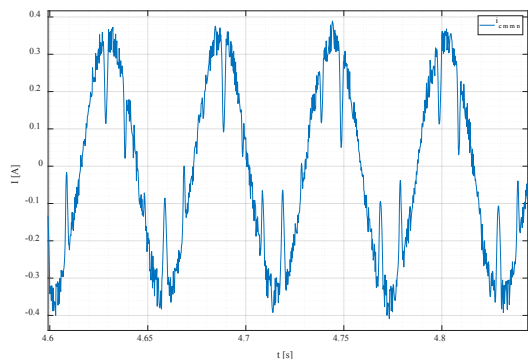

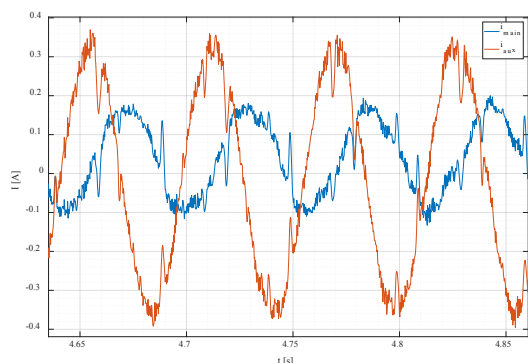**Fig. 24** Detail of the common current of main and auxiliary phases

Fig. 25 Detail of the currents of main and auxiliary phases main (blue) and auxiliary (red).

filter, its optimal design. Also, selecting the right value of capacitor for the auxiliary phase is important. It can be used modern control method, torque and angular speed ripple reduction, and so on.

6 Conclusion

The paper brings simulation and experimental result of single-phase motor drive consist of single-phase induction motor fed by enhanced single leg MxC with switched capacitors.

Simulations were done with both resistive-inductive load and motoric load. Due to strongly non- harmonic phase voltages the additional circuits were implemented and investigated: resonant LC filter and/or low-pass filter, respectively. Accepting mentioned measures, the phase-currents are nearly harmonic. It is very important from the point of view of the influence of the supply network.

As can be seen from the Fig. 14 and Fig. 16 respectively, the common phase current taken from the network is nearly sinusoidal with harmonic time waveform. This is one of the advantages of the described drive system. Another advantage is minimum active switching devices. The single-leg matrix converter in basic connection topology needs just two bidirectional switches. But for demanded vector control is necessary to use a switched capacitor to maintenance 90 deg phase-shift in whole speed range under a no-load and nominal load of the motor. Application of the switched capacitors brings the possibility of a wider range of angular speed and improvement of electromagnetic torque. The switching frequency of the capacitors direct impacts the voltage ripple on the capacitors.

Speed control was realized using adapted vector control with current controlled pulse width modulation (hysteresis regulator). Verification of such a drive system was done using dSpace environment. The results showed the good behavior of the motor. Experimental verification was realized without additional LC circuit, so far. Future work can be focused on selecting the proper type of the

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