Vector Control of Tandem Converter Fed Induction Motor Drive Using Configurable Hardware

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Abstract — The paper deals with the vector control systems of the induction motor supplied from the failed and non-failed tandem converter. There are described the research results regarding the reconfiguration aspects of the control strategy for the transition from a control structure to another. Simulation results are presented for both control system topologies. Implementation of the general computing block in the *Configurable Logic Cells*® of the Triscend's *Configurable System on Chip*® is presented together with the results of the path delay analyses.

I. INTRODUCTION

Reconfigurable computing - often called „custom" or „adaptive" - was defined in [2], [3], [5]. In paper [13] the authors introduced the reconfigurable computing concept also for vector control systems in AC drives.

From the practical observation, that the performance of various types of vector-controlled drives is different depending on the range of speed, mechanical-load characteristics results the necessity of reconfiguration. On the other hand, the structure of the vector control system is also depending on the type of the supply power electronic converter and its pulse-modulation method, on the orientation field and its identification procedure [14].

In vector control systems, the rotor-field orientation is widely used. If a voltage-source inverter operating with voltage PWM feeds the motor, the computation of the stator-voltage reference value, taking into account the cross-effect, becomes simpler using stator-field orientation.

The so-called "*tandem*" converter contains two different types of inverters, a voltage- and a current-source one. Usually the tandem converter is sensible to the failure of the component voltage-source inverter. If it fails, it has to be disconnected from the motor terminals and the structure of the vector control system will be reconfigured according to the new character of the motor actuator (now i.e. the current-source inverter) in order to be able to continue the drive to work. This is the reason why the reconfigurable computing was applied to the tandem converter-fed AC drive control [15], [16].

II. TANDEM CONVERTER FED INDUCTION MOTOR

The tandem configuration was proposed as a new solution of the Static Frequency Converters (SFC) for medium- and high-power AC drives [6], [7], and [10]. In fact, it combines the character of the two component DC link converters, which are of different type and different power range, and they work in parallel arrangement. The larger one is consisting of a conventional Current-Source Inverter (CSI) operating with 120° current wave-forms controlled by Pulse-Amplitude Modulation (PAM) and it converts the most part of the motor feeding energy. The smaller component SFC contains a well-known Voltage-Source Inverter (VSI) controlled by Pulse-Width Modulation (PWM) and it supplies the reactive power required to improve the quality of the motor currents in order to compensate them into sine wave form. Consequently, the current i_s in each stator phase (*a*, *b* and *c*) will be given by the two parallel working inverters, i.e. by the CSI and the VSI, as follows:

$$i_{s\text{-}a,b,c} = i_{CSI\text{-}a,b,c} + i_{VSI\text{-}a,b,c}. \tag{1}$$

In Fig. 1 there are shown the above-presented currents, resulting from simulation.

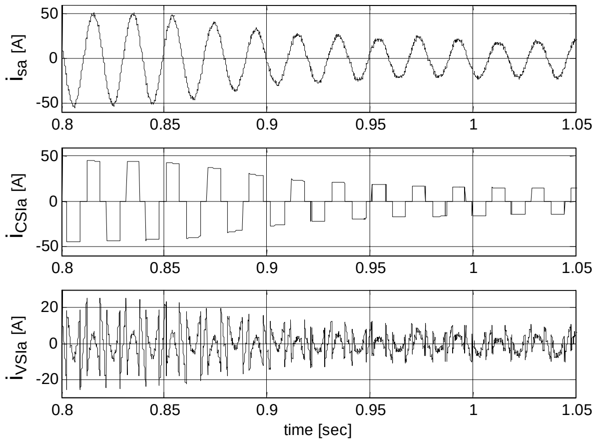

Fig. 1: Current wave-forms at the output of the tandem converter.

Using two parallel converters for the supplying of the induction motor is no more necessary to apply PWM procedure to control the whole energy, because a large value of the energy is transferred through the PAM-CSI. Usually it is realised by means of GTO thyristors and it is fed with filtered DC-link current, given by a phase-controlled rectifier, which can realize the bi-directional energy flow. Due to the PAM control the CSI works with reduced number of commutations of the power electronic devices. Consequently, in comparison with an equivalent PWM-VSI, the tandem converter switching losses are considerable reduced [10].

Due to the voltage-source character of the VSI, the motor absorbs freely its stator currents. A part of this current will be injected by the CSI. For this reason in tandem operation mode, the component converters need a rigorous synchronization [12], [17].

The synchronization circuitry will ensure the desired time shift and magnitude of injected current, of which fundamental component has to be equal with the stator-current one in each phase of the motor.

The VSI will deliver only the currents according to the harmonics, as is shown in (1). Consequently, a very proper aspect of the tandem converter control is the synchronization in time and in amplitude between the CSI currents with respect to the tandem output ones, i.e. the stator currents.

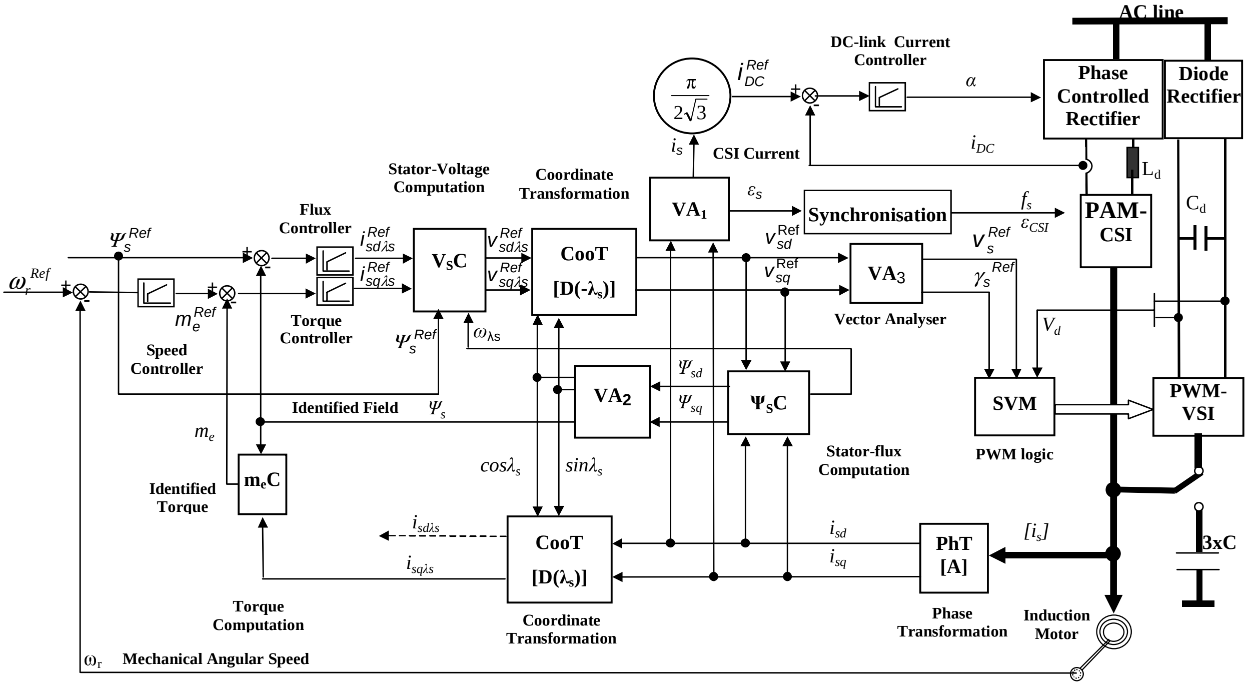

Fig. 2: Stator-field-oriented vector control system for the tandem converter-fed induction motor.

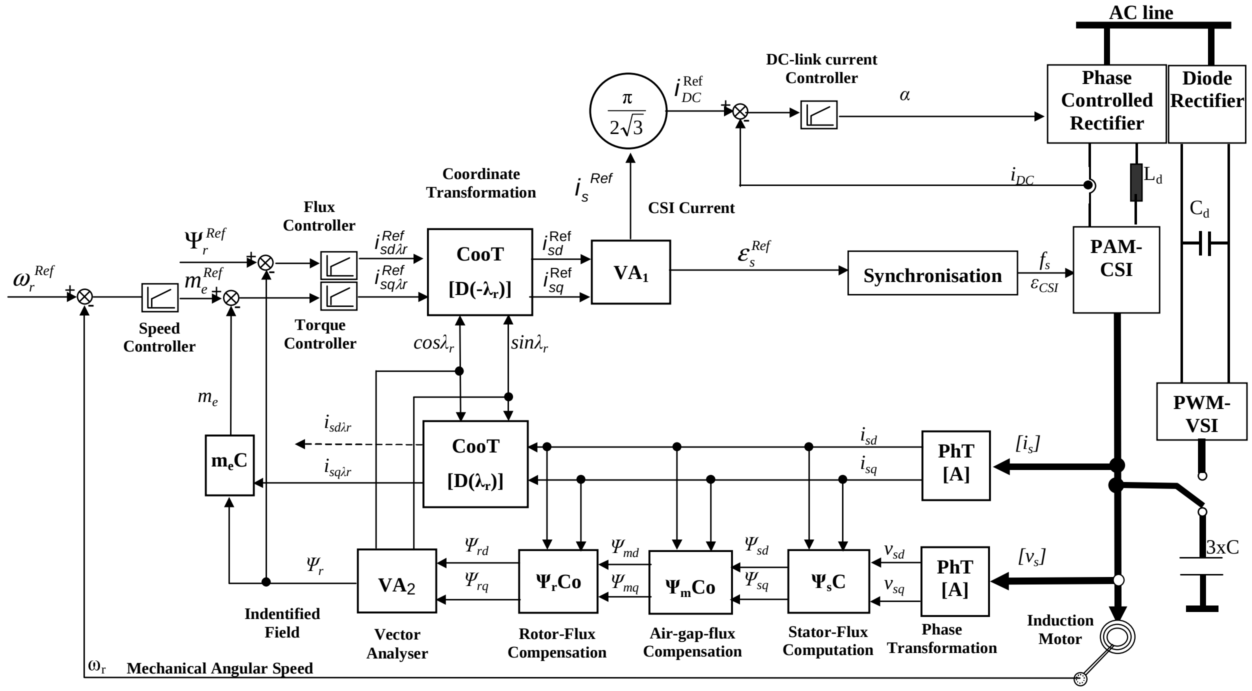

Fig. 3: Rotor-field-oriented vector control system for current-source inverter-fed induction motor.

In Fig. 2 the induction motor is supplied from a three-phase tandem converter. The synchronization in time is made by means of the switching moments ε_{CSI} (i.e. the electrical angle of the stator-current space-phasor position) of the CSI currents with respect to the actual stator-current. Inherently result also the switching frequency f_s.

The reference stator-current space phasor is computed in the vector-analyser block VA$_1$, using the *d*-*q* components of the previously measured three-phase stator-currents. The reference stator-current vector is rotating continuously. The space-phasor of the CSI currents has an intermittent motion step-by-step with 60°. Its position ε_{CSI} has to be synchronized with the reference value ε_s. The synchronization in amplitude of the CSI-currents is realized by means of the DC-link current i_{DC}, with respect to the amplitude of the actual stator-current vector i_s.

If the synchronization of the CSI is not made (computed) correctly with respect to the stator current, the VSI will be loaded excessively by an uncontrolled part of the motor current.

In spite of the fact the most part of the motor current is given by the CSI, the behaviour of the tandem converter had voltage-source character [12]. That means the VSI will be the actuator for the control of the motor.

The tandem converter needs different control strategies depending on the type of the PWM procedure used for the VSI. The selected PWM procedure can change the source character of the VSI and of the tandem converter, too [11], [12]. The open-loop voltage-control PWM procedures, i.e. carrier wave or Space-Vector Modulation (SVM), keeps the voltage-source character of the VSI, but using closed-loop current-control PWM procedures (e.g. the common bang-bang current control) the behaviour of the VSI becomes of current-source character [8], [9].

The vector control system needs also different control strategy, i.e. different structure, depending on the component converters, which are actually working.

If the VSI fails, in order to continue the drive its mission, the motor can be supplied only from the CSI. The failed VSI is decoupled from the motor terminals and there will be connected three current filtering condensers. In such a situation the motor can be controlled exclusively in current directly taking into account the reference current variables, as is shown in Fig. 3. Consequently, the structure of the control system needs reconfiguration.

In Fig. 3 the current synchronisation of the alone working CSI is realized in the same manner like in Fig. 2, but it is computed from the reference values instead of the actual ones of the stator currents.

The field identification in the first step is made in the same way, by integration of the stator-voltage equations (using computation block Ψ_sC), which gives the stator-flux natural *d*-*q* components. This part needs also reconfiguration because in Fig. 3 the stator voltage can be measured directly (due to the PAM operation mode of the CSI), instead to be computed it, as is made in PWM operation mode, presented in Fig. 2. Furthermore, in Fig. 3 it is necessary to compensate the stator-field components in block Ψ_mCo and Ψ_rCo in order to obtain, by means of the air-gap field component, the orientation rotor flux.

III. VECTOR CONTROL OF THE INDUCTION MOTOR

The dynamic behaviour of the AC machines is very improved by vector control based on the field-orientation principle. The classical part of a vector control structure consists of an active- (speed and/or torque) and a reactive- (flux) control loop.

Usually for vector control of the induction motor is preferred the rotor-flux orientation due to the perpendicular position of the rotor-current and rotor-field space phasors, which interaction yields the motor torque.

In Fig. 2, where the VSI is also working, the motor in fact is controlled in voltage. In such a case, stator-field orientation is proposed, which simplifies the cross-effect computation. The field-oriented current reference variables $i_{sd\lambda s}$ and $i_{sq\lambda s}$ obtained from the flux and torque controllers will generate the field-oriented stator-voltage reference values $v_{sd\lambda r}$ and $v_{sq\lambda r}$ using the computation block V_sC [17].

Because the VSI is operating with SVM, it needs polar control variables, corresponding to the reference stator-voltage space-phasor, i.e. its module and position, which are obtained from a vector analyser VA_3. The computation of the stator-voltage reference variables offers also the possibility to apply the simplest identification procedure of the orientation field, which is based on the integration of the stator-voltage equation. That presents importance, because usually in PWM operation mode the terminal voltages of the motor cannot be measured.

IV. IMPLEMENTATION IN CSoC CHIP

In order to apply the *"reconfigurable computing concept"* for the both control schemes of the tandem converter fed induction motor a suitable hardware support was needed [13]. One of them is the Triscend's Configurable System on Chip (CSoC), which allows self reconfiguration. The implementation was started using a CSoC with ARM7 thumb RISC processor core.

Each control system structure will be seen as a distinct state of a logic state machine as it was presented in [15], [16]. The control system will start a self-reconfiguration process and will change the configuration of the control system automatically from structure in Fig. 2 to structure in Fig. 3.

If each block is implemented in CSoC Configurable System Logic (CSL), as was already presented in [16], the implemented structure will result with very good performance, but it is of high percentage consuming of the CSL hardware resources. In addition, the CSoC-CSL cells have insufficient capacity for the implementation of the whole control system. In order to reduce the number of the required CSL cells for implementation, the algorithms of the computing blocks were decomposed in elementary mathematical operations. For this reason the equations of the control system blocks were analysed. The result of the decomposition yields the general form, as follows:

$$g_d = a_d\, x_d + b_d\, y_d; \tag{2}$$

$$g_q = a_q\, x_q + b_q\, y_q, \tag{3}$$

where g_d and g_q are the output variables of the actual working block, $a_{d,q}$ and $b_{d,q}$ may be parameters or input variables resulting from a previous block, $x_{d,q}$ and $y_{d,q}$ are also input variables of the same block resulting from another previous block (see implementation in Fig. 4).

```
CSL Cells: 1197/2048  58 %   I/O Pins: 26/93  27 %   CSI Selectors: 10/128  7 %   GBUFs: 1/6  16 %
```

```
Closing project C:\...\myproj\myproj.tcp
Opening project C:\...\egy\egy.tcp
Opening project C:\...\egy\egy.tcp
```

Fig. 4. Implementation of dq-processor (in Triscend CSoC environment).

For example the above-defined calculation block describes any one from Fig. 2 and Fig. 3, such as the "P" operation of the PI controllers (for speed, current, flux, etc.), conventional vector control blocks, such as VA (Vector Analyser), CooT (Coordinate Transformation), orientation-field computation- and compensation blocks, etc. or others. The implementation of (2) and (3) is shown in Fig. 4 and it also contains accumulators for the "I" operation of the PI controllers and PWM registers.

The general form of the decomposition of a block is consisting of the well-known "multiply and accumulate" operations often used in Digital Signal Processors (DSP). In this case, the difference between the DSP and this implementation is that here the operations from (2) and (3) are executed in parallel and not sequentially. In such a way, the execution speed is reduced by the parallel computation.

The worst-case analysis for the longest path delay of the dqP calculation block named "*dq-processor*" is 135.073 *ns* and the path delay for the PWM registers is 11.156 *ns*. The processor core of the CSoC supplies the variables for the dqP block, it supervises the control system and executes calculations. The processor core makes the reconfiguration process of the control system structure, too.

V. SIMULATION RESULTS

The simulation was performed in MATLAB Simulink environment. The induction motor data are: 5.5 *kW*, 50 *Hz*, 220 V_{rms}, 14 A_{rms}, $\cos\varphi = 0.735$ and 720 *rpm* (4 pole-pairs).

A. Simulation results for the tandem converter-fed induction motor with stator-field orientation vector control

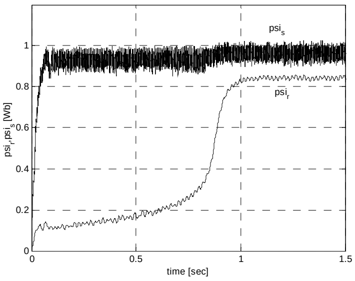

Fig. 5: Rotor and stator resultant flux.

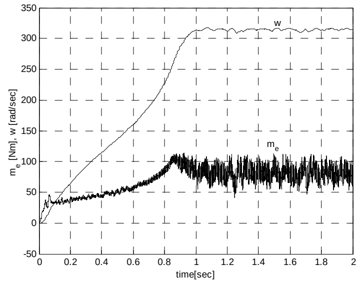

Fig.6: Electromagnetic torque and electric angular speed.

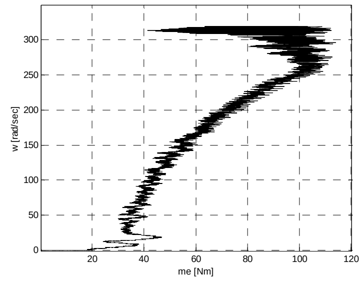

Fig. 7: Dynamic speed-torque mechanical diagram.

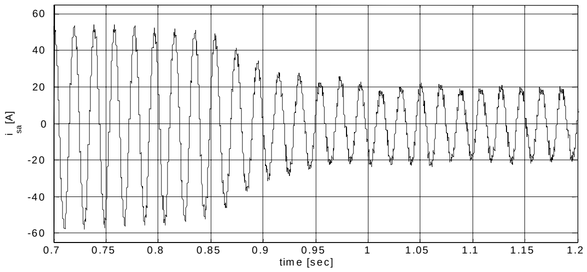

Fig. 8: Stator current on phase "*a*".

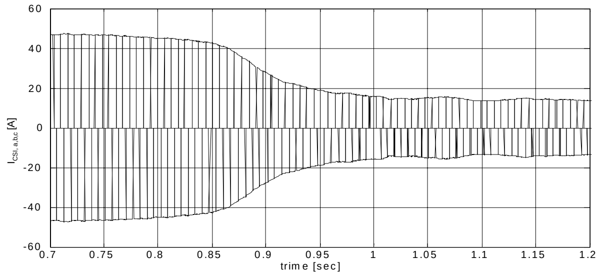

Fig. 9: CSI output currents on phases "*a*", "*b*" and "*c*".

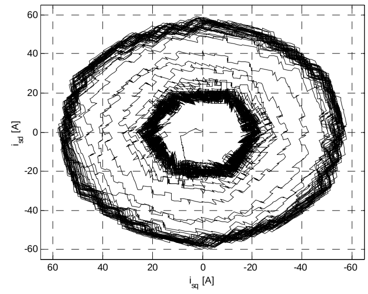

Fig. 10: Stator-current space-phasor.

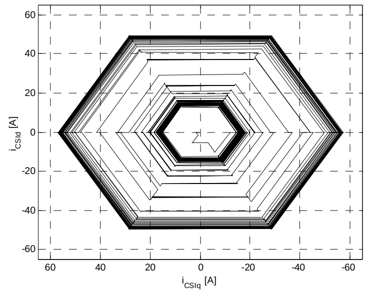

Fig. 11: CSI output-current space-phasor.

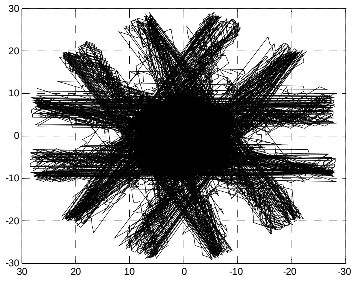

Fig. 12: VSI output-current space-phasor.

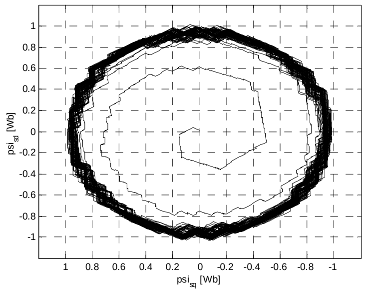

Fig. 13: Space-phasor of the controlled stator flux.

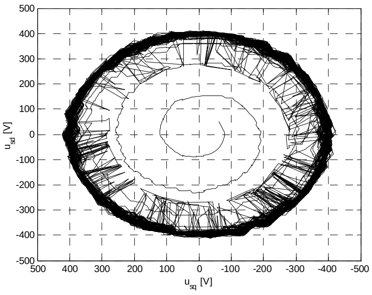

Fig. 14: Stator-terminal-voltage space-phasor.

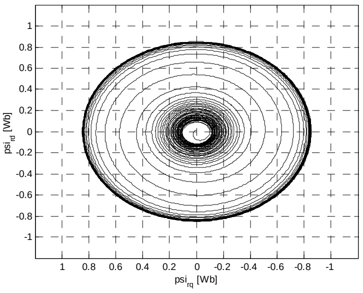

Fig. 15: Space-phasor of the resultant rotor flux.

B. *Simulation results for the CSI-fed induction motor with rotor-field orientation vector control*

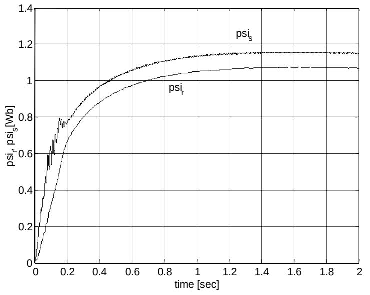

Fig. 16: Rotor and stator resultant flux.

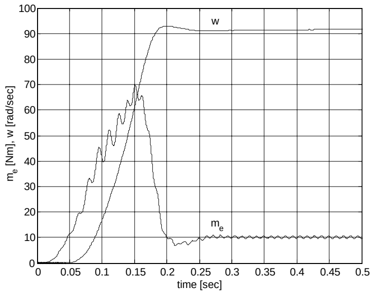

Fig. 17: Electromagnetic torque and electric angular speed.

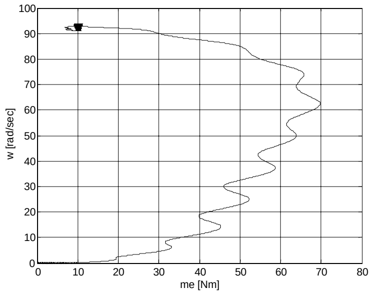

Fig. 18: Dynamical mechanical speed-torque diagram.

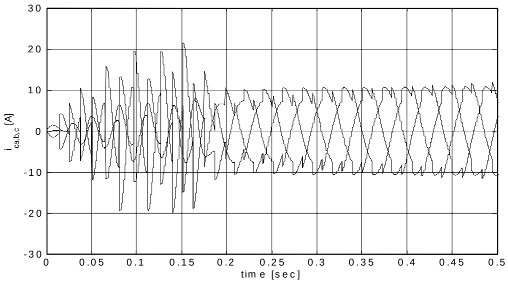

Fig. 19: Stator currents on phases "*a*", "*b*", "*c*".

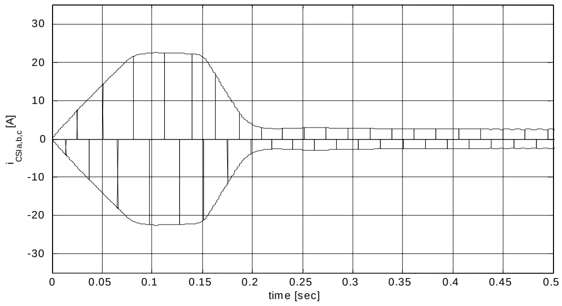

Fig. 20: CSI currents on phases "*a*", "*b*" and "*c*".

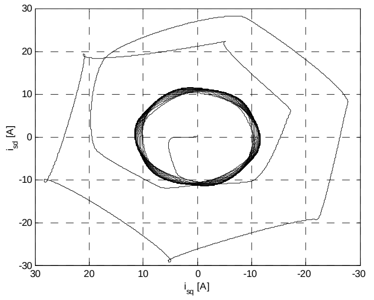

Fig. 21: Stator-current space-phasor.

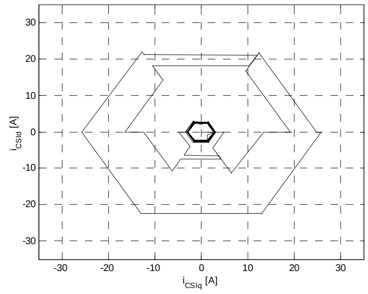

Fig. 22: CSI-current space-phasor.

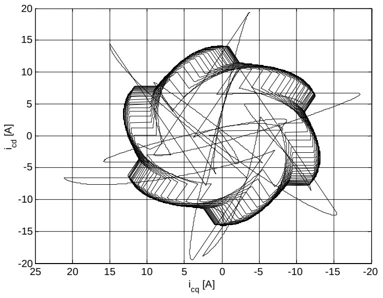

Fig. 23: Condenser current space-phasor.

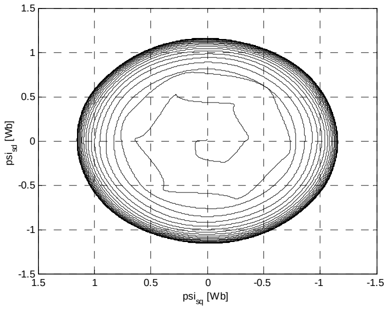

Fig. 23: Space-phasor of the resultant stator flux.

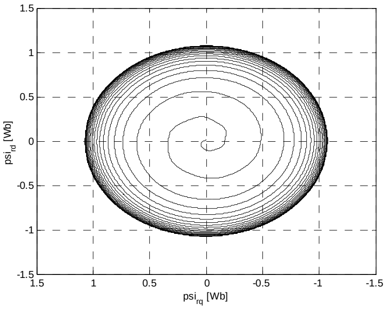

Fig. 24: Space-phasor of the controlled rotor flux.

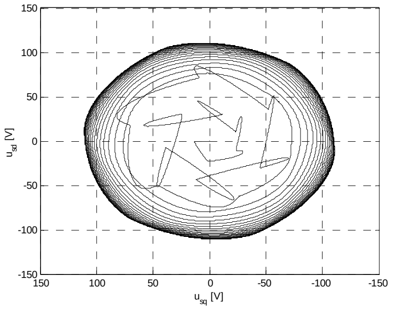

Fig. 25: Stator-terminal-voltage space-phasor.

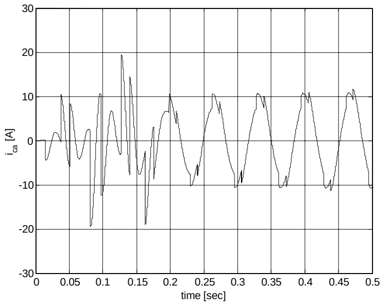

Fig. 26: Condensator current phase "*a*".

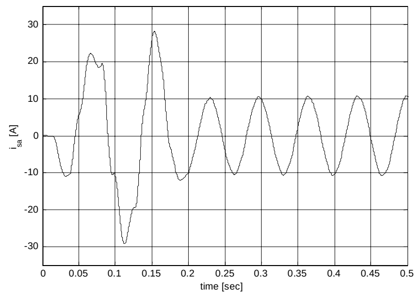

Fig. 27: Stator current on phase "*a*".

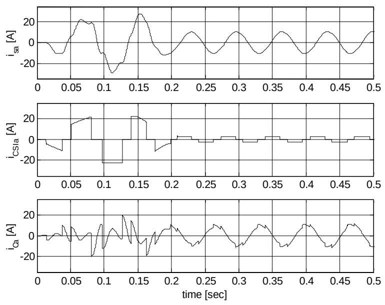

Fig. 28: Currents in phase "*a*" of the motor, CSI and condenser.

The simulation was made for the both control schemes presented in Fig. 2 and Fig. 3. Both schemes were simulated for the starting of the motor. The tandem-fed induction machine achieves the steady state corresponding to a working point near the rated values i.e. 314 *rad/s* electrical angular speed (50 *Hz*) of the rotor shaft and approximative 80 *N.m* load torque. The simulation results are presented in Fig. 5 - 15. The CSI-fed induction motor was simulated under reduced load-torque condition (10 *N.m*) and 94.2 *rad/s* reference value of the electrical angular speed (15 *Hz*) prescribed for the rotor shaft. The correspondig simulation results are shown in Fig. 16 – 28.

VI. CONCLUSIONS

The simulation results show that the tandem converter produces an improved output current waveform due to the PWM procedure of the VSI inverter. Experimental results are also presented in [6], [7], [10], [11] and [12]. Consequently, the tandem SFC is a viable solution for high- and medium-power AC drives.

The CSoC allows the partition of data processing either in hardware or in software algorithm, which results in a faster processing time. The implementation of the dqP, the PWM registers and the accumulators needed for the controllers occupies 56% of the CSL space. The IO Pins needed for the PWM outputs, six channel AD converter, CSI control (not shown in the implementation Fig. 4), occupies 34% of the available pins. The computation is executed sequentially for the blocks of the control structure. The path delay introduced by each block obtained from the worst-case analysis is about 140 *ns* and the estimated computation time for all the blocks will result about 4410 *ns*.

The simulation of the reconfiguration process will be the subject of a future paper.

ACKNOWLEDGMENT

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