RUN-TIME RECONFIGURATION OF TANDEM INVERTER USED IN INDUCTION MOTOR DRIVES

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ABSTRACT

The paper presents a short introduction to reconfigurable systems and why are they used or should be used in control of AC drives. The reconfigurable concept is introduced and there are treated the reconfiguration problems. Reconfigurable hardware is analysed from the point of view of reconfiguration times and reconfiguration strategies. There is introduced the reconfigurable control system and the need for reconfiguration in motor control it is explained. The control of the induction motor fed by the tandem inverter needs reconfiguration if the supply is made only from one inverter instead of the both component ones.

Keywords: run-time reconfiguration, embedded control system, vector control, tandem inverter.

1. INTRODUCTION

Reconfigurable computing technology is the ability to modify a computer system's hardware architecture in real time. Reconfigurable computing is also often called „custom" or „adaptive". Several definitions co-exists concerning the reconfigurable systems and. There was demonstrated significant potential for the acceleration of computing in general-purpose applications and in embedded systems [1], [5], [7], [10], [12].

Reconfigurable systems are those computing platforms whose architecture is modified by the software to suit the application at hand. This means that within the application program a software routine exists, that downloads a digital design directly into the reconfigurable space of the system. Most of reconfigurable computing systems are plug-in boards made for standard computers and they act as a coprocessor attached to the main microprocessing unit.

Comparing to the number of applications known in the reconfigurable field just a few of them are concentrated in the study of vector control for AC drives. Some successful implementations of vector control are referred in the literature. A DSP implementation of speed-sensor-less induction motor drive using artificial intelligence is presented in Vas [9]. Unfortunately, all these implementations and especially their hardware structures do not correspond to the reconfigurable system paradigm.

The implementation of an efficient vector control algorithm for a single AC machine in a DSP processor is no longer a problem. Difficulties arise when one try to extend this implementation to multiple-machine control [8] or appears the need of implementation for reconfigurable control system for the same machine [2].

The necessity of reconfiguration is based upon the practical observations that the performances of various types of vector controlled drives are different, depending on the range of speed, mechanical load characteristics, and the type of the supply power electronic converter. It is known that the rotor flux oriented vector control is widely used.

2. CONTROL SYSTEM STRUCTURE

Research efforts are concentrating to find the optimal solution for AC motor control. Since the reconfiguration idea appeared by the introduction of Field Programmable Gate Arrays (FPGA) there is an increasing interest to find other solutions then DSP for AC motor control. Vector control systems using the Park's direct and reverse field orientation transformations make the AC drives analogue to that of the separately exited DC machines, which can control de-coupled the mechanic and the magnetical effects in the motor [4]. In Figure 1 the direct (d) path is representing the flux building component of the stator current and the quadrature (q) path sets the motor torque producing one.

The so-called tandem converter is a new solution of variable frequency supply mode for medium- and high-power AC drives [3]. It combines the advantages of two types DC-link Static Frequency Converters (SFC), which work in parallel arrangement. They are of different power range. The larger SFC converts the real power and it is realised with GTO-thyristor-based Current-Source Inverter (CSI) working with Pulse Amplitude Modulation (PAM). The smaller SFC supplies the reactive power required to improve the quality of the motor currents and it contains an IGBT-based Pulse-Width Modulation (PWM) Voltage-Source Inverter (VSI). If the VSI fails the CSI still can run the motor. The VSI is also able to supply the motor at low power range without help from CSI.

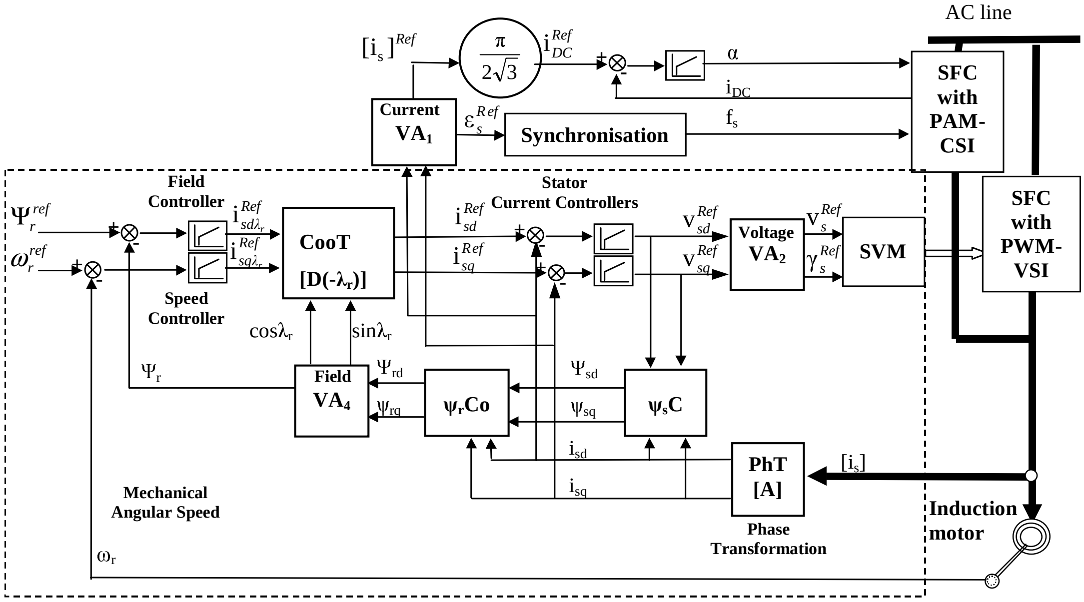


Figure 1. Vector control system for tandem inverter-fed induction machine.

The tandem converter needs different control strategies depending on the component inverters, which are actually working, and on the type of the PWM procedure used for the VSI. This can change its source character of the tandem. The open-loop voltage-control PWM procedures, i.e. carrier-wave or Space-Vector Modulation (SVM), keeps the voltage source 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.

The SFC control is fundamentally depending on the source character of the inverters and the type of the PWM procedure. They are basically determining the structure of the whole vector system even the same type of motor.

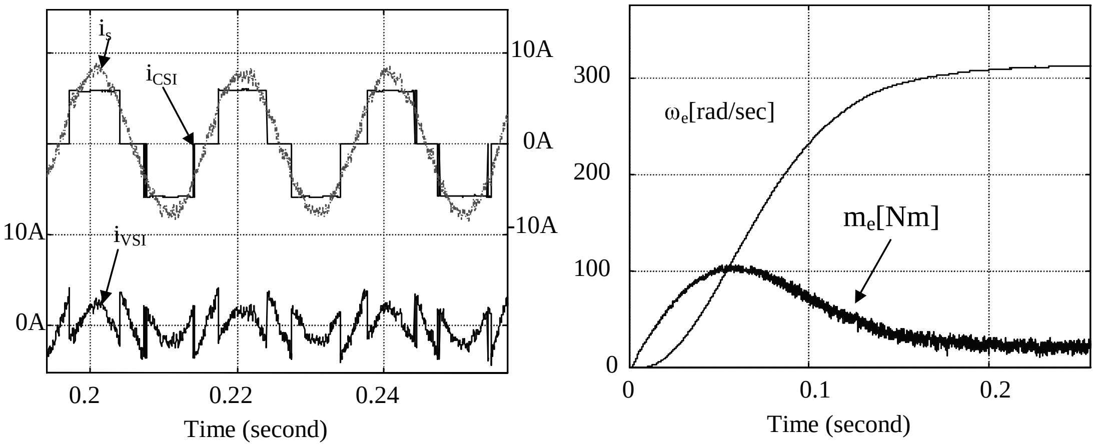
In Figure 1 the synchronisation in time and in amplitude of the CSI-currents is realised by means of the switching frequency f_s and the DC-link current i_{DC}, respectively with respect to the actual stator-current vector (in the tandem SFC) or to the reference one (if it works alone). This part of the control structure doesn't need any reconfiguration.

Best results are obtained if the rotor flux Ψ_r is kept constant because the induction motor will have linear mechanical characteristics. For current-fed motors also the rotor-field-orientation gives the most simple control structure. In Figure 1 the VSI is operating with SVM and it needs polar control variables, corresponding to the reference stator-voltage space-phasor position γ_s and module v_s, which are obtained from a vector analyser (VA).

The classical part of a vector control structure consists of producing the field-oriented current two-phase components corresponding to the active- (speed-torque) and reactive- (flux) loops. The current reference values, after a co-ordinate transformation (CooT), become natural d-q components and they will generate the voltage references using current controllers [3]. If the load has active character it is suggested to make reconfiguration in order to take in to account the electromagnetic cross effect in the motor.

The field identification is also a special part of the vector control systems. the most simple solution is computing by integration the stator-voltage equations (block Ψ_sC), which gives the stator flux d-q components. They are compensated in block Ψ_sCo in order to obtain the orientation rotor field.

For long transient operation, as starting and speed reversal at quasi-constant torque, the rotor field orientation structure is used, neglecting the cross effect. In steady state near the rated speed for load-torque perturbations the control scheme will be reconfigured into a stator-field-oriented structure, which can take into account the cross effect in the simplest mode [4].



a) Stator, CSI and VSI currents.

b) Electrical angular speed of the rotor and the electromagnetic torque.

Figure 2. Simulation results of the tandem converter-fed induction motor.

Figure 2 presents simulation results of the tandem converter-fed induction motor no-load starting controlled by scheme from figure 1 without taking into account the electromagnetic cross effect.

3. IMPLEMENTATION MODULARITY

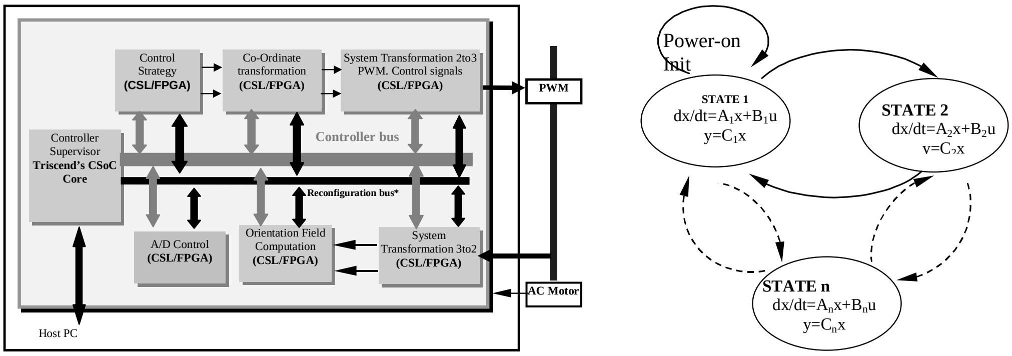
The control system (CS) presents modularity as is shown in Figure 1 represented by the computing blocks such as:

- phase transformations (PhT);
- co-ordinate transformation;
- vector analyser;
- orientation field computation and compensation;
- stator-voltage computation (cross effect);
- SVM block and etc.

This modularity allows exploiting of all the parallelism of the control algorithm. The most significant result introduced in reconfigurable control was the parallel-machine control architecture. The current vector control algorithm has been applied to four AC drives. The control system uses pipeline computing, but parallel control [8].

Starting from the mentioned modularity and the parallel structure introduced in [11], can be implemented a universal reconfigurable control system structure as is shown in Figure 3, *a*.

The introduction of the reconfigurable control system concept solves the problem of the tandem converter-fed induction machine. In fact the same hardware support, which implements one control system structure, can be used also to switch to another control scheme.



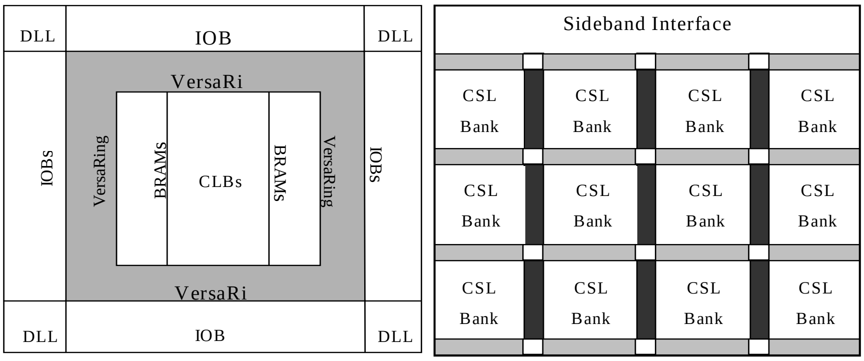
a) *b)*

Figure 3. The reconfigurable structure and its the state transition graph of the control system.

Each control structure can be seen as a distinct state of a logic state machine. In fact, each state represents a different hardware configuration. Figure 3, *b* shows a possible two-state control system structure (with STATE1 and STATE2). The transition from one state to another can be determined by the state variables of the controlled system. If a transition condition occurs, (i.e. the motor speed reference transits a limit value) the need for reconfiguration is fulfilled. The control system will start a self-reconfiguration process and will change its configuration automatically. In equal the logic state machine switches between two control system schemes. These could be: the rotor-flux oriented vector control allocated to State 1 and the stator-flux oriented vector control allocated to State 2. In principle, the logic state machine can be extended to implement other states, respectively other control system schemes.

As is described in [2] the desired reconfigurable control system can be implemented under the following conditions:

a) External memory is needed to store the several configurations (Configuration Store).
b) Either software or hardware has to be capable to start a reconfiguration on need.
c) The evolution of the system must be predictable in order to pre-compute the possible configurations.
d) The system control states have to be quantified and finite. This condition is due to the finite capacity of the available external memory.
e) The existence of 'high-fidelity' models and very effective approximation-identification algorithms for multivariable systems.



a) Virtex FPGA Structure b) Configurable System Logic of CSoC Structure

Figure 4. Overview of reconfigurable architectures.

To implement the configurable control system one may have to consider the existing hardware supports, which are suitable. The structures are shown in Figure 4 and their selection criteria are presented in Table 1.

The reconfiguration limits conditions have to be correlated with two values of the rotor speed, both depending on the reference value and taking into account the sign of the acceleration. For motor control scheme from figure 1 State 1 is chosen if the speed is under the limit values given in the following expressions:

$$\omega_{1L} = \omega_r^{Ref} - sign(\omega_r^{Ref})\Delta\omega_1, \quad \text{and} \quad \omega_{2L} = \omega_r^{Ref} - sign(\omega_r^{Ref})\Delta\omega_2, \qquad (1)$$

where the speed control thresholds $\Delta\omega_1$ and $\Delta\omega_2$ are both positive, and $\Delta\omega_1 < \Delta\omega_2$. State 2 is chosen if the speed is over these limits depending on the motor acceleration, respectively.

Table 1. The criteria to select the right reconfigurable structures for implementation of the control system

Triscend Configurable System on Chip (CSoC)	**Xilinx Virtex FPGA**
Configurable System Logic (CSL)	Abundant logic resources
Incorporated processor core	Ready made IP modules
External and internal memory	Internal memory
Ability to start self reconfiguration	Ability for partial reconfiguration
	High computing speed
	Highest known reconfiguration frequency

There it is very difficult to select a reconfigurable hardware structure without to analyse the performing reconfiguration structures available, and without to consider their reconfiguration times. Also one may have to consider future chips what will appear in the close future. Of course it is not impossible to use combination of these hardware. Let us take a closer look to the time constraints of the control system and what are the interdependencies between the sampling period of the control system and the reconfiguration times.

4. RECONFIGURATION STRATEGIES AND TIME CONSTRAINTS

The control of the execution element, represented by the AC motor together with the PWM and the electrical and mechanical sensors assembly, impose real-time performance of the control system algorithm. One may conclude that decreasing the sampling period the control system can perform better. On the other hand decreasing the sampling period can be imposed very short reconfiguration time (partial or total). The sampling period have to accomplish the following criterion. Considering that the AC motor should not be left without control, the reconfiguration time (partial or total) have to be less equal then the sampling period of the control system:

$$t_{\text{reconfiguration}} \leq T_{\text{sampling}} \qquad (2)$$

Consequently, a compromise it can be made between the control system performance and the existing hardware support reconfiguration time in order to achieve the final target, i.e. to implement the reconfigurable control system.

Depending on the hardware support of the implementation the reconfiguration can be done as:

- *Partial reconfiguration* – reconfiguring each module step by step conform to the method introduced by Luk. The method is called *pipeline morphing*, intended to reduce the latency involved in reconfiguring from one pipeline to another. The basic idea is to overlap computation and reconfiguration: the first few pipeline stages are being reconfigured to implement new functions so that data can start flowing into the newly configured stages of the pipeline, while the rest of the pipeline stages are completing the current computation. It is particularly suitable for devices supporting rapid reconfiguration and it works best when reconfiguration time is comparable to the pipeline computation time. To meet this condition, the user can build single cycle reconfigurable structures [12].

- *Total reconfiguration* – reconfiguring the control system as a whole. This is the case when it is used Triscend's CSoC, which in some circumstances can reconfigure the CSL starting a reconfiguration process.

The reconfiguration time for partial or total reconfiguration methods is:

- For the *partial reconfiguration* the maximum reconfiguration frequency known is 66 MHz if the best existing hardware support is the Virtex FPGA.

- The time needed for *total reconfiguration* of a CSoC by using the parallel mode initialisation, is 7.4ms at 40MHz reconfiguration frequency. This involves for implementation of the reconfigurable control system the use of two CSoC chips or CSoC in combination with FPGAs.

The research was started with the implementation of the control system modules in a CSoC as reported in [2] and [10].

5. CONCLUSIONS

The control system modularity helps reconfiguration in order to reduce the reconfiguration time. The control system states are quantified because of the limited capacity of reconfiguration memory. Reconfiguration of the control system is critical if the sampling period is comparable with the reconfiguration time: it has to be made less then the sampling period of the control system. Reconfiguration has to be done between two sampling events.

Hardware supports with faster reconfiguration time are needed for the proposed control system structures.

Future work and further research has to be done for finalising the CSoC implementation and for testing it in practice. It is necessary first to create a standalone module library using Xilinx Virtex FPGA for the reconfigurable structures of AC control systems.

6. ACKNOWLEDGEMENT

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