Managing Transients Generated by the Reconfiguration Process at the Tandem Inverter Fed Induction Motor

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Abstract **The paper focuses on the reconfiguration process of vector control systems of the induction motor supplied from the tandem (hybrid) static-frequency converter. Reconfigurable control structure ensures different strategies for operating modes with non-failed and partial-failed converter. The reconfiguration process introduces perturbations in the vector controlled AC drives. The paper analyses the perturbation effects of the control system reconfiguration and presents simulation results. The paper tries to give some solutions for the transient management. Problems related to hardware and software implementation of the transition from a control structure to another are discussed. Simulation results are presented for both basic topologies of the field-oriented control system The simulation results were obtained with the help of a module library created in Matlab Simulink special for implementation in Field Programmable Gate Arrays (FPGA) of vector control structures for AC drives**.

I. INTRODUCTION

Reconfigurable hardware was used in vector control in the last years for control system implementations [1.], [3.], [15.]. In vector control systems, the reconfigurability was introduced by Imecs et all in [4.]. When reconfiguration condition occurs, the system will start reconfiguration process in which it switches the current configuration to the next corresponding one. This type of configuration is the context switching and was developed by Scalera in [11.]. While context switching is a reconfiguration technology for Field Programmable Gate Arrays (FPGA), the logic state machine (with different control system structure in each state) is a reconfiguration method for vector control systems.

Reconfiguration of vector control systems was treated in [4.]. For each vector control scheme one have to associate a state of the configuration state machine supervised by the configuration manager. Shirazi et al in [12.] treated the run-time management of dynamically reconfigurable devices. The configuration state machine associated to the reconfiguration of the *tandem converter system* was treated in [5.] (Fig 1). The perturbations introduced by the reconfiguration process were treated in [16.]. This paper tries to analyse and give a solution for the transient management during the reconfiguration process.

II. RECONFIGURATION OF TANDEM CONVERTER CONTROL SYSTEM

The term "*tandem converter*" denotes a solution of DC link Static Frequency Converters (SFC), used in medium- and high-power AC drives [13.], [14.]. It combines the advantages of the two component inverters, with different source character (current and voltage) and different modulation method. The larger Current-Source Inverter (CSI) is operating in Pulse Amplitude Modulation (PAM) and converts the active power, while the smaller Voltage-Source Inverter (VSI) is working in Pulse Width Modulation (PWM) and supplies the reactive power required for improving the quality of the motor currents [5.], [13.] and [14.].

If one of the two converters is not working (i.e. it fails) the control system structure needs to be re-conFig.d in order to be able to maintain the control of the drive. The vector control system should be reconFig.d if one of the converters fails. The most sensitive situation for the tandem converter is when the VSI fails, because the control structure looses its voltage-source character [5.].

In such a situation, the motor is fed only by the CSI and the current control concept will be applied. Under these circumstances the control structure does not corresponding any more for the new demands and this justifies the need for reconfiguration.

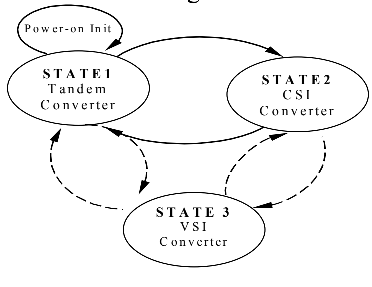

Fig 1. Reconfigurable state machine with different vector control structures in each state

Several reconfiguration methods were treated by Luk [8.], but the most suitable method for the vector control systems is to so called "context switching" method mentioned in [11.], where the configuration manager switch between the configuration contexts. One has to allocate for each context a control structure of the vector control system.

There are three possible pre-computed structures as presented in Fig 1 and the first two control structures are described in detail in [4.], [5.]. These control structures are as follows: tandem converter (the VSI + CSI is working together), voltage source inverter (CSI fails) and current-source inverter structure (when VSI fails).

The reconfiguration of a control system introduces perturbations in the control system, which actually are transients generated by the changes of the control structure. The main problem of the reconfiguration is that, while the transients generated in the control system are low power transients, the perturbations, which appear in the induction motor and converter, have high power character.

In order to make possible the reconfiguration and analyse the perturbations introduced by the reconfiguration process in the AC drive let us present wo control schemes on which the reconfiguration was studied. Fig. 2 present the vector control system corresponding to the reconfiguration state machine presented in Fig 1, for the state 1 and 2. The third possibility reconfiguration to state 3 was not studied yet.

The multiplexers from Fig. 2 are a possible representation of the transition from one state to the other. But one should note that, while these components may be indeed possible implementations, they are intended to be abstract entities did not need any implementation as was presented by Luk in [8.]

Fig. 2 represent the schemes for the control structures of the induction motor in two different situations, as follows [5.].

Tandem-converter-fed induction motor operates with stator-field orientation (Fig. 2 state 1). Using two parallel inverters to supply the motor is no more necessary to apply PWM procedure to control the whole energy of the load, because a large value of the energy is transferred through the PAM-CSI converter. Consequently, in comparison with an equivalent PWM-VSI, the tandem inverter switching losses will be considerable reduced. The currents of the AC machine should achieve the sine-wave pattern. The output currents of the tandem converter (i.e. the load currents) in each phase are to be equal to the fundamental currents of the primary CSI inverter. The current in a phase of the secondary VSI can be expressed as the output fundamental current of the primary inverter minus the square-wave CSI current in the same phase. In Fig. 3 are shown the motor, CSI and VSI currents, and the currents in the AC drive are:

$$i_{s\_a,b,c}=i_{CSI\_a,b,c}+i_{VSI\_a,b,c}. \quad (1)$$

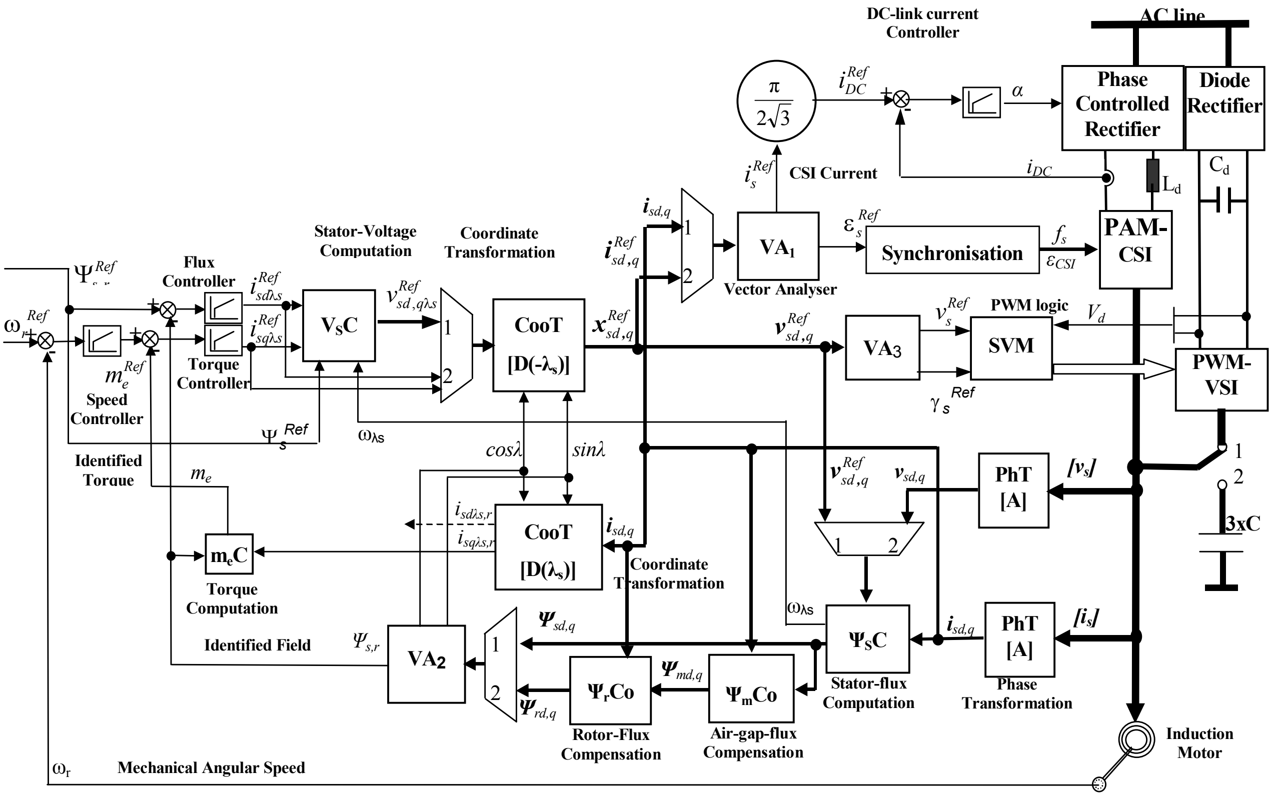

Fig. 2. Stator-field-oriented vector control system for the tandem converter-fed induction motor

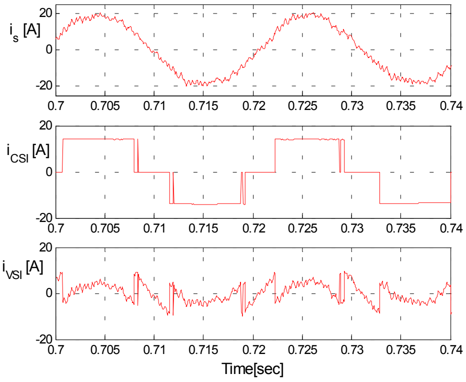

Fig. 3. Current waveforms at the output of the tandem converter.

CSI-fed induction motor. If the VSI fails, it is decoupled from the motor terminals and the CSI will supply alone the motor. Due to the current-source-character of the CSI the motor control need to be reconFig.d to rotor field orientation (see Fig. 2 corresponding to state 2) or stator field orientation.

III. PERTURBATIONS INTRODUCED BY THE RECONFIGURATION PROCESS

In the case of the tandem inverter when the VSI fails control system will start a self- reconfiguration process conform to the reconfiguration diagram presented in Fig 1. To visualise the reconfiguration process, the control structure from Fig. 2 was simulated using MATLAB-Simulink® environment.

The motor was started with the tandem converter and the reconfiguration was made after 0.5s.

The simulation structure used the module library created with the Xilinx System Generator and presented in [16.].

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

As mentioned the reconfiguration of a vector control system is necessary in certain circumstances, so the effects introduced by the transients are unavoidable. For this reason one have to pay attention to the transient management during the reconfiguration process. The transients appear usually as damped oscillatory motions, which persist for relatively short time after the reconfiguration has occurred as was treated for the transients in digital signal processing for linear systems [9.]. For vector control systems, which are non-linear systems, the perturbations introduced in the AC drive appear mainly because of the transition from voltage-controlled character (tandem converter fed - CSI+VSI) to the current or/and voltage controlled character (current inverter fed – CSI or/and voltage fed CSI) of the AC drive.

In Fig. 4 can be observed the perturbations introduced in the stator currents. The transient effects on the AC drive – while the stator current waveforms became sinusoidal again - can be observed for 0.1s. During this time the motor change its working parameters compared to the reference.

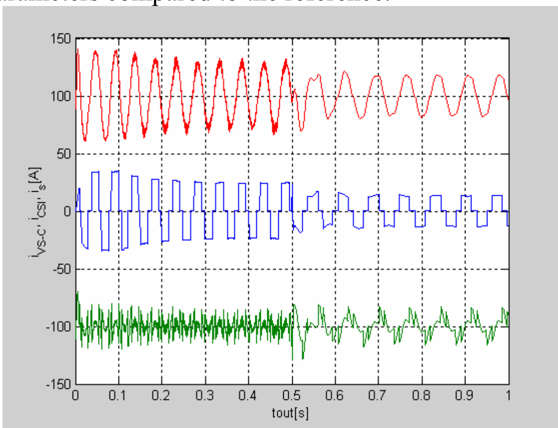

Fig. 4. Current waveforms before and after reconfiguration.

It can be observed that the reconfiguration introduces perturbations in every observed parameter of the drive (Fig. 5 and Fig. 6).

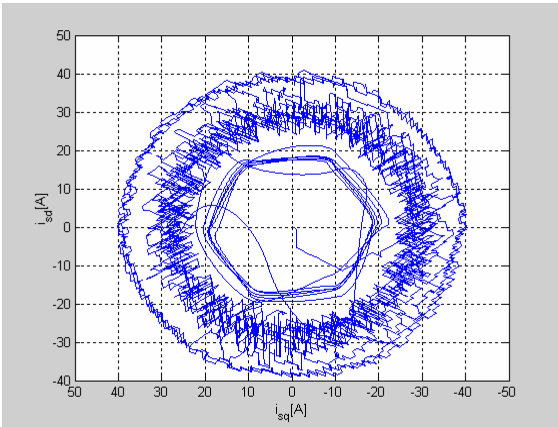

Fig. 5. Stator-current space-phasor.

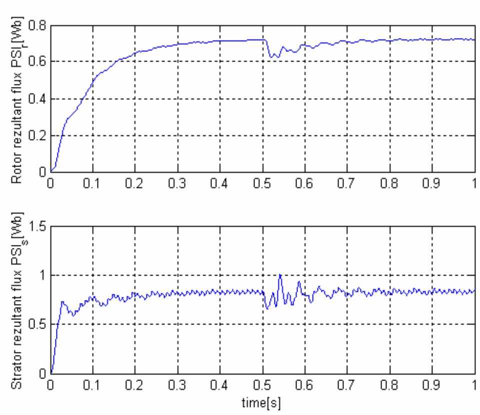

Fig. 6. Rotor and stator resultant flux.

The simulation results were compared with [5.], and they show that the reconfiguration fulfils the expectations, and influences the motor performances, too.

IV. Implementation

The algorithms of the computing blocks were decomposed in elementary mathematical operations, and a module library was issued for the re-configuration, using Matlab in order to implement it in FPGA structure.

From the analysis of vector control schemes results that vector control schemes presents modularity [1.], [2.], [3.] and [6.]. The modules used at one vector control scheme are reusable to another one. One can conclude that the modularity is independent of the used vector control schemes. Also the modules can be reduced to a common form represented by the equations:

$$g_d = a_d x_d + b_d y_d; \quad (1a)$$
$$g_q = a_q x_q + b_q y_q, \quad (1b)$$

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 [16.].

The module library allows a rapid prototyping and fast implementation of the vector control structures in FPGAs [16.].

As presented in equation (1) the modules have a general form, which is also presented in [15.]. Using this generalised module to implement each module of the module library will result in similar hardware resource consumption for each module.

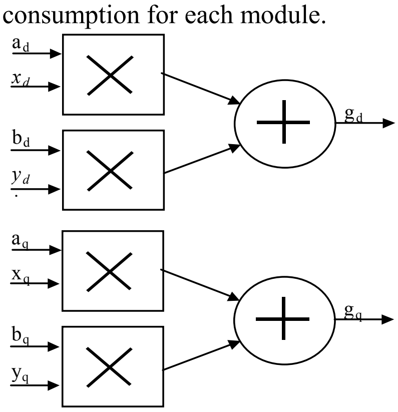

Fig. 7. Universal computation module of vector control systems

Naturally where constants are one of the inputs the modules became much simple.

Usually the implementations of control systems for AC drives make use of the mentioned general form of the equations. And they are sequential ones as presented by [1.], [3.]. As the tandem inverter has to be conFig.d and there are variable value transfer problems, for the control structure presented in Fig. 2, it was chosen the parallel implementation method.

In the mean time some modules present exceptions from the generalised form. These modules are the PI controllers and the Vector Analyser (VA) module.

When analysing the performances of the modules of the parallel implementations one should consider the followings:

- The time delay introduced by each module,
- The maximum working frequency of the FPGA,
- The hardware resources occupied in the FPGA by each module
- The quantisation error of the module

All these criteria influence the implementation of the vector control system in one FPGA or in a distributed FPGA array.

To show the hardware resources consumed by one module with the mathematical form of equations (1), in Table 1. The simulation of the control structure shown that the quantisation error is smaller then 0.6 * 10^{-3}, and is presented in Fig. 8

Release 4.1.03i - Map E.33			
Xilinx Mapping Report File for Design			
Design Information			
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Number of Slices:	25 out of	3,072	20%
Number of Slices containing			
Unrelated logic:	0 out of	625	0%
Total Number 4 input LUTs:	1,222 out of		6,144 19%
Number used as LUTs:			1,208
Number used as a route-thru:			14
Total equivalent gate count for design:			15,579
The Delay Summary Report			
The Score for this design is: 5342			
The Average Connection Delay for this design is:			1.969 ns
The Maximum Pin Delay is:			10.256 ns
The Average Connection Delay on the 10 Worst Nets is:			7.306 ns
Listing Pin Delays by value: (ns)			
d<2.00<d<4.00<d<6.00<d<8.00<d<11.00 d >=11.00			
2432 1211 395 92 6 0			

Table 1. Hardware resources consumed and time delay introduced by the module CooT[D(-λ)]

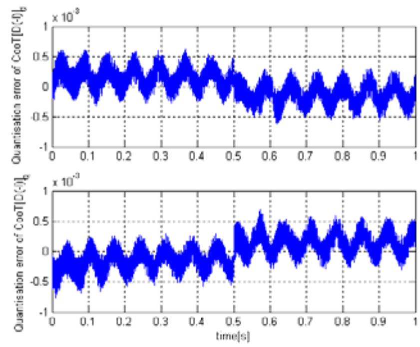

Fig. 8. Quantisation error of block CooT[D(-λ)]

V. Transient Management

Because of the reconfiguration from one control structure to another (i.e. from tandem CSI+VSI to CSI structure), may appear some unavoidable and undesired transients in the controlled variables of the drive. The transients appear usually as damped oscillatory signals, which persist for relatively short time after the reconfiguration has occurred. The transients were treated for reconfigurable control loops also in [9.], [10.]. There are several solutions for the reduction of reconfiguration transients. Péceli presented the transient reduction methods and treated for filtering problems in [9.]

The transients in the reconfigurable vector control system appear at the drive as high power perturbations, and influence the dynamic performance of the drive system. The perturbations are generated due to the changes of the control structure, i.e. of the hardware structure. The reconfiguration transients for the AC drive act as disturbances and reduce the quality of the drive performances (Fig. 9).

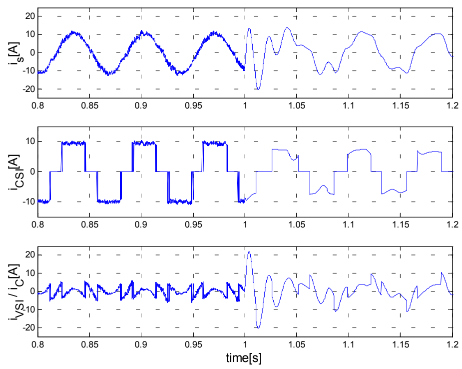

Fig. 9. Simulated current waveforms before and after reconfiguration.

For this reason it is important to reduce the reconfiguration transients. Let us take the case of the reconfiguration from State 1 to State 2, the case when the VSI fails. The source of perturbation is also the switching process from the failed VSI to the capacitors. This switching is also part of the reconfiguration but this has directly influences on the stator currents. The overall influence of the reconfiguration, i.e. the introduced perturbations, can be observed in Fig. 9. In this case, the perturbations introduced in the AC drive appear mainly because of the reconfiguration from a structure, which has voltage-controlled character (i.e. for the tandem converter-fed motor) to another structure with current-controlled character (i.e. for the CSI-fed-motor) of the drive. The transients amplitude and durations also depends on the controlled character of the state in which it will be reconFig.d the tandem converter. If both control structures, have the same control character (i.e. voltage or current), then the transient maximal amplitude will be smaller and the duration shorter.

If one has a look on the possibilities to manage the transients then on Fig. 2, may be observed that are very few modules where the transient filtering can be solved. There are the PI controllers of flux, torque, and speed, and there is the DC link PI controller.

One may found that if the DC link Controller will have PID character there is possible to filter the transients, but this influence the controller actions on the controlled reference flux and speed. So the transient management should act in concordance with the stability of the control system but the action have to be done in all the controllers.

Taking the flux controller function for example one should consider the control function continuity at the reconfiguration time t_r, which means:

$$i_{sd\lambda r}^{Ref}(t) = = \begin{cases} k_{p1}\left(\Psi_r^{Ref} - \Psi_r\right) + k_{i1}\int\left(\Psi_r^{Ref} - \Psi_r\right)dt \;\; for\, t \le t_{tec}; \\ k_{p2}\left(\Psi_r^{Ref} - \Psi_r\right) + k_{i2}\int\left(\Psi_r^{Ref} - \Psi_r\right)dt \;\; for\, t < t_{tec}; \end{cases} \quad (2)$$

where the $i_{sd\lambda r}^{Ref}$ is the d component stator reference current, Ψ_r^{Ref} is the reference rotor flux, Ψ_r is the calculated actual rotor flux and t_{rec} is the time when the reconfiguration is done. The transient filtering it would be successful, when the controlled d component stator current function conform - equation (2) – is continue at t_{rec}. This means:

$$i_{sd\lambda r}^{Ref}(t_{rec} - 0) = i_{sd\lambda r}^{Ref}(t_{rec} + 0); \quad (3)$$

To show the partial results achieved by the transient management in Fig. 10, Fig. 11 are presented some simulation results.

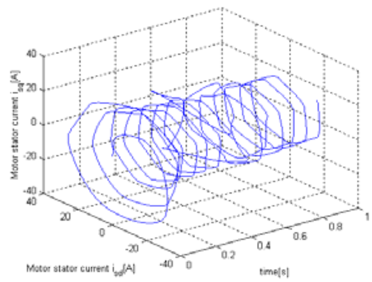

Fig. 10. *Motor current stator space phasor*

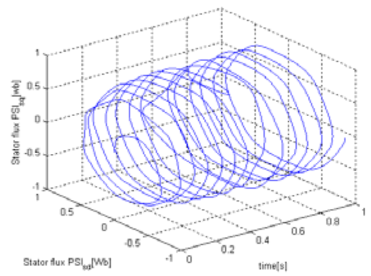

Fig. 11. *Stator-flux space phasor.*

There can be observed in the simulation results that the transient influences were diminished.

VI. CONCLUSIONS

The transients of the reconfiguration-reconfiguration process generate perturbations in the AC. Each variable reacts in particular way to the reconfiguration. The stator flux – controlled before reconfiguration – is sensitive to the transients for about 0.05s, while the rotor flux, which is controlled after reconfiguration, will reach the controlled level in about 0.11s. The transient management should filter completely the perturbation in the drive. The obtained partial results are promising, but still not give the expected filtering level. Further research should be made to find solutions for the compensation of these negative effects.

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