TRANSIENTS IN THE RECONFIGURATION OF TANDEM CONVERTER FED AC DRIVES

József Vásárhelyi[1], Mária Imecs[2], Csaba Szabó[2] and János J. Incze[2]

[1] Deptartment of Automation University of Miskolc,, 3515 Miskolc-Egyetemváros, Hungary
email: vajo@mazsola.iit.uni-miskolc.hu

[2] Department of Electrical Drives and Robots, Technical University of Cluj-Napoca, ,str. Daicoviciu 15, RO3400 Cluj, Romania
email: {imecs, csaba.szabo,ioan.incze}@edr.utcluj.ro

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. 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 for implementation and rapid prototyping for Field Programmable Gate Arrays.

1 Introduction

Reconfigurable hardware was used in vector control in the last years for control system implementations [Aubépart et al.2001, Cirstea et al..2002, Imecs et al. 2000b, Vásárhelyi et al. 2002a],. In vector control systems, the reconfigurability was introduced by Imecs et all in [Imecs et al. 2000b]. 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 [Scalera and Vázquez 1998]. 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 [Imecs et al. 2000a and Imecs et al..2000b] For each vector control scheme one have to associate a state of the configuration state machine supervised by the configuration manager. Run-time management of dynamically reconfigurable devices was treated by Shirazi [Shirazi et al. 1998]. The configuration state machine associated to the reconfiguration of the *tandem converter system* was treated in [Vásárhelyi et al.2002b] (see Figure 1)

2 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 [Trzynadlowski et al. 1998, Trzynadlowski et al. 1999]. 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 [Imecs et al. 2001d].

If one of the two converters is not working (i.e. it fails) the control system structure needs to be re-configured in order to be able to maintain the control of the drive [Trzynadlowski et al. 1999].

The vector control system should be reconfigured 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. 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.

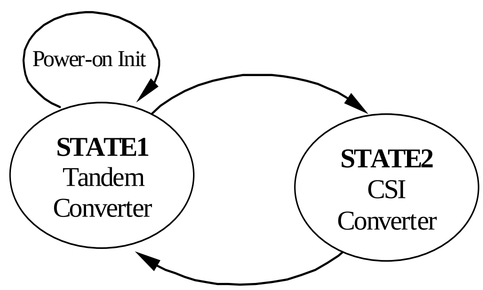

Figure 1. Reconfigurable state machine with different vector control structures in each state

Several reconfiguration methods were treated by Luk in [Luk et al. 1996], but the most suitable method for the vector control systems is to so called "context switching" method mentioned in [Scalera and Vázquez 1998], 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 Figure 1 and described in detail in [Imecs et al. 2000b and Imecs et al. 2001b]. 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 two control schemes on which the reconfiguration was studied. Figure 2 present the vector control system corresponding to the reconfiguration state machine presented in Figure 1, for the state 1 and 2. The third possibility reconfiguration to state 3 was not studied yet.

The multiplexers from Figure 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 [Luk et al. 1996] Figure 2 represent the schemes for the control structures of the induction motor in two different situations, as follows [Imecs et al. 2001b].

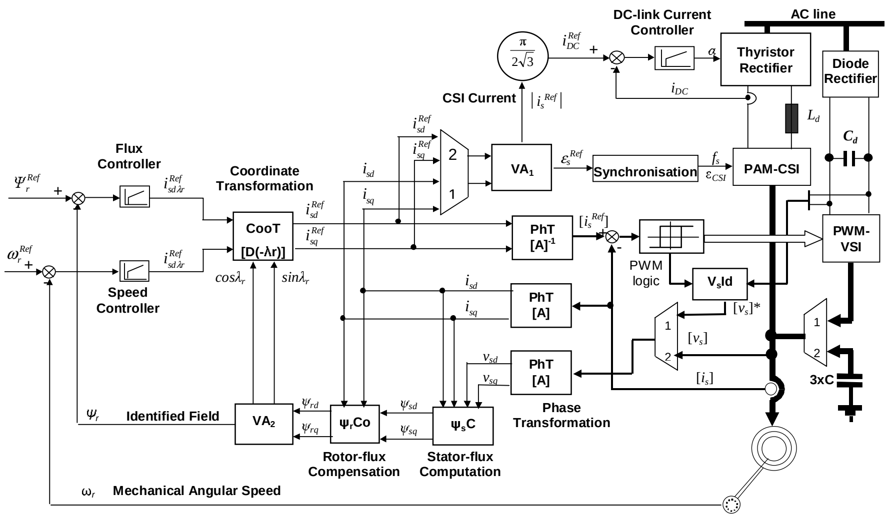

Figure 2. Stator-field-oriented vector control system for the tandem converter-fed induction motor

Tandem-converter-fed induction motor operates with stator-field orientation (Figure 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 Figure 3 are shown the motor, CSI and VSI currents, and the currents in the AC drive are:

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

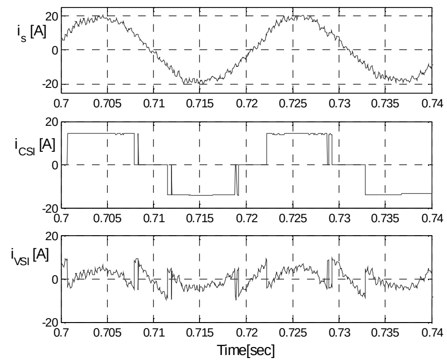

Figure 3. Current waveforms at the output of the tandem converter.

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 reconfigured to rotor field orientation (see Figure 2 corresponding to state 2) [Imecs et al. 2001b].

3 Perturbations Introduced by the Reconfiguration

The application of reconfigurable systems in vector control was treated in [Imecs et al. 2000a, Imecs et al. 2000b, Imecs et al. 2001b and Imecs et al. 2001d]. In the case of the tandem inverter when the VSI fails the control system will start a self- reconfiguration process conform to the reconfiguration diagram presented in Figure 1. To visualise the reconfiguration process, the control structure from Figure 2, reconfiguration from the tandem converter fed structure to the current inverter fed structure was simulated using MATLAB-Simulink® environment. (The motor was started with the tandem converter and the reconfiguration was made after 0.5s. The motor data are: 5.5 *kW*, 50 *Hz*, 220 *V r.m.s.* 14 *A r.m.s.* and 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 [Péceli et al. 1999]. 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 controlled character (current inverter fed - CSI) of the AC drive.

The most sensitive situation for the tandem converter is when the VSI (Voltage Source Inverter) fails, because the control structure looses its voltage-source character Imecs et al. 2001c]. In such a situation, the motor is fed only by the CSI (Current Source Inverter) and the current control concept will be applied. Under these circumstances the control structure does not correspond any more for the new demands and this justifies the need for reconfiguration, otherwise the motor will work in regenerative mode [Vásárhelyi et al. 2002a].

The reconfiguration process introduces perturbations, which were treated in [Vásárhelyi et al. 2002a]. 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.

The reconfiguration transients for the AC drive act as disturbances and reduce the quality of the drive performances. For this reason it is important to reduce the reconfiguration transients.

The transients amplitude and durations also depends on the controlled character of the state in which it will be reconfigured the tandem converter.

To manage the transients then, one may observe that are very few IP cores of the control structure), 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.

This means that the entire controller functions (for example the flux one) one should show function continuity at the reconfiguration time t_r, which means:

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

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_r is the time when the reconfiguration is done.

The transient filtering it would be successful, when the controlled d or q component stator/rotor current (or voltage) function is continue at t_c. This means:

$$\begin{aligned} &\underrightarrow{lim}\, i_{sd\lambda r}^{Ref}(t\to t_r-0)=\underrightarrow{\lim}\, i_{sd\lambda r}^{Ref}(t\to t_r+0); \\ &\underrightarrow{lim}\, i_{sq\lambda r}^{Ref}(t\to t_r-0)=\underrightarrow{\lim}\, i_{sq\lambda r}^{Ref}(t\to t_r+0); \end{aligned} \qquad (3)$$

These conditions have to be implemented in reconfigurable hardware and they impose implementation conditions for the variable transfer at the reconfiguration moment.

4 Simulation Results

The simulations were made in Matlab-Simulink environment. The rated data of the motor are: 5.5 *kW*, 720 *rpm*, 50 *Hz*, 220/380 V_{rms}, 24.3/14 A_{rms}, cos $\varphi = 0.735$. In Figure 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.

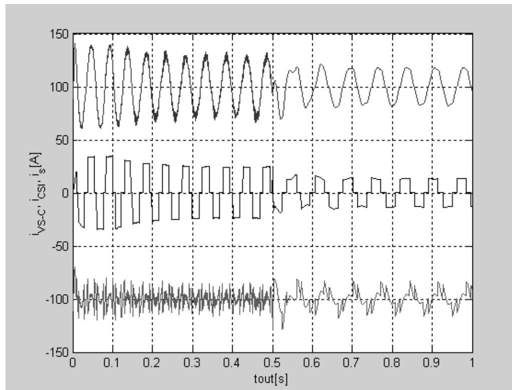

Figure 4. Current waveforms before and after reconfiguration.

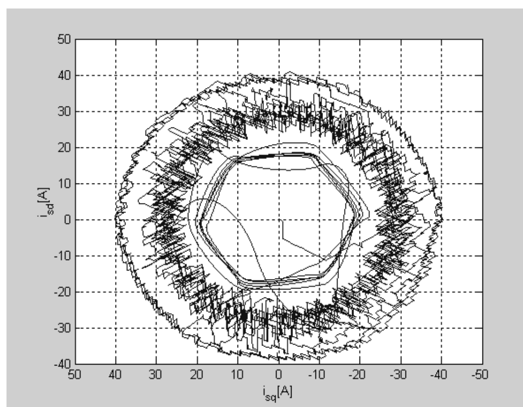

Figure 5. Stator-current space-phasor.

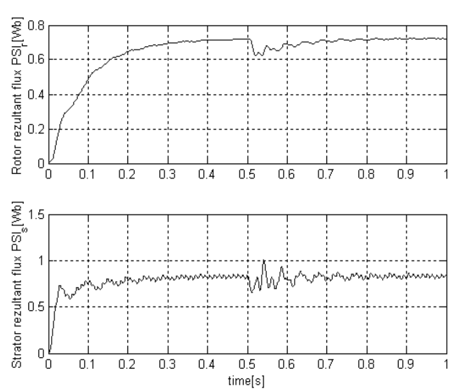

Figure 6. Rotor and stator resultant flux.

The motor was started with the tandem converter and the reconfiguration was made after 0.5s. It can be observed that the reconfiguration introduces perturbations in every observed parameter of the drive.

The simulation results were compared with [Imecs et al. 2001a, Imecs et al. 2001b, Imecs et al. 2001d] and they show that the reconfiguration fulfils the expectations, and influences the motor performances, too.

5 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 Xilinx Toolbox in order to implement it in FPGA structure.

The situation when the CSI fails it was not treated in [Imecs et al. 2001b] and for this reason the reconfiguration state machine should be extended to this situation.

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 in Table 1 and 2 we presents the implementation results and the time delay introduced by the coordinate transformation. The simulation of the control structure shown that the quantisation error is smaller then $0.6 * 10^{-3}$, and is presented in Figure 7

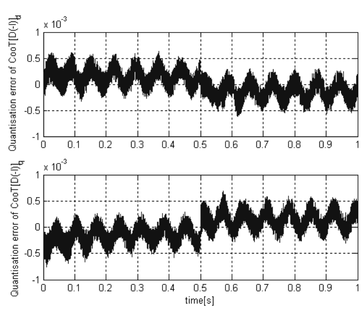

Figure 7. Quantisation error of block CooT[D(-λ)]

Table 1. Hardware resources consumed by the coordinate transformation module CooT[D(-λ)]

Release 4.1.03i - Map E.33			
Xilinx Mapping Report File for Design			
Design Information			
--			
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:			15579

Table 2. Time delay introduced by the module CooT[D(-λ)]

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

In the implementation we considered that he algorithms of each computing block can be decomposed in elementary mathematical operations (such as multiply and accumulate), and a module library was issued for the reconfiguration, using Matlab [Vásárhelyi et al. 2002c].

6 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.

7 ACKNOWLEDGEMENT

The “*tandem inverter*” - the subject of a research project supported by Danfoss Drives A/S – was realized at the Institute of Energy Technology, Aalborg University, Denmark. Special thanks to *Prof. A. Trzynadlowski* from Nevada University, Reno, USA for the collaboration in this theme, *to Prof. F. Blaabjerg* from the Aalborg University and to the *Danfoss Drive A/S*, Denmark for their generous support.

8 REFERENCES

AUBÉPART F., POURE P., BRAUN F. (2001), *Contribution to System-on-Chip in motion control: VLSI design of a digital controller for an induction machine,* PCIM 2001 Power Electronics Intelligent Motion Power Quality, June 19-21, 2001 Nuremberg, Germany, pp. 211-216

BELMIMOUN M. H., MONMASSON E., SAMBUIS E. (2002), *Modularity in Code Development for DTSFC Algorithms Implementation on a Fixed-Point DSP,* PCIM 2002 Power Electronics Intelligent Motion Power Quality, May 12-16, 2002 Nuremberg, Germany, pp.129-135

CIRSTEA M., AOUNIS A., MCCORMICK M. (2002), Rapid Prototyping of Induction Motor Vector Control System Based on Reusable VHDL Digital Architectures and FPGA Implementation, PCIM 2002 Power Electronics Intelligent Motion Power Quality, May 14-16, 2002 Nuremberg, Germany, pp. 199-203.

HAUCK S.(1998) *The Future of Re-configurable Systems Keynote Address*, 5th Canadian Conference on Field Programmable Devices, Montreal, Canada, June 1998.

IMECS Maria, ÁDÁM T., NEDEVSCHI S., VÁSÁRHELYI J., BIKFALVI P. (2000a) *Dynamically Reconfigurable Adaptive Controller for AC Drive Control,* - Proceeding of EPE-PEMC 2000, Košice, Vol. 7, pp. 81-84.

IMECS Maria, BIKFALVI P., NEDEVSCHI S., VÁSÁRHELYI J. (2000b) *Implementation of a Configurable Controller for an AC Drive Control a Case Study*, Proceedings of the Conference on Field Programmable Custom Computing Machines FCCM 2000 Conference, Napa Valley, USA, 16-19 April 2000. pp. 323-324.

IMECS Mária, INCZE I. I., SZABÓ Cs. (2001a), Control Strategies of Induction Motor Fed by a Tandem DC Link Frequency Converter, EPE2001, Proceedings of the International Conference on Power Electronics and Application Graz, 27-29 Aug. 2001. CD-ROM.

IMECS Mária, VÁSÁRHELYI J., INCZE J. J., SZABÓ Cs. (2001c) *Tandem Converter Fed Induction Motor Drive Controlled With Re-Configurable Vector Control System*, Power Electronics Intelligent Motion Power Quality Conference PCIM 2001, Nürnberg, Germany, pp. 341-346

IMECS Mária, VÁSÁRHELYI J., INCZE J. J., SZABÓ Cs.(2001d) *Vector Control Of Tandem Converter Fed Induction Motor Drive Using Configurable System On A Chip,* INES 2001 IEEE International Conference on Intelligent Engineering Systems, Sept. 16-18, 2001, Helsinki-Stockholm, Finland-Sweden, pp. 489-495.

KELEMEN Á., IMECS Maria (1991) *Vector Control of AC Drives.* Volume 1*: Vector Control of Induction Machine Drives*. OMIKK Publisher Budapest, 1991, ISBN 963-593-140-9.

LUK W., SHIRAZI N., CHEUNG P. (1996), *Modeling and Optimizing Run-time Reconfigurable Systems*, Proceedings FCCM96, IEEE Computer Society Press, 1996, pp. 167 – 176.

PÉCELI G., KOVÁCSHÁZY T. (1999), *Transients in Reconfigurable Digital Signal Processing Systems*, IEEE Transactions on Instrumentation and Measurement, Vol. 48, No.5, Oct. 1999, pp.986-989.

SCALERA M. S., VÁZQUEZ R. J. (1998)**,** *The Design and Implementation of Context Switching FPGA*, IEEE Symposium on FPGAs for Custom Computing Machines FCCM 1998, Los Alamitos California, USA, April 15-17, 1998, pp. 78-85.

SHIRAZI N., LUK W., CHEUNG P. Y. K. (1998) *Run-Time Management of dynamically reconfigurable Designs*, Proceedings of Field Programmable Logic and Applications 8th International Workshop, FPL'98, Tallinn, Estonia, Aug. 31 – Sept. 3, 1998, Editors Hartenstein R. W and Keevallik A., Springer, ISBN 3-540-64948-4, pp. 59-68.

TRZYNADLOWSKI A. M., BLAABJERG F., PEDERSEN J. K., PATRICIU Niculina (1998) *The Tandem Inverter: Combining the Advantages of Voltage-Source and Current-Source Inverters*, Applied Power Electronics Conference, APEC'98, Anaheim, USA, pp. 315-320.

TRZYNADLOWSKI A. M., IMECS Maria, PATRICIU Niculina (1999) *Modelling and Simulation of inverter Topologies Used in AC Drives: Comparison and Validation of Models*, ELECTRIMACS'99, Volume I/3, Lisboa, Portugal, 1999, pp. 47-52.

VÁSÁRHELYI J., IMECS Maria, INCZE J. J. (2000) *Run-time Reconfiguration of Tandem Inverter used in Induction Motor Drives*, Proceedings of Symposium on Intelligent Systems in Control and Measurement, Veszprém, Hungary, 2000, pp. 138-143.

VÁSÁRHELYI J., IMECS Maria, INCZE J. J., SZABÓ Cs.*(2002a)*, *Reconfiguration Generated Perturbations In The Vector Controlled AC Drives*, Power Electronics Intelligent Motion Power Quality PCIM 2002, May 12-16, 2002 Nuremberg, Germany, pp. 219-225.

VÁSÁRHELYI J., IMECS Maria, INCZE J.J., SZABÓ Cs (2002b) *Module Library for Rapid Prototyping and Hardware Implementation of Vector Control Systems*, INES 2002 IEEE International Conference on Intelligent Engineering Systems, May 26-28, 2002, Opatija, Croatia, ISBN 953-6071-17-7, pp. 447-452.