TANDEM CONVERTER FED INDUCTION MOTOR DRIVE CONTROLLED WITH RE-CONFIGURABLE VECTOR CONTROL SYSTEM

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Abstract - The paper deals with rotor-field-oriented vector control structures for the induction motor drives fed by the so-called “tandem” frequency converter. It is consisting in two different types of frequency converters in parallel arrangement. MATLAB-Simulink simulation results of the tandem-fed motor with vector control are presented. In different operating mode of the tandem converter the induction motor needs different control strategies. The control structures are presented in a synthesised scheme, which needs reconfiguration depending on the actually working converter topology. The implementation results are analysed from the point of view of efficiency and time delays. The implementation efficiency is considered as the percentage of the used resources. The time delay is defined from pin-to-pin in each module.

1. INTRODUCTION

The *tandem* configuration is a new solution of DC link Static Frequency Converters (SFC) for medium- and high-power AC drives. Two converters of different power range are working in parallel arrangement [9]. 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.

Consequently, using two parallel inverters to supply the motor, it is no more necessary to apply PWM procedure to control the whole energy of the motor, because a large value of it is transferred through the PAM-CSI [5]. In comparison with an equivalent PWM-VSI, the tandem inverter switching losses will be considerable reduced. In fact the tandem converter combines the advantages of the two component inverters, with different source character (current and voltage) and different modulation method (PAM and PWM) [10].
The dynamic behaviour of the AC machines is very improved by vector control procedures based on the field-orientation principle. The necessity of reconfiguration is based on the observation that the performance of the drive is depending on the vector control structure correlated with the type of the supply power frequency converter [7], [11].

In spite on the fact the most part of the motor current is given by the CSI, the behaviour of the tandem converter is like a VSI [4]. That means the motor will be controlled in voltage. If one of the two converters is not working, the control system structure needs to be re-configured in order to be able to control the energy transfer and the motor running.

At low power range the VSI is capable alone to supply the motor, without any help from the CSI. In this case the same control structure can be used. If the VSI fails, the CSI still can run the motor. But the control structure will be changed, because the CSI-fed motor needs a control structure realised directly in current due to the current-source character of the actually working inverter. Consequently, the tandem converter requires different control strategies depending on the component converters, which are actually working.

2. TANDEM CONVERTER OPERATING AND CONTROL PRINCIPLE

Figure 1 presents the induction motor fed by the tandem converter. The PAM-CSI works theoretically with full 120° waves. The PWM-VSI operates with Space-Vector Modulation (SVM), because this procedure is suitable for optimisation from point of view of switching loses in the inverter [6].

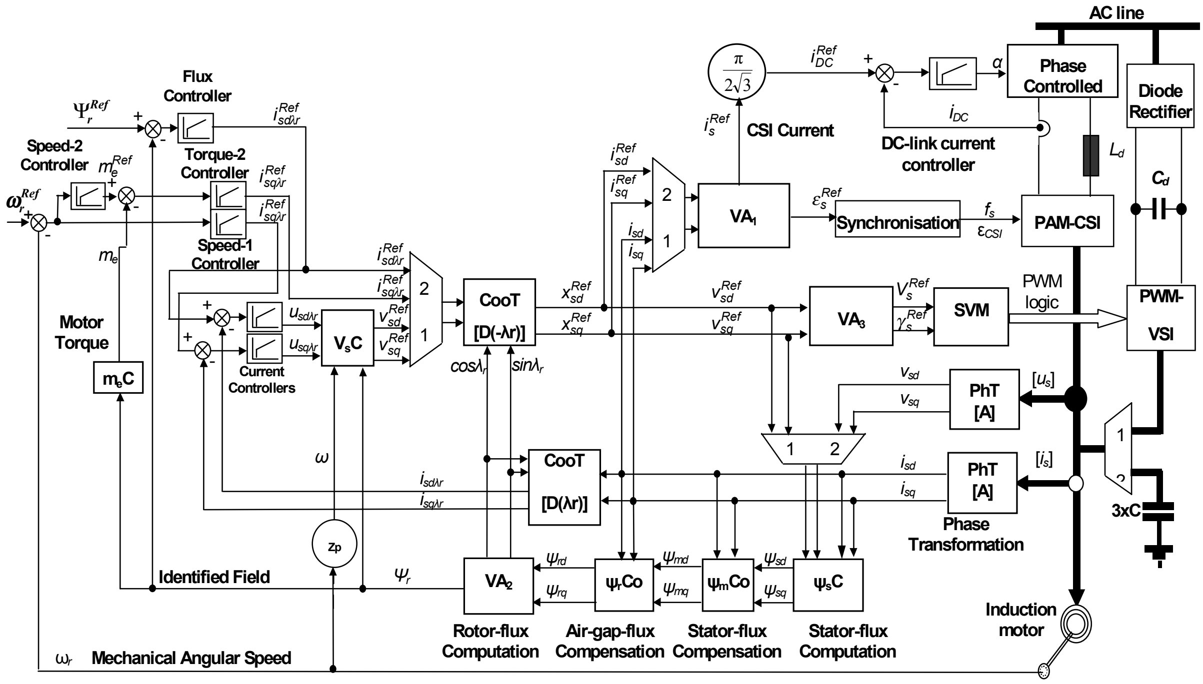

Figure 1. Rotor-field oriented vector control system for the tandem converter-fed induction motor.

The currents of an AC machine should achieve the sine-wave pattern, corresponding to the fundamentals of the three square-wave currents of the CSI. Consequently, the current in a phase of the secondary VSI can be expressed as the output fundamental of the CSI currents minus its square-wave currents in the same phases. The most important aspect of the tandem converter control is consisting of the synchronization in time and in amplitude between the CSI currents with respect to the tandem output ones. The synchronization is made by means of the stator-current space phasor computed in the vector analyser block VA_1 (see Figure 1). The angle ε_S^{Ref} is the position of the continuously rotating reference vector. The space-phasor of the CSI currents has an intermittent motion and it is rotating step-by-step with 60°. Its position ε_{CSI} will be synchronized with the reference value ε_S^{Ref}.

The synchronisation in time and in amplitude of the CSI-currents is realised by means of the switching moments ε_{CSI} (inherently results the switching frequency f_s) and by means of the DC-link current i_{DC}, respectively with respect to the magnitude of the actual stator-current vector. If the synchronization of the CSI is not made correctly with respect to the stator current, the VSI will be loaded excessively by an uncontrolled part of the motor current.

3. VECTOR CONTROL STRUCTURES

Usually for vector control of the induction motor is preferred the resultant rotor-field orientation due to the perpendicularity of the rotor-current and rotor-flux space phasor. The classical part of a vector control structure consists of an active- (speed and/or torque) and a reactive- (flux) control loop. They generate the two field-oriented components of the stator-current space phasor and then they will give the natural two-phase components of the stator current, i_{sd}^{Ref} and i_{sq}^{Ref}, or of the stator voltage v_{sd}^{Ref} and v_{sq}^{Ref}, depending on the current- or voltage-character of the motor control structure, respectively [7].

The field identification is made by integration the stator-voltage equations (using computation block Ψ_sC). In rotor-field orientation it is necessary to compensate the stator-flux d-q components in block Ψ_mCo and Ψ_rCo in order to obtain - first the air gap field and then - the orientation one. The identified rotor-flux components are analysed in block VA_2, which gives the field magnitude Ψ_r and its position λ_r.

Tandem fed induction motor. From point of view of the motor control in the tandem converter the actuator is the VSI. That means in control it becomes the primary converter, in spite on the fact it is working only with the reactive energy, which compensates the output current harmonics in order to improve the quality of the motor currents. That is due to the fact the voltage at the motor terminal in tandem operation mode is given by the PWM-VSI and not by the PAM-CSI, which can be considered primary only from point of view of the transferred energy. The CSI in tandem operation mode cannot control the motor running. It can only to take over the most part of the stator current. But this current in fact is controlled by the control loops realised in concordance with respect to the VSI-fed induction motor.

In Figure 1 the tandem operation mode corresponds to stage 1 and due to the fact the VSI is working, the motor should be controlled in voltage. The current reference variables $i_{sd\lambda s}$ and $i_{sq\lambda s}$ obtained from the flux and speed controllers will generate the field-oriented voltage reference values corresponding to Ohm's law, i.e. $u_{sd\lambda r}$ and $u_{sq\lambda r}$ and using the computation block V_sC the cross-effect is taken into account and results the field-oriented control variables of the motor terminal voltage $v_{sd\lambda r}$ and $v_{sq\lambda r}$, according to the equations, as follows:

$$v_{sd\lambda r} = u_{sd\lambda r} + (-\omega_{\lambda r}\sigma L_s i_{sq\lambda r} + \frac{1}{1+\sigma_r}\frac{\mathrm{d}\Psi_r}{\mathrm{d}t}); \quad (1)$$

$$v_{sq\lambda r} = u_{sq\lambda r} + (+\omega_{\lambda r}\sigma L_s i_{sd\lambda r} + \frac{1}{1+\sigma_r}\omega_{\lambda r}\Psi_r). \quad (2)$$

The electromagnetic cross effect is represented by the expressions in brackets.

Because the VSI is operating with SVM, it needs polar control variables, corresponding to the reference stator-voltage space-phasor, i.e. its module v_s^{Ref} and position γ_s^{Ref}, which are obtained from a vector analyser VA_3.

CSI fed induction motor. If the VSI fails, it is decoupled from the motor terminals and there will be connected 3 filtering condensers. In this case the CSI will supply alone the motor represented by stage 2 in Figure 1 and the inverter currents are synchronized with respect to the control variables of the stator-current d-q components. This control structure is much simpler than that of stage 1 due to the fact the CSI is directly controlled with current variables and there are no more needed current controllers and cross-effect computation. The rotor-field orientation is very suitable because the computation of the control variables, in such a case, is not affected by the motor parameters.

The field identification is made in the same way, but it needs also reconfiguration because in stage 2 the stator voltage is measurable directly on the motor terminals (due to the PAM operation mode of the CSI), instead to be computed, as was before in stage1, during the PWM operation mode.

4. SIMULATION RESULTS

The simulation was performed for the control scheme in Figure 1 Stage 1 (i.e. tandem operation mode) in MATLAB-Simulink environment. The motor data are: 5.5 *kW*, 50 *Hz*, 220 *V r.m.s.* 14 *A r.m.s.* and 4 pole-pairs. Figure 2…7 shows the simulation results for the same running of the motor. The drive was started unloaded and then it supports a load step.

The obtained results confirm the performance of the vector control system based on the rotor-field orientation for the tandem-fed induction motor. It confirms also the supposition, that the motor must be controlled in voltage by means of the VSI (taking into account the cross-effect) and not in current by means of the CSI, if it is supplied in parallel arrangement by two different type inverters.

5. RECONFIGURABLE CONTROL (5)

Reconfigurable systems, often called „Custom” or „Adaptive” [1], [13], [14], are those computing platforms, whose architecture is modified by the software to suit the application at hand. That means within the application program a software routine exists, that downloads a digital design directly into the reconfigurable space of the system. Reconfiguration can be applied when the changes in the system parameters demand a much more effective control law and no adaptive control facilities are implemented.

Flexible reconfigurable platform support, such as FPGAs (Field Programmable Gate Array) and CSoC (Configurable System On a Chip) with its flexible structures, can implement the desired re-configurable control system for AC drives under the conditions defined in [3]. These conditions refer to the demands, what have to be accomplished by the hardware in order to make possible the reconfiguration.

Applying the *reconfigurable system concept,* introduced in [3], for the vector control system, the same hardware support, which implements one control system structure, can be used also to switch to another one.

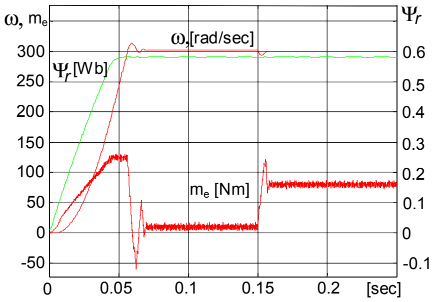

Figure 2. Speed and torque diagram for motor starting and load perturbations.

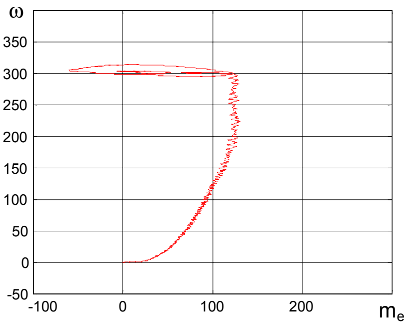

Figure 3. Mechanical characteristics of the induction motor.

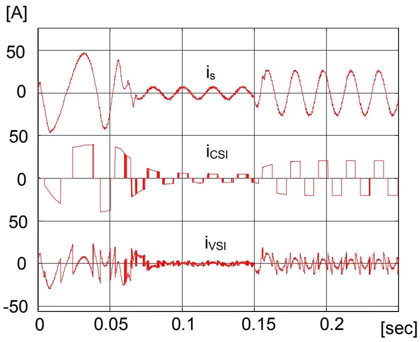

Figure 4. Time diagram of the tandem inverter output currents.

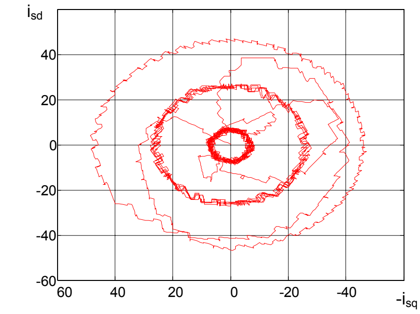

Figure 5. The space-phasor diagram of the stator currents.

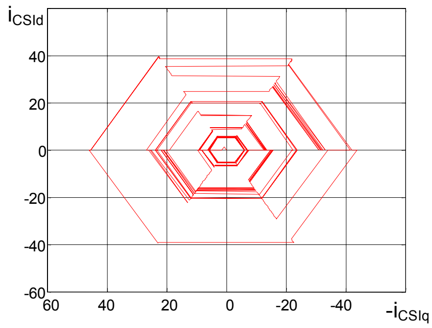

Figure 6. Space-phasor diagram of the PAM-CSI output current.

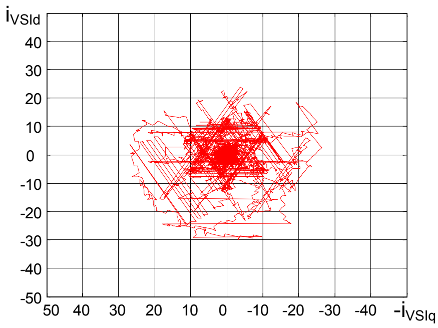

Figure 7. Space-phasor diagram of the PWM-VSI output current.

Each control system structure can be seen as a distinct state of a logic state machine (Figure 8) as it was sated in [11]. The transitions from one logic state, i.e. one control system structure, in other words from one hardware configuration, to another control system structure, i.e. another hardware configuration. The change can be determined by the value of the state variables of the controlled system. If a transition condition occurs, (i.e. the motor speed reference transits a limit value or the control system detects fault in the sensors or any other imposed condition) the need for reconfiguration is fulfilled and the control system will start a self-reconfiguration process. This will change the control system structure automatically.

The conditions, which determine the start of the reconfiguration, are various and depend on the application on hand. The tandem vector control system should be reconfigured if the VSI fails as the control structure looses its voltage-controlled character and the current control concept gains importance. This justifies the need for reconfiguration.

Luk in [8] has presented the two types of possible reconfiguration models - i.e. partial or total reconfiguration. The method to be used in the implementations is: *total reconfiguration* for the CSoC and *partial reconfiguration* for the FPGA hardware support.

For technological reasons, during the research process the *total reconfiguration* model was chosen, which reconfigures the control system as a whole. The basic idea is straightforward:

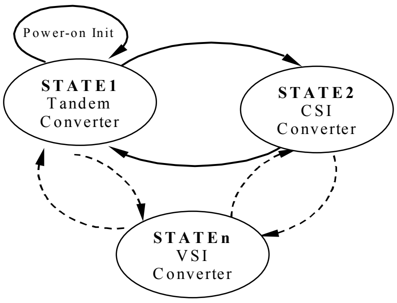

Figure 8. Principle block diagram of total reconfiguration procedure.

After power-up the control system of the AC drive, which works as ‘tandem converter’ (state 1 of the state machine), when the VSI fails will be reconfigured to work as CSI converter (state 2 of the state machine). A possible representation of the transition from one state to the other, in fact, may be a demultiplexer and a multiplexer. 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.

The two schemes are working in parallel, so the reconfiguration really is switching between the two control system schemes. The switching between the two configurations was named “ping-pong” reconfiguration.

6. IMPLEMENTATION PROBLEMS

The control of the actuators, represented by the AC motor together with the SFC and the electrical and mechanical sensors assembly, impose real-time performance of the control system algorithm. Also one may conclude that decreasing the sampling period the control system can perform better. On the other hand, decreasing the sampling period, this can impose very short reconfiguration time.

Considering that the AC motor should not be left without control, the reconfiguration time have to be less equal then the sampling period of the control system: $t_{reconfiguration} < T_{sampling}$.

The main problem of the reconfigurable control system is not the criteria mentioned above, as the transition can be done in real time if the control system detects the variation of the mechanical angular speed (ω_r) caused by the fail of the VSI. The core of the CSoC, which supervise the control system, is doing also a threshold observation of ω_r.

Clock: XTAL

Summary

Start Pin	End Pin	Total Delay (ns)	Details
Ib.0_INLATCH.g	Sin_I.0_OUTREG.d	614.361	X

Details

Ib.0_INLATCH.g --> Ib.0_INLATCH.q delay=2.197 ns
Ib.0_INLATCH.q --> M2q.MULT_Y0_X0_M.x delay=15.112 ns
M2q.MULT_Y0_X0_M.x --> M2q.MULT_Y0_X0_M.co delay=2.922 ns
M2q.MULT_Y0_X0_M.co --> M2q.MULT_Y0_X1_M.ci delay=1.174 ns

CSL Resource Utilization

	Total CSL Cell Count	Used CSL Cell Count	Percentage Used
CSL Cells	2048	1147	56.0%

CSL cells each contain one LUT and one DFF. CSL cells are counted as used if either or both of these are in use.

Resource Type	Available Resource Count	Used Resource Count	Percentage Used
LUT	2048	1113	54.3%
DFF	2048	0	0.0%
PAD	227	82	36.1%
SELECT	128	0	0.0%
GBUF	6	6	100.0%

Figure 9. Time delay in the CSoC and resources used for implementation of **VA**s.

The performance of the implemented modules and the consumed hardware resources are different, depending on the type of the chip (FPGA and CSoC). As the implementation process uses the method called hardware-software co-design, there were implemented in both type of chips the same modules, in order to decide, which is performing better and which occupies less hardware resources since the structure of the CSoC Configurable System Logic (CSL) is slightly different from the FPGA Configurable Logic Block (CLB).

Analysing the structure of the vector control system presented in Figure 1 one can conclude that the system is modular. Implementing each module such as the Phase Transformation {PhT[A]}, the Coordinate Transformations {CooT[D(±λ)]}, the PI Controllers, etc. an universal module library can be created. Using this library one may easily design any other vector control system.

One of the most resource-consuming module is the Vector Analyser (VA), which computes the equations:

$$g = \sqrt{g_q^2 + g_d^2};\ \sin(\lambda) = \frac{g_q}{g};\ \cos(\lambda) = \frac{g_d}{g}; \quad (3)$$

As is shown in Figure 9, the VA implementation in the CSoC occupied 1068 CSL cells before binding operation and after there were 1147 CSL cells used, which unfortunately is 56% of the available 2048 CSL cells and the worth path delay is: Path Delay = 614.361 ns.

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Device utilization summary:

  Number of External IOBs        50 out of 224    22%
    Flops:                  0
    Latches:                0

  Number of CLBs               288 out of 784    36%
    Total Latches:           0 out of 1568      0%
    Total CLB Flops:       543 out of 1568     34%
    4 input LUTs:          151 out of 1568      9%
    3 input LUTs:          193 out of 784      24%

The Number of signals not completely routed for this
design is: 0
The Average Connection Delay for this design is:
                                                  5.384 ns
The Maximum Pin Delay is:                        42.090 ns
The Average Connection Delay on the 10 Worst Nets is:
                                                  8.730 ns
```

Figure 10. FPGA resources used in the SQRT function implementation and time delays.

When FPGA chips are used for implementation only the square root operation resources allocated and the time delays of this operation are shown in Figure 10, which shows a little bit better results. But the implementation of the VA as a whole presents similar rates on lower density members of the FPGA chips.

7. CONCLUSIONS

The tandem converter combines the advantages of the current- and voltage-source inverters.

The implementation results show that the algorithms are very intensive resource consuming, but very fast with short delay times.

There is need for intensive analyses on the algorithm partitioning. The hardware-software co-design process should consider which module has to be implemented finally in the CSL, and which in the FPGA and which module should be implemented as software.

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