DSP-Based Controller For Direct Torque Control Of Induction Motor Drives In Railway Traction System

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Abstract - *This paper presents the implementation of Direct Torque Control (DTC) on a highly flexible Digital Signal Processor (DSP)-based controller. The flexible structure of this controller permits implementation of control techniques for induction motor drives in railway traction systems. The flexibility is given by a modular structure, i.e. the controller can be adapted to the requirements of the current control algorithm. First a description of the system is given, and finally the implementation of the classic DTC algorithm on the system is presented. The DTC will be applied to a Simulator of traction bogie for high-speed system.*

I. INTRODUCTION

To achieve requirements of traction operators, traction drive control systems have become significantly more complex involving the careful integration of microprocessors, power electronics, machines and transmissions. In particular much attention is being focused on accurate tractive effort profiling and speed control, and high adhesion [I].

In the field of traction electrical drive systems a great interest is devoted to develop highly integrated compact systems in order to satisfy, essentially, features like better dynamic performances and parameter adjustments for different mechanical loads. The development that DSP have had in the last years makes it feasible the design and realisation of particular flexible electric drives. Thus, an accurate control of the drives is possible, in order to make the output quantities of electric motors always fully satisfying the load operating conditions and the required performance values.

Since the availability of powerful DSP, the current high performance drive systems are usually digitally controlled, since these processors allow more accuracy and more flexibility. Modern state of the art digital control systems are characterised by a flexible hardware architecture and a powerful processor. This processor has to be capable of making calculations quickly and with a high accuracy. DSP, which are especially designed for these tasks, can be considered as the keys to success in advanced power electronics, nowadays.

The modularity and flexibility of the DSP controller proposed in this paper allow a lot of freedom in implementing new control and test algorithms. The Direct Torque Control method proposed by Depenbrock (Direct Self Control DSC) [2] and the method proposed by Takahashi and Noguchi [3] are appropriate for solving the problems of dynamic performance of three-phase AC drives in railway traction systems because of their short response times [4,5]. Both methods are oriented by the instantaneous

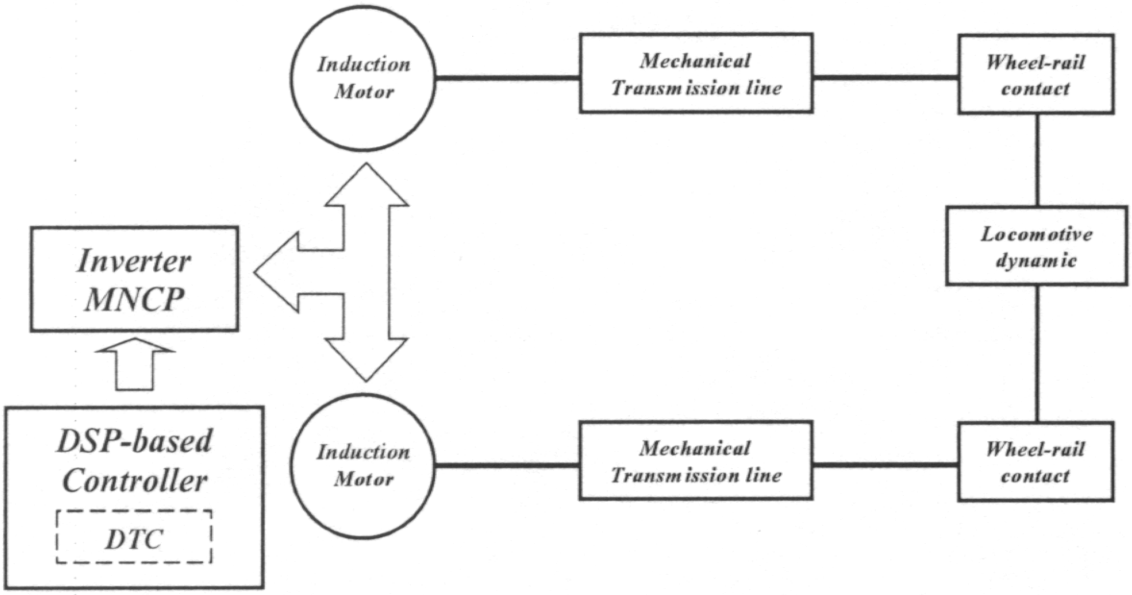

Figure 1. Traction drive system scheme.

values of torque and stator flux of the motor. The outputs are the switching commands for the inverter without using interfaces for generating pulse patterns.

A DSP-controller has been set up for DTC implementation, experimental test are presented in the paper.

II. RAILWAY TRACTION SYSTEM

The considered high power physical system is mainly constituted of two squirrel cage induction motors, both supplied by a voltage source inverter, driven by digital control unit (Fig. 1). These motors drive a mechanical transmission line, which creates driving forces through a wheel/rail contact law. The locomotive dynamics is common to both motors and creates a mechanical link between the two motors. The power converter is a classical Voltage Source Inverter supplied by a voltage source DC link. In the paper it has been proposed, as reference for our studies, the main electrical and mechanical structure of the most recent generation of Italian Locomotive for high-speed lines, ETR500.

The ETR500 consists of two Motorcars and eleven Trailer cars. One motorcar has two sets of bogie, and one bogie has two wheel-sets, that is, two motors. Table I shows typical specifications of ETR500.

Table I. Main Features of ETR500.

Train mass	598 [T[
Maximum speed	300 [kW/h]
Continuing rating at rim	8800 [kW]
Axle mass	17 [T]
Diameter of wheel	1070 [mm]
Gear ratio	2.54
Propulsion system	Inverter + Induction Motor

The locomotive of ETR500 is a B0 type characterized by electric motors and the reduction gears directly suspended to the body frame; this solution was adopted in order to obtain a high critical speed and reduced dynamic wheel-rail actions, by reducing the weight of each single suspended part of the truck. In order to realize this solution a new type of homokinetic transmission has been designed, connecting the reduction gear and wheel set, which enables higher axial and radial movements. The transmission of the motions consists of two coaxial hollow shafts, united by means of rods (together forming a dancing ring), to two flanges one of which is splined to the output shaft of the reduction unit and one, on the opposite side, to the axle. An elastic spacer, which allows small angular shifts between the shafts, is placed between the two shafts; these shifts make the articulation of the dancing ring kinetically possible with the consequent possibility of reciprocal shifting between the assembly of hollow shafts and axle. The adopted solution was specifically studied so as to allow the transmission to absorb the relatively ample shifting between the motor gear unit assembly and axle, since the former is directly connected to the body frame.

Both propulsion and locomotive control systems correspond to the standard MICAS-S2. The MICAS-S2 is a microprocessor control system for traction, decentralized, with multiprocessor data bus. The type of control employed for traction converter, "Direct self control" controls the motor couple and speed. So a better dynamic answer in terms of torque is obtained.

The converter consists of a single inverter stage, that uses GTOs connected according to the "three level" diagram, or NPC (Neutral-Point-Clamped). This connection permits to have a lower harmonic content than two level design. With NPC type inverter, in fact, five output line voltage levels may be obtained.

In order to simulate the dynamic system represented in Fig. l, we have reproduced the electrical and mechanical part of ETR500 by means of the designing of a scale model presented in next section.

A. Simulator ETR500

We have designed and realized a simulator to reproduce, in detail, the same mechanical structure of transmission of the ETR500 bogie. In particular we want to reproduce the mechanical torsional oscillations in order to study the interaction between the external forces, e.g., electromagnetic force, friction forces, and internal forces like elastic torques. For this purpose it is necessary to ensure dynamic resemblance between the real system and the simulator. In fact the criteria of reduction is based on the reproduction of the same characteristic frequencies (eigenvalues). The table II shows the main features of the simulator.

Table II. Main Features of Simulator.

Translating mass Energy	215 [kJ[
Nominal angular speed of driving wheel	600 [rpm]
Rating Power of Induction motor	5.5 [kW]
Maximum torque applied to transmission system	100 [Nm]
Diameter of driving wheel	480 [mm]
Gear ratio	2.54
Scale coefficient	200
Range frequency of interest for mechanical oscillation	[0…200 Hz]
Propulsion system	Inverter + Induction Motor

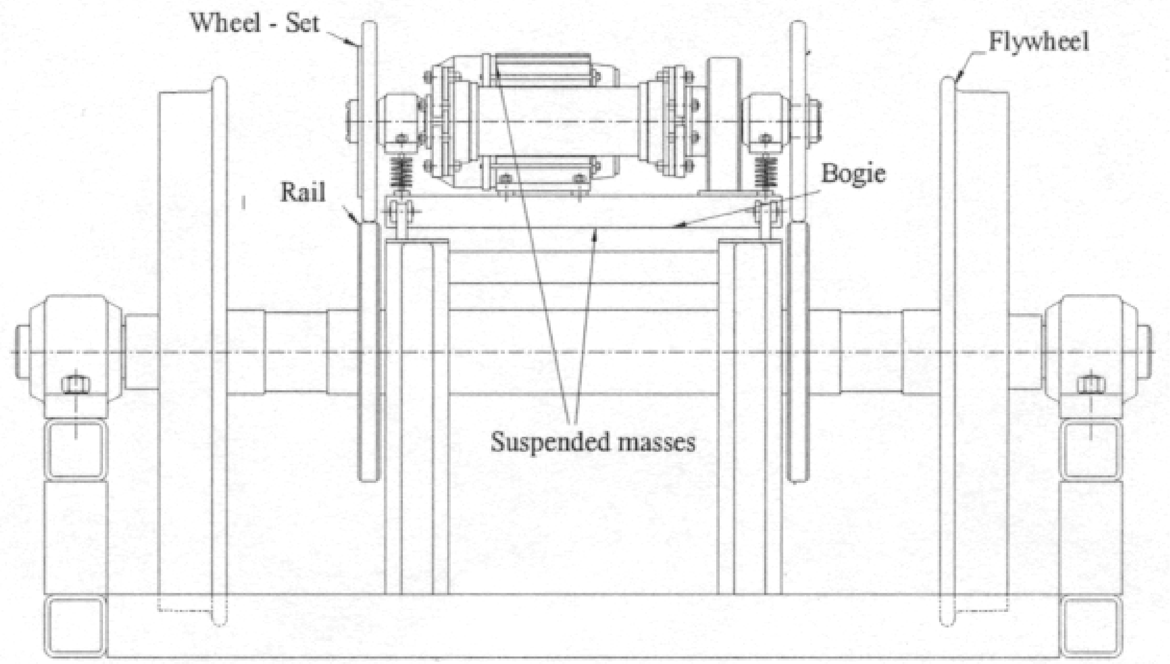

Figure 2. Front view.

The simulator mainly is composed of a mechanical transmission unit (motor, gearbox, wheel-set) as shown in Fig. 2, fixed on a mobile frame and four wheels set on a rigid axle. The transmission and the mobile frame lean on a couple of wheels by means of a wheel-set, which represents a pair of driving wheels of the locomotive. In order to obtain different touching forces between the pairs of contacting wheels there has been added a mass fixed on the mobile frame (Fig.3). The flywheels represent the inertia of translating masses, which is proportionally direct to the mass of the real train.

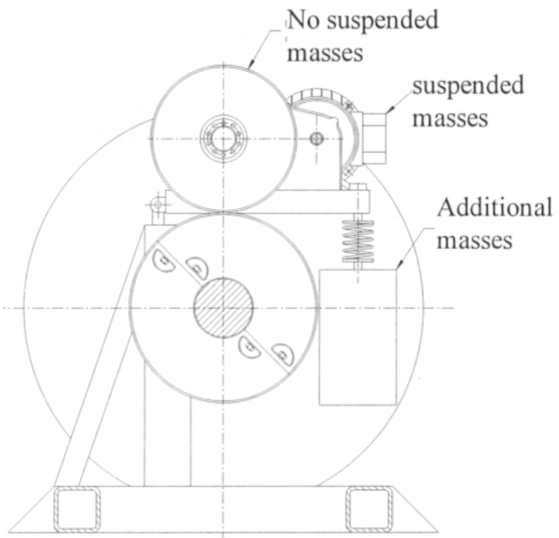

Figure 3. Side view.

The simulator is also composed of two additional spoke wheels in case it is necessary to simulate the elasticity of the rail. The propulsion system consists of inverter and induction motor. The motion resistances are simulated by an air-brake, which gives rise to a braking force independent of the speed, and by a DC generator, feeding ballast resistances, which gives rise to a force linearly dependent on the shaft speed.

B. DSP-based Controller

The system presented in this paper is controlled by a Digital Signal Processor (DSP) TMS320C30.

The flexibility of the DSP-controller can be found in the modular structure of the total system that is constituted mainly by the DSP-based motherboard, directly connected to a data-bus accessible by a back plane. This back plane is the flexible connection to the different modules, in particular, there are: two analogue to digital converters cards, two digital to analogue converters cards, a digital interface card, an encoder card, a PWM card and an hysteresis current regulated PWM card (Fig.4).

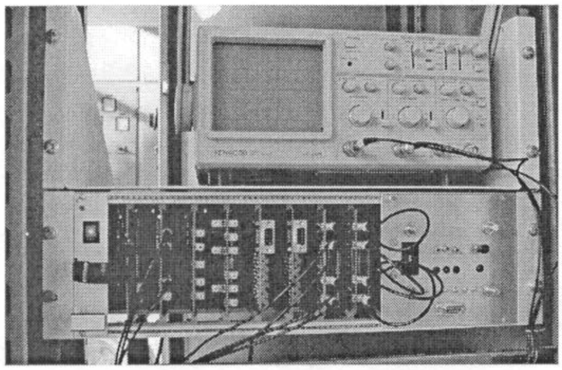

Figure 4. View of a DSP-system.

The DSP has a clock frequency of 40MHz and a cycle time equal to 50 ns. The most interesting feature is its two external data-buses. One bus (primary) is dedicated for a fast I/O-control with for instance memory, which is located near the processor. The expansion bus will be used for the communication with the peripherals and is therefore directly connected to the back plane. Figure 5 shows the overview of the DSP-system, with different buses.

For the conversion of the analogue quantities, 12 bit A/D converters are used, they are characterised by a fast and parallel conversion (every analogue input signal is converted in 2.7 μS).

The PWM/Digital (on/off) card contains 6 independent PWM outputs, or 6 independent digital outputs. This card is especially designed for power electronics applications. During the initialisation section of the DSP, into a special register is written which output is desired: Pulse Width Modulation, Digital (on/off), or hysteresis current regulated PWM.

To optimize a control algorithm for drive traction system it is necessary to study the nature of the load. The load can be investigated i.e. through the interaction between torsional oscillation of all

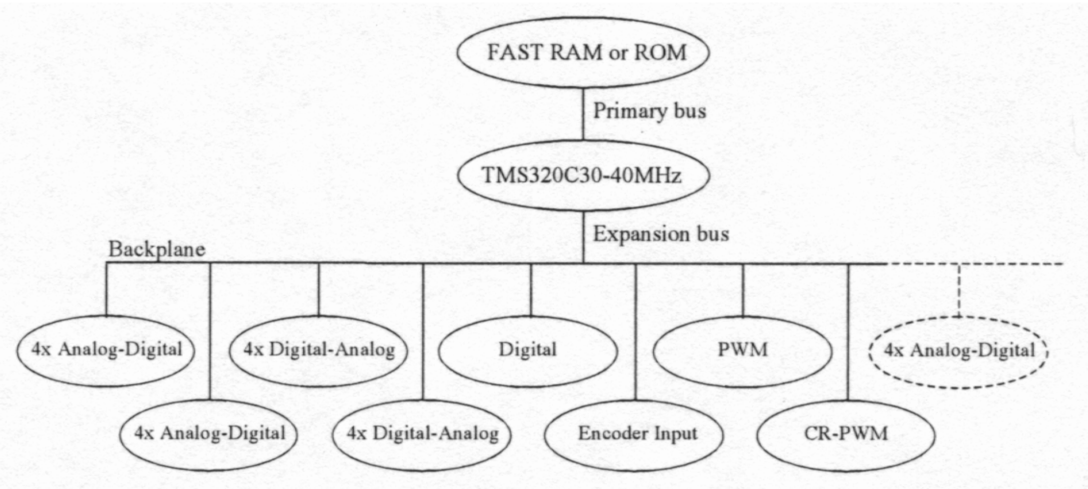

Figure 5. The overview of the flexible real-time DSP-system.

components of motion mechanical transmission and the friction force during skidding phenomena. Therefore the DSP-controller will be utilized as part of a complete system that includes a scale-model of the train. By means of this simulator the dynamic behaviour of railway traction system may be simulated and all the significant quantities may be detected.

III. DTC IMPLEMENTATION

Nowadays, the Direct Torque Control method (DTC) [2,3] is already widely applied, especially in the field of electrical traction. DTC, which is a true competitor of Field Oriented Control, is characterised by its fast torque response and its simple implementation. Furthermore, the algorithm takes care of a low switching frequency, which is still desired in high power applications. However, due to developments in the field of power semiconductors, new DTC-strategies based on a high torque performance have been introduced in literature [6,7]. It is evident that these strategies will require higher switching frequencies. The DTC algorithm selects the most convenient voltage space vector from a look-up table, based on the actual flux and torque values. The stator flux is described by the stator equation:

$$\mathbf{v}_s^s = \dot{\boldsymbol{\psi}}_s^s + \mathbf{r}_s \cdot \mathbf{i}_s^s \tag{1}$$

wherein the voltage and current space vectors are calculated with:

$$\mathbf{v}_s^s = \begin{bmatrix} \mathrm{v}_s^{s1} \\ \mathrm{v}_s^{s2} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{1}{2}\sqrt{3} & -\frac{1}{2}\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} \mathrm{v}_{sa} \\ \mathrm{v}_{sb} \\ \mathrm{v}_{sc} \end{bmatrix} \tag{2}$$

and

$$\mathbf{i}_s^s = \begin{bmatrix} \mathrm{i}_s^{s1} \\ \mathrm{i}_s^{s2} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{1}{2}\sqrt{3} & -\frac{1}{2}\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} \mathrm{i}_{sa} \\ \mathrm{i}_{sb} \\ \mathrm{i}_{sc} \end{bmatrix} \tag{3}$$

respectively.

The torque of an induction machine will now be described by:

$$m_{el} = \frac{3}{2} \cdot p \cdot \left[\mathbf{R}(\pi/2) \cdot \boldsymbol{\psi}_s^s\right]^T \cdot \mathbf{i}_s^s \tag{4}$$

The actual flux and torque values, given by the previous equations, are compared with their reference values on the hand of a two-level and a three-level hysteresis comparators, respectively. The outputs of these comparators, λ_ψ and λ_ψ for flux and torque, respectively, with the section where the actual flux is located form together the input values of a predefined look-up table [3,8]. The DTC algorithm is based on the control of the flux on the basis of the stator equation. After neglecting the ohmic voltage drop in (1), there remains:

$$\dot{\boldsymbol{\psi}}_s^s = \mathbf{v}_s^s \tag{5}$$

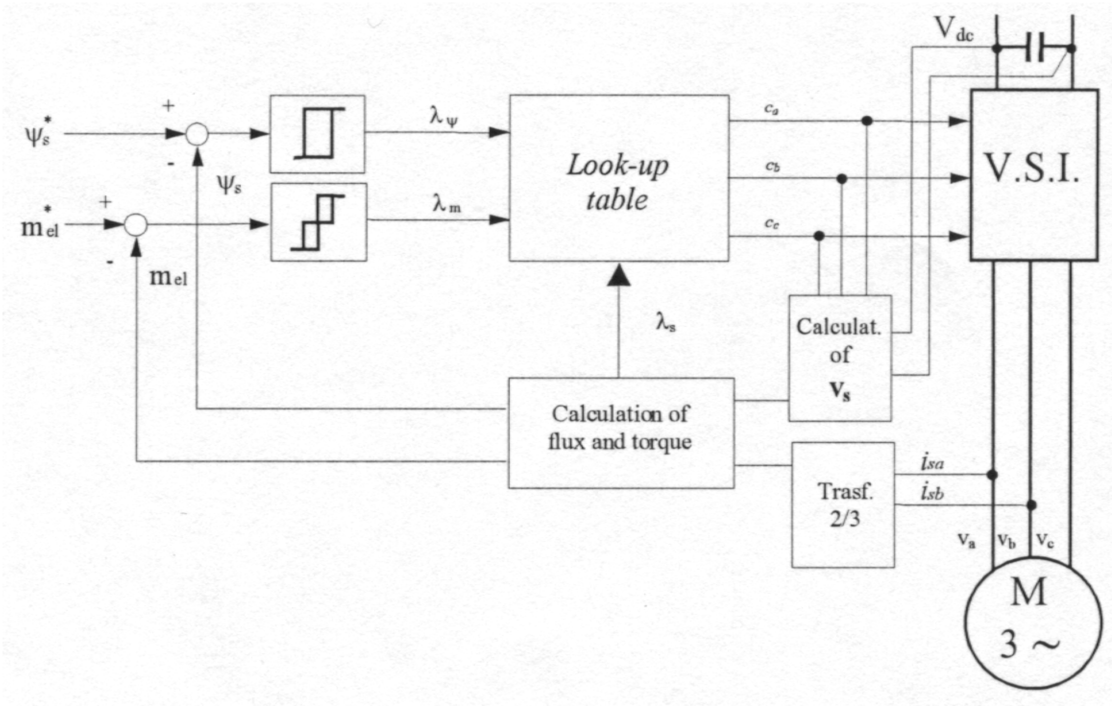

Figure 6. The overview of the direct torque controlled system.

which will imply that the flux will tend to follow the direction of the applied stator voltage.

IV. EXPERIMENTAL RESULTS AND NEXT APPLICATION ON SIMULATOR

Figure 6 shows the overview of the total drive system. The stator voltage space vector is calculated from the DC-link voltage and from its actual position [6].

The algorithm is implemented on the DSP-system and it requires just 19 μs. Extra computation time is needed for visualising some variables in real-time on the oscilloscopes and for writing variables directly into the memory of the DSP. Therefore the sampling time of the control is taken to 50 μs, which means a sampling frequency of 20 kHz. As known the switching frequency of the inverter will be at least below half of the sampling frequency and depends on the different bands of the flux and torque comparators.

Figure 7 and Fig. 8 show different machine's quantities for different hysteresis bands. The flux and the torque bands of Fig.8 are narrower and this implies higher

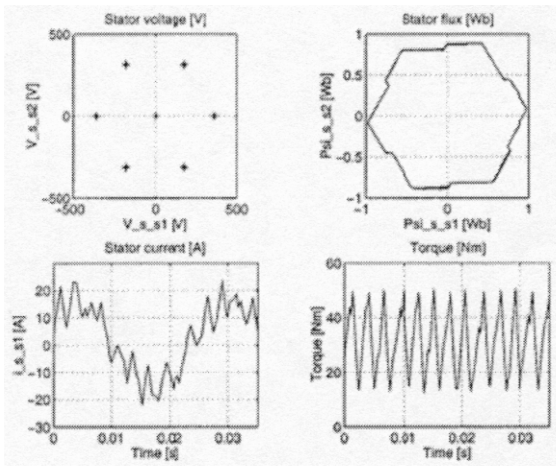

Figure 7. The different machine's quantities for specific bands of the torque and flux comparators.

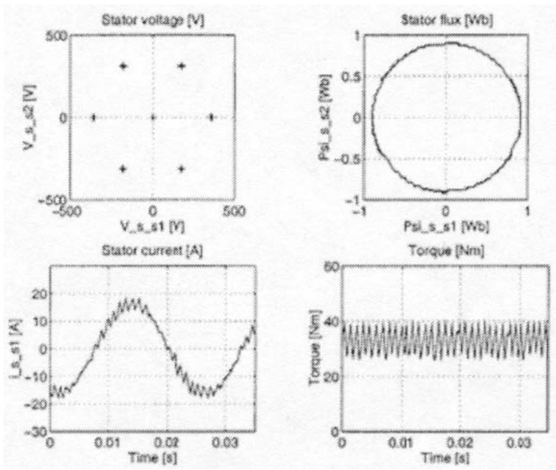

Figure 8. The different machine's quantities for specific bands of the torque and flux comparators.

switching frequencies, which can clearly be noticed on the quality on line current. After that the response on an inversion in the reference torque is observed, see Fig. 9. We are using the voltage/current model for observing the flux, that is the reason why the machine passes frequency zero with a small problem, since the estimated stator flux in the vicinity of frequency zero will not be valid. However, the decline in the flux level due to the so-called "demagnetization problem" can be observed [6].

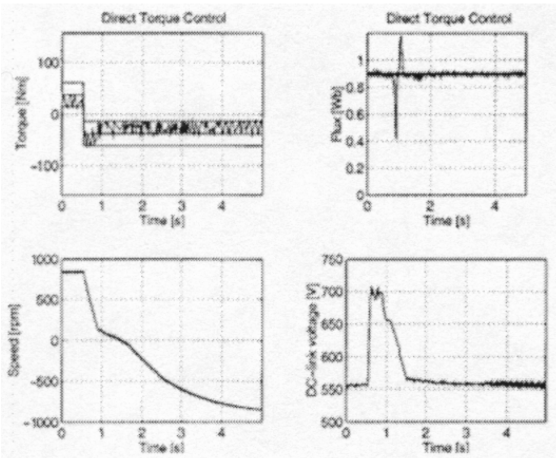

Figure 9. The response on an inversion in reference torque.

The next step is to set up an anti-slip control adjusted on the mechanical simulator described in the previous section.

The ideal drive control maintains the force transmitted from wheel to rail without transients. The drive control includes the elasticity of mechanical drive and dynamics of the power converter. The main control task is to guarantee transmission of the required torque to the rails, maintaining the stability of the system. Considering the poorly damped wheel shaft, the control system has to provide active damping of oscillations by increasing the damping. The difficulty lies in the absence of sensors that measure the wheel speed, so the traction control is based on motor control.

The purpose of the control strategy is to keep the force between wheel and rail near the maximum of adhesion and to prevent the slip-stick oscillations. To drive a motor at a certain slip velocity, where adhesive effort has the maximum value, the peak point of adhesive effort has to be known [10]. The derivative of adhesive effort, F, with respect to the slip velocity, a, is as follows:

$$\frac{dF}{d\sigma} = \frac{dF}{dt} \Big/ \frac{d\sigma}{dt} = 0 \qquad (6)$$

However, it is difficult to utilise the derivative of the slip velocity because the resolution of the speed sensor is very low and the derivative of slip velocity is very sensitive to measurement noise. In (6), the derivative of adhesive effort with respect to slip velocity

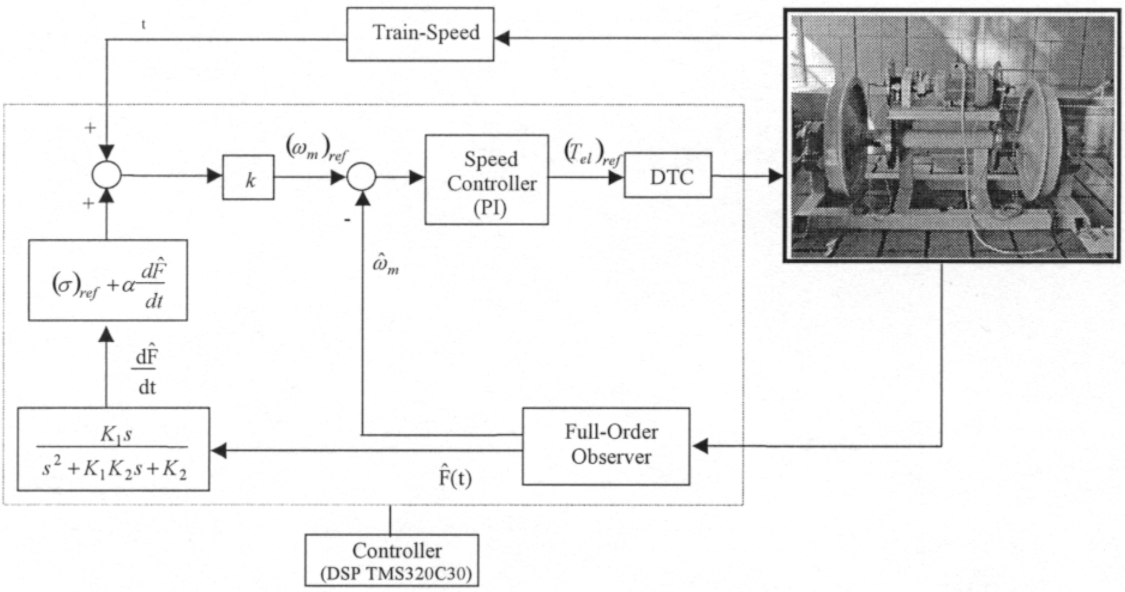

Figure 10. Block diagram of control strategy for ETR500 simulator.

is zero if numerator is zero. Thus, the reference of slip velocity is as follow:

$$\left(\sigma^{k+1}\right)_{ref} = \left(\sigma^{k}\right)_{ref} + \alpha \frac{d\hat{F}}{dt}$$

$$\frac{dF}{d\alpha} = \frac{dF}{dt} \Big/ \frac{d\sigma}{dt} = 0.$$

where α is positive constant, which makes the slip velocity stay at the peak point of adhesive effort. The reference of angular velocity is as follows:

$$\left(\omega_r\right)_{ref} = k\left[v + \left(\sigma^{k+1}\right)_{ref}\right]$$

V. CONCLUSIONS

A highly flexible DSP-controller has been set up and has been utilized for the implementation of control technique for induction motor drives in railway traction systems application.

The DSP-controller has been integrated in a complete system that includes a scale-model of ETR500 train. By mean of this simulator the dynamic behaviour of the railway traction system may be simulated and all the significant quantities may be detected.

The classic DTC algorithm can be applied to a Simulator of traction bogie. This control technique is particularly appropriate for solving the problems of dynamic performance of a three-phase AC drive in railway traction systems because of their short response times.

Experimental results have been presented and discussed evidencing the good response on inversion in reference torque.

To optimize the control algorithm is necessary to study the nature of the load, therefore as an example an anti-slip control adjusted on the mechanical simulator is proposed.

VI. LIST OF SYMBOLS

Quantities:

c	Control signal of inverter
f	Frequency
i	Current
p	Number of pole-pairs
v	Voltage
m	Torque
r	Resistance
V	Voltage
λ	Output of a hysteresis comparator
ψ	Flux

Subscripts:

a, b, c	Stator phases
el	Electromagnetic
m	Torque
s	Stator
ψ	Flux

Superscripts:

s	With respect to stator coordinate axis
s1	Direct axis of the stator reference
s2	Quadrature axis of the stator reference

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