Model of Parallel-Connected Multiple Induction Motors for HIL simulation of railway anti-skid-anti-slip systems

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SUMMARY.
In this paper a scaled roller rig for HIL testing of safety relevant railway sub-system is shown. The rig, completely designed by authors will be installed in the new laboratory of Mechatronics and Modeling of Dynamical Systems (MDM) of Pistoia. The design of the proposed solution is quite innovative respect to existing solutions since degraded adhesion conditions are simulated through Hardware in The Loop Simulation (HIL). Simulation of degraded adhesion conditions is quite useful for fast prototyping and testing of safety relevant on board railway subsystems which interact with axles dynamics: for example traction controls, WSP (wheel slide protection systems), odometry boards for ATP/ATC systems, innovative active/semi-active stability-steering controls.
In order to perform such simulations also the scaled bogie used on the rig has to be designed to reproduce the behaviors of traction and braking systems which interact with axle dynamics when degraded adhesion occurs. The actuation system has to be designed, in order to be as much customizable as possible, in order to simulate different vehicle and plant layout. In particular in this paper the attention is focused on the design of the scaled bogie that will be used to simulate the behavior of E404 the locomotive of ETR 500 Italian high speed train which is equipped with parallel connected induction traction motors, a solution that is quite common on both high speed and standard railway vehicles.

1 INTRODUCTION

The use of Hardware in The Loop techniques to simulate degraded adhesion conditions is a very fashionable matter, since this kind of tests are quite expensive and not very repeatable on real railway lines in which the adhesion has to be degraded using water based contaminants solutions that have to be applied and then removed from the line once the test has been concluded. Contaminants are usually distributed on the lines by injectors placed on the tested vehicle or manually using particular devices as visible in figures 1.
The physical reproduction of degraded adhesion conditions on roller rigs using contaminants is not feasible, since if heavy sliding occurred rolling surface of the rollers could be damaged or worn causing an unacceptable increase of costs and a reduced availability of the plant. Furthermore both on track and on roller test rig the simulations of long slidings conditions with prolonged and deterministic testing conditions is quite impossible.

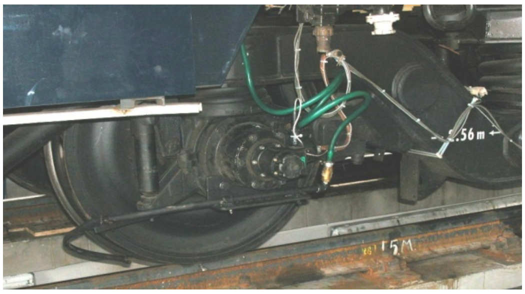

Figure 1/a: wheel rail injector used to pump water based contaminants solutions during degraded adhesion tests

Figure 1/b: special device used to speed up the manual applications on contaminants on rail surfaces to perform WSP testing according UIC 541-005[1,2]

For these reasons in the railway research center of Firenze Osmannoro, an innovative full scale roller rig with Hardware In the Loop simulation of degraded adhesion conditions has been designed and is currently in the realization phase. The railway research center of Firenze Osmannoro is a structure financed by the Italian government which SIMPRO SPA is building on the basis of ther specifications requirements [3] developed by the synergistic cooperation of Trenitalia SPA and many Italian research group with the supervision of RFI SPA. In figures 2 a simplified scheme taken from some preliminary studies done by University of Florence are shown

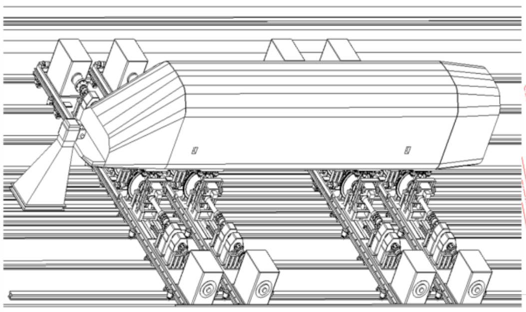

Figure 2/a: preliminary design of the full scale roller rig of Firenze Osmannoro, (picture taken from some preliminary studies of University of Florence of the year 2002)

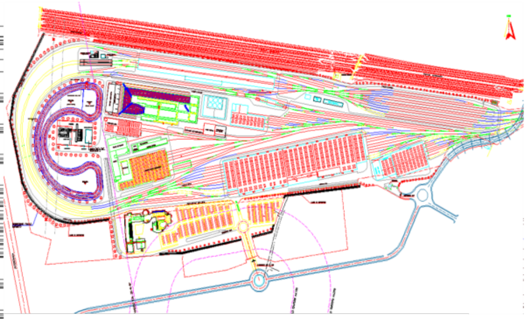

Figure 2/b: layout of the future Osmannoro Research center (Florence, Italy)

Since the costs and investments involved in the building of the full scale roller rig are significant, actuation and control system used for the rig has to be carefully designed and calibrated.
Some simulations of the proposed systems have been previously performed on models developed and the obtained results have been published [5,6], however the importance of the proposed applications and the difficulty to simulate complex interactions between many mechatronic sub-system, sensors and actuators justified further investment in the design of a scaled version of the rig that will be used to speed up the prototyping of the control algorithms and models that will be used on the full scale test rig of Firenze Osmannoro. Once the scaled rig will complete this first task it will remain to the MDM Lab as an important tool for research and didactics activities for the mechanical engineering faculty and the specialization courses concerning railway vehicle

simulation and design. A simple scheme of the proposed test rig is shown in figures 3: an half vehicle model, a bogie with an half of the carbody, is simulated. The reference vehicle is the E404 loco, the scaling factor is 1:5, the scaled bogie is mounted on a roller rig that has been designed using a scaled version of the same motors, power electronics and sensors that will be used on the full scale one.

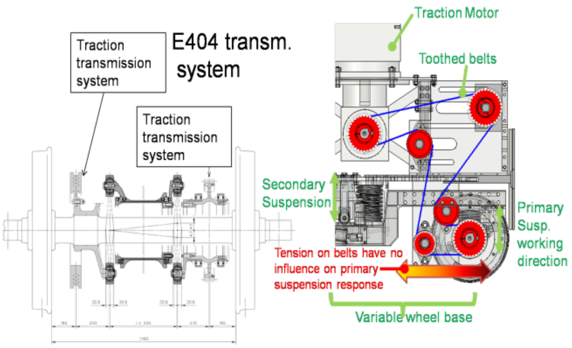

Figure 3/a: comparison between the transmission of an existing locomotive and the solution proposed for the test rig

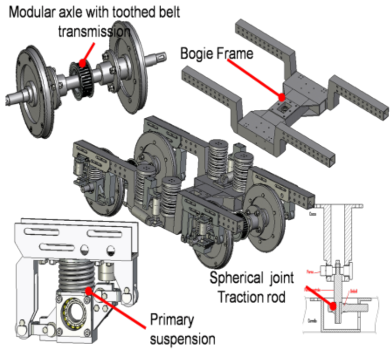

Figure 3/b: design of the scaled bogie with details of primary suspension, traction rod, bogie frame

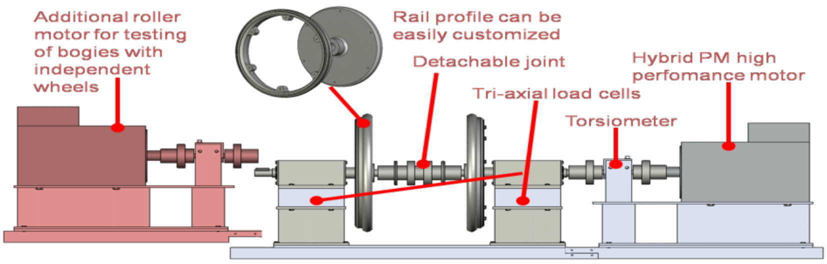

Figure 3/c: roller rig mechanical design

Even if the bogie has been designed to simulate a well known vehicle, the authors decided to use a parametric and customizable layout in order to reduce costs and times neecessary to adjust the scaled bogie for the simulation of different vehicles. The chosen scaling criteria is the Iwnicky one [7,8,9] since other similitude criteria like Jaschinski or Pascal produced a scaling factor between time on the scaled rig and the corresponding time of the simulated vehicle involving that simulations on scaled models require less time than the full scale condition. An accelerated time scaling may be interesting feature for time consuming activities like fatigue tests, but in this case HIL simulation involve heavy computational load, a broad bandwidth of sensors and actuators that have to be carefully evaluated even with an unitary time scaling. So accelerated testing have to be avoided since it involve an increase of computational resources and required bandwidth for sensor and actuators. Also for HIL simulation existing hardware, for example a WSP board that have to be tested, may have to be interfaced with the rig. In this case time scaling on simulation may create interfacing problems between the tested/integrated mechatronic sub-system and the rig. Some mechanical data of the simulated vehicle and of the corresponding scaled model are shown in table 1.

Description	Full scale value	Scaled Value	Description	Full scale value	Scaled Value
Carbody mass	48638 kg	389 kg	Pivot Pitch	11.44m	2.28 m
Bogie mass	6580 kg	52.6kg	bogiewheel base	3m	0.6m
Axle mass	1765kg	14.1kg	Prim. susp. stiff.	2267000 N/m	18140N/m
Carbody inertia	1273000kgm^2	407kgm^2	Prim.susp.damp.	17062Ns/m	136.5Ns/m
Bogie inertia	7293kgm^2	2,33 kgm^2	Second.susp.stiff.	448000N/m	3585N/m
Axle inertia	159,2 kgm^2	0.051 kgm^2	Second.susp.damp	98707Ns/m	790Ns/m
Wheel diameter	1.1m	0,202m	Prim. susp. stiff.	2267000N/m	18140N/m
Roller diameter	-	0,5 m			

Table 1: Some Mechanical data of E404 and corresponding scaled values on the MDM scaled rig

2 TRACTION AND BRAKING PLANT: LAYOUT ON THE REAL VEHICLE AND CORRESPONDING SOLUTION ON THE SCALED ONE

In the simulated locomotive (E404) both traction and braking efforts are applied on the same axle. In particular the wheelset is B_0-B_0, so two bogies with two axles are connected to the carbody. Each axle is driven by an independent electric motor and braked by an independent braking disk unit. Electric motor is also used for dissipative or regenerative braking. As a consequence during the braking phase, both traction and pneumatic braking are applied at the same time. The application of braking forces is controlled by two mechatronic systems working and mutually interacting in parallel:

- Pneumatic WSP(wheel slide protection system): as visible in figure 4/a, a typical WSP system is composed by an ECU (Electronic Control Unit) which is able to estimate the current train speed filtering the signal of the tachometers placed on each axle. Comparing train estimated speed with the measured behavior of each axle, the WSP is able to limit excessive wheel-rail sliding preventing axle locking. Braking effort in each cylinder is controlled by a system of electro-pneumatic valves usually called EVR-EVC.
- Traction/electric braking control: as visible in figure 4/b, an independent control unit, briefly indicated in this paper as TCU (Traction Control Unit) is able to estimate train speed and detect wheel-rail slidings using the measurements of axle tachometers. TCU estimation criteria are quite similar to BCU ones. However the response bandwidth of electric actuators is much higher than pneumatic ones. Typically the dynamical behavior of the system is limited by imposing saturations and rate limitations on power drive reference command. In this way the action of the electric braking control is faster than the pneumatic WSP preventing excessive air consumption but at the same time the regulated torque is smooth enough to avoid unpredictable interactions with WSP logic or excitation of structural modes of the mechanical system. In particular, in the simulated vehicle the same power-drive/inverter control the two induction motors of a bogie which are parallel connected. This is a quite common configuration for locomotives, however as a consequence if the TCU detect that an axle is sliding the corresponding correction affects all the motors that are connected to the same power drive. Also since both the motor are fed with the same frequency and connected in parallel indirect electromechanical interactions between the two corresponding axles are possible.

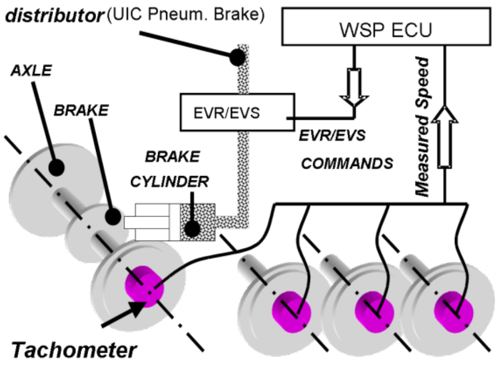

Figure 4/a: WSP typical layout

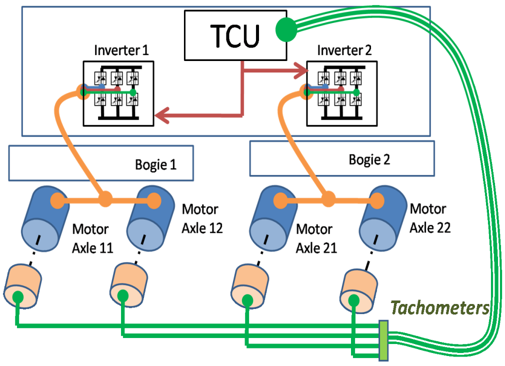

Figure 4/b: electric braking/traction control of E404 (simplified scheme)

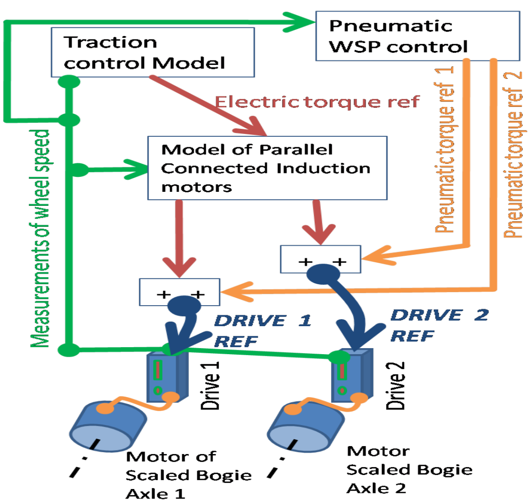

Figure 4/c: tabulated model of parallel connected model and general simulation layout of traction and braking system

Typical behavior of BCU/TCU have been analyzed and modeled by the authors in previous works [2,10]. In this work the attention is focused on the modeling of parallel connected motors for the real time simulation on the scaled test rig of the MDM lab of Pistoia. In fact, as shown in figure 3/ a, in the proposed scaled rig both traction an braking efforts are exerted by a servo induction motor on each axle. In this way the design and the management of the rig is quite simplified since a single torque controlled electric actuator is used to simulate the action of each traction/braking system installed on the vehicle. So a simplified tabulated model of the response of parallel connected induction motors is needed as those shown in figure 4/c.

The induction motors are driven using a DTC [11] power system able to regulate the applied torque with a precision of about 1-5% according different working conditions and a bandwidth of about 10Hz. This performances are sufficientfor the simulation requirements since in a real locomotive the bandwidth of pneumatic actuators is limited to 1-2Hz and furthermore the response of the electric traction and braking system is software/firmware limited to few hertz. The purpose of the rig is not the simulation of high frequency harmonics introduced on exerted torque by power electronics switching criteria or during very fast transients. The precision achieved with the open loop torque control of the motor is considered sufficient for the application considering the corresponding tolerances of the system installed on the real vehicle. The mechanical transmission between motors and wheels is assured by a toothed timing belts; this mechanical solution has been selected in order to recover suspension deformations and to simplify an easy customization of axles inter axis for the simulation of different vehicles. Furthermore the horizontal position of the toothed belts assure that the tension of the belt has no influence on primary suspension deformation. In this way this simplified solution is able to approximate the behavior of the hollow shaft transmission usually installed on the real vehicle as visible in figure 3/a.

3 MODELLING OF PARALLEL CONNECTED MOTORS OF E404

3.1 reverse engineering from technical documentation

From technical documentation[12] available from Trenitalia the authors defined the typical parameters (equivalent impedances, applied tension, torque speed curves) of the E404 motors. Considering an axial symmetric asynchronous motor, modeled in a synchronously rotating reference [13] the model described by equation (1) is obtained. In figure 5 rotor, stator and synchronous reference and some parameters are shown. In particular since "*s*" for induction motor is the symbol of the electrical slip the letter "*p*" is used to define the complex Laplace variable.

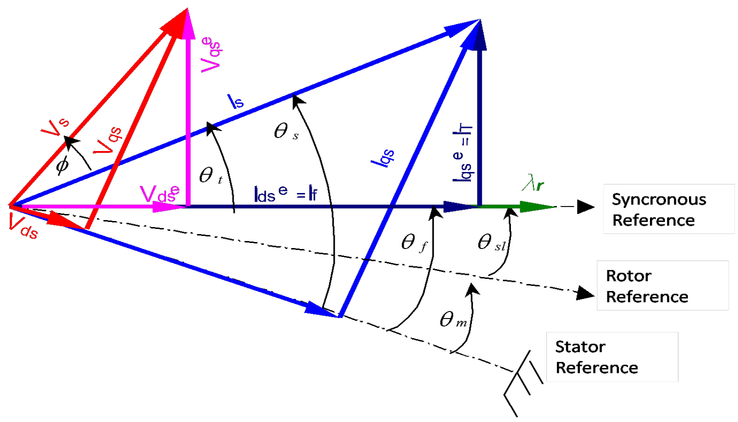

Figure 5: Stator, Rotor and Syncronous references

$$\begin{bmatrix} v_{qs}^e \\ v_{ds}^e \\ v_{qr}^e \\ v_{dr}^e \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega_s L_s & L_m p & \omega_s L_m \\ -\omega_s L_s & R_s + L_s p & -\omega_s L_m & L_m p \\ L_m p & (\omega_s - \omega_r) L_m & R_r + L_r p & (\omega_s - \omega_r) L_m \\ -(\omega_s - \omega_r) L_m & L_m p & -(\omega_s - \omega_r) L_m & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ i_{qr}^e \\ i_{dr}^e \end{bmatrix} \qquad (1)$$

From (1) torque T_e can be calculated as a function of different parameters as described in the following equations in relations (2/a), (2/b), (2/c), in which "*P*" is the symbol used to describe the number of poles:

$$T_e = \frac{3}{2}\frac{P}{2}L_m\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right) = \frac{3}{2}\frac{P}{2}L_m\left(i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e\right) \quad (2\text{ a})$$

$$T_e = \frac{3}{2}P\frac{R_r i_r^2}{s\omega_s} = \frac{3}{2}P\left[\frac{v_s^2}{\left(R_s + \frac{R_r}{s}\right) + \omega_s^2\left(L_r + L_s\right)^2}\right]\frac{R_r}{\omega_s s} \quad (2\text{ b})$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) = \frac{3}{2}\frac{P}{2}\left(i_{qs}^e\lambda_{ds}^e - i_{ds}^e\lambda_{qs}^e\right) \quad (2\text{ c})$$

In the preceding equations:

- v_{ij}^e represents the *i*-th component of the voltage applied on the *j*-th side;
- i_{ij}^e represents the *i*-th component of the current applied on the *j*-th side;
- $i = d$ is the direct component, $i = q$ is the quadrature component;
- λ_{ij}^e represents the *i*-th component of the flux linkage applied on the *j*-th side;
- ω_r, ω_s are respectively the rotor and stator electrical speeds, expressed in [rad/s];
- L_r, L_s, L_m are respectively the rotor, stator, magnetizing inductances;
- R_r, R_s are the equivalent rotor and stator resistances respectively;
- The index ^{e} indicates that the corresponding parameter is evaluated for the synchronous reference,

From equation(2/b) the exerted torque $T_e\,(v_{qs}\;,s,\omega_s\,)$ and consequently the mechanical power $W_m\;(v_{qs}\;,s,\omega_s)$ can be calculated as function of v_{qs}, motor slip s and stator frequency ω_s [13,14,15]. The corresponding surfaces calculated with the data of E404 motor supposing a constant feeding tension v_s equal to the nominal value are shown in figure 6.

In figure 6 the curve corresponding to the nominal performances assured by the power drive system is represented: the motor is controlled in order to produce an almost constant torque (constant torque region) from starting to the so-called nominal speed, then increasing the speed the system is regulated in order to keep approximately constant the power (constant power region). In particular in the constant torque region the stator voltage v_s is approximately proportional to motor speed and the to the stator frequency ω_s . Once nominal speed is reached the applied tension is kept constant and the torque is regulated according equation 2(c) by gradually reducing magnetic flux linkages using the so called "flux weakening" technique.

In both regulating regions the modulus of the stator current i_s is almost constant as visible in figure 7. From a macroscopic point of view flux weakening involve a gradual increase of machine slip "s" in order to compensate the increasing effect of inductive loads at higher frequencies.

As clearly evident in figure 8 the nominal performance curve corresponds to a near to optimal energy efficiency of the motor which involves also an optimized thermal design of the system.

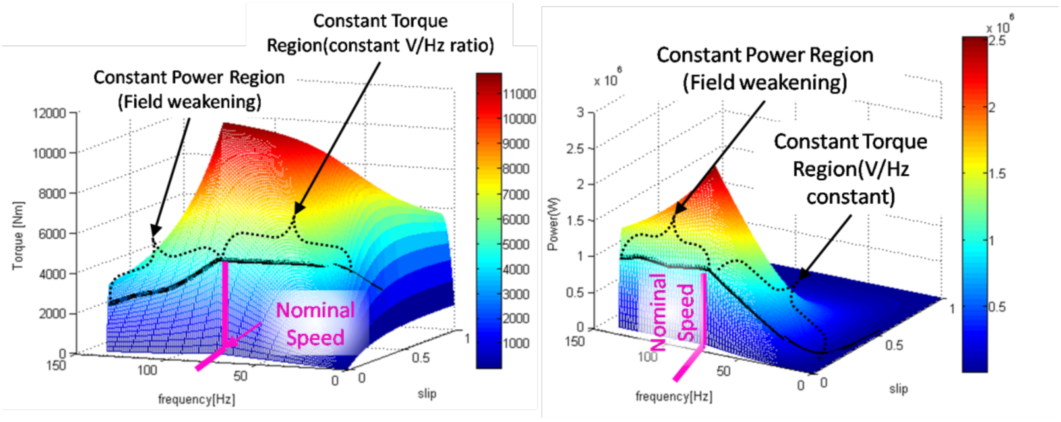

Figure 6: T_e and W_m surfaces calculated for E404 motors supposing constant stator voltage v_s and curves (in black) corresponding to the nominal performance assured by the power-drive system

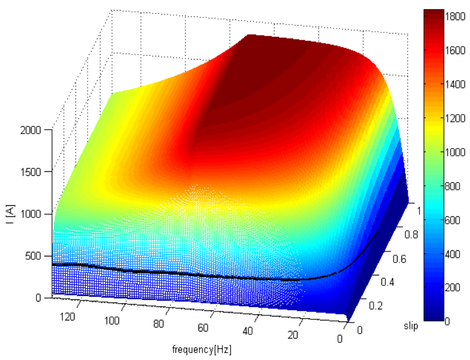

Figure 7: stator current surface calculated for E404 motors supposing constant stator voltage v_s and curves (in black) corresponding to the nominal performance assured by the power-drive system.

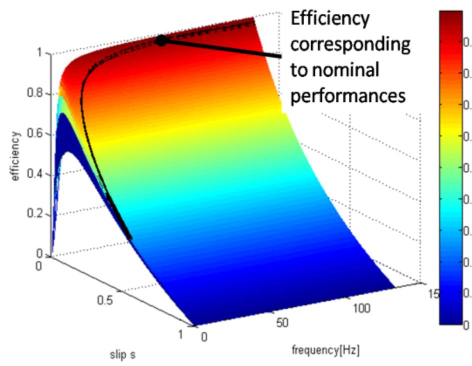

Figure 8: efficiency surface calculated for E404 motors supposing constant stator voltage v_s and curves (in black) corresponding to the nominal performance assured by the power-drive system.

3.2 Simplified model of the vector control and motors

In order to roughly simulate the mutual interactions between power drive and parallel connected motors a simplified model of the system has been built using Simulink Simscape Sim-Power toolbox[tm] . The internal logic of the drive system is modeled supposing a direct vector control scheme[13], also known as field oriented control [16,17,18] since is calculated in a synchronous reference which is constrained, whose simplified scheme is visible in figure 9:

- An external speed loop is used to regulate the mean speed ω_{mean} of the controlled motors.
- The desired torque motor T^*_e and desired field linkage λ^*_r are tabulated as a functions of motors mean speed
- Comparing desired values of torque and field linkage with the estimated ones, field and torque regulators are able to calculate the desired values i_f and i_t of stator currents i^e_{qs} e i^e_{ds}.
- The current regulator controls inverter switching in order to reproduce the desired currents on the motors. Mechanical speed of the two motors can be different since the two axes are mechanically independent. In particular the slips of the two motors s_1 and s_2 can be modified

adjusting the applied mechanical loads.

- Speed of the motors is measured by tachometers, ω_{mean} is then calculated closing the external speed loop.

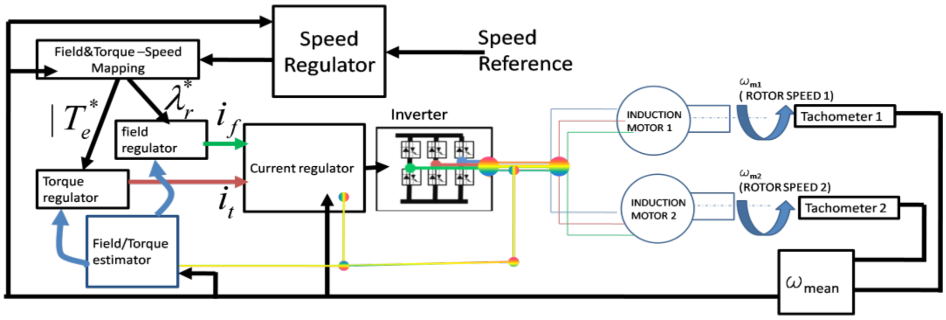

Figure 9: simplified scheme of the Simulink Simscape Sim-Power toolbox[tm] used to simulate interactions between power drive system and parallel connected induction motors.

Using the model described in figure 9 the authors have been able to iteratively simulate different working and loading conditions building a tabulated relationship between torque exerted by motors and mean motor speed, slips s_1 ,s_2 reference torque T_{ref} required to power drive.

In figure 10 some results of the simulation model are shown: it is clearly noticeable the how small slip difference of slip between parallel connected motor can produce big differences in the torque exerted by the two motors. In particular this behavior deeply influence improve the dynamical stability of axle driven by parallel connected motors.

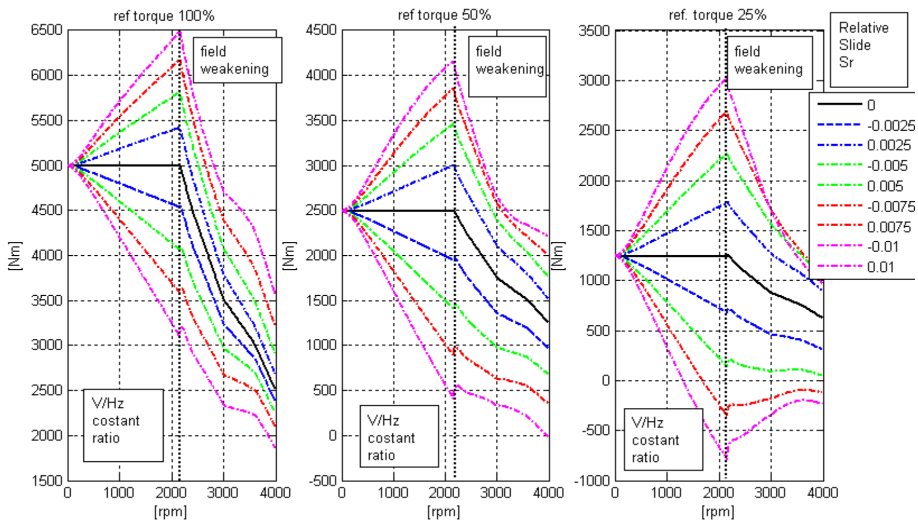

Figure 10: tabulated torque exerted by motors as a functions of motor motors mean speed, slips and imposed reference torque.

4 CONCLUSIONS

In this paper some aspect concerning the design of a scaled railway roller rig have been presented. In particular this work is focused on modeling of parallel connected induction motors.

This feature is quite important since the new scaled rig of the MDM lab of Pistoia has been

designed for testing and research activities on mechatronic on board systems like traction, braking and stability controls. A simplified model of motor vector control has been used to produce a steady state tabulated functions that will be used in the real time model of the vehicle traction-braking equipment that will be implemented on the rig.
Results of simulations are referred to the traction system of a real vehicle, whose behavior has been reproduced using data partially taken from technical documentation and partially reconstructed using reverse engineering procedures.

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