New model of Asynchronous Motor based on Nonlinear Model Predictive Control in Railway drive application

Ahmad Atiyah
Instruments and Control Engineering Department
Czech Technical University in Prague
Prague, Czech Republic
ahmad.atiyah@fs.cvut.cz

Bohumil Sulc
Instruments and Control Engineering Department
Czech Technical University in Prague
Prague, Czech Republic
bohumil.sulc@fs.cvut.cz

***Abstract*— The use of Park transformations is common when modelling an asynchronous motor (ASM), as it eliminates the time-varying inductance between stator and rotor and decoupling of the magnetic flux, thus ensuring that torque and flux can be controlled independently of each other. In contrast, it is very difficult to model and analyze the space harmonics of an ASM with nonlinear components such as saturation using dq0 frame. In this paper, a new ASM motor model based on the ABC natural coordinate frame is proposed as a replacement of the current implemented dq0 model. This approach led us to reconsider replacing the implemented torque control PI controllers with a Nonlinear Model Predictive Control (NMPC). The expected results include a more robust, better system performance and stability, with the possibility of improving torque control delivered to the railway wheelset under undesirable operating conditions such as torque ripple and adhesion loss associated with power loss decreased.**

***Keywords*— asynchronous motor, model predictive control, dynamics model, adhesion, torque, abc natural coordinate.**

I. Introduction

Modern trains are characterized by their powerful and high speed, which allowed it to compete with other means of transport such as means of air and road transport. This great development in their performance, power, and speed are accompanied by problems, like determining the optimal torque value transmitted from the electrical motor to the wheels, where the traction motor force and the undesirable dynamic changes in addition to the adhesion conditions play the largest role in determining the optimal operating conditions and the maximum torque transmitted to the wheels.

Economic and technical concerns limit implementing the practical experiments which help in studying the mechanical and electrical problems of railway systems. Therefore, due to their effectiveness in testing and examining the equipment and systems under development before deploying the real experimental model, computer modeling techniques represent a necessary and important tool in the research practice.

High performance, high-speed computation, robustness, flexibility, and ability to obtain a highly advanced and complex model. All those features of the modeling and simulation systems allowed us to develop a computer model that simulates some of the undesired dynamic parameters which affect the torque transmission from the ASM to the wheels during the loss of adhesion.

Within the results of the research conducted on the simulation model, it is shown that there is a necessity to design a comprehensive simulation model for the wheelset drive unit includes an ASM model, in order to obtain a more accurate simulation model of the torque transfer process from the ASM to the wheelset, taking into account the effect of the dynamic phenomena's of the system components, such as torsional oscillations [1] and adhesion conditions [2].

So far, the designed model has been able to satisfy the mechanical requirements of the wheelset drive system, while the electrical part is subject to further developments that include preparing various ASM models to study its effect on optimizing torque control in addition to studying the ability of Modern control systems in predicting unwanted dynamic changes in the locomotive under different operating conditions and its impact on the performance of the motor proposed models, the latest of which is the model that is the subject of this paper.

II. Train Drive Dynamic and Asynchronous Motor Model

The main parts participating in the torque transmission to the wheelset [3] are simulated in Simulink and depicted in the form of blocks as is it is illustrated in Fig.1.

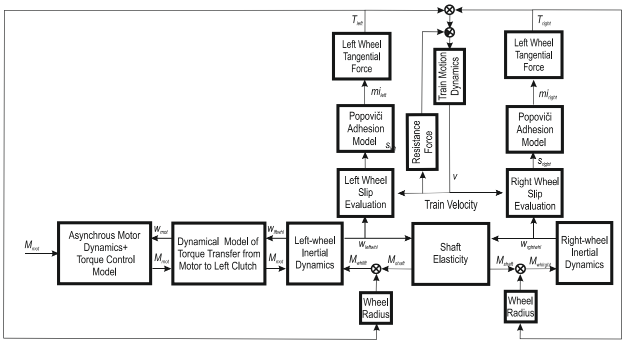

Fig. 1. Block scheme representing the system model dynamoics of a weelset torque transmission.

A. *Models of mechanical components nfluencing torque generation dynamics with impact on train movement*

Both mechanical and electrical components contributing taking part in transmission of the torque from the motor to the wheels are shown in Fig. 2 which represents a cross section of a locomotive wheelset drive.

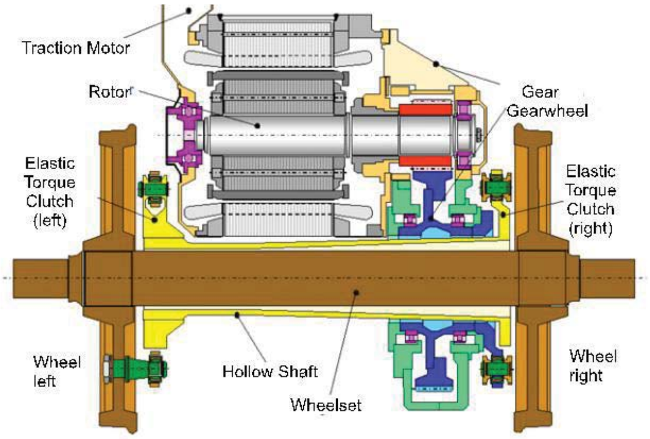

Fig. 2. Cross section of a wheel-set drive

The whole torque transmission path from the ASM to wheels, including the gear, right clutch, hollow shaft, left clutch, left wheel, axle, right wheel, we can depict it as if it were composed of such fictive substitutes. One of the possible ways how to do this is depicted in Fig. 3.

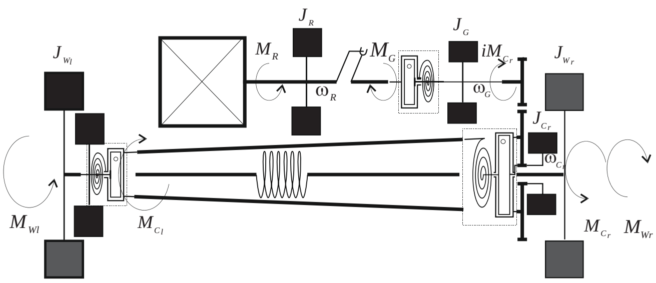

Fig. 3. Substitute concept of modelling dynamic behaviour of mechanical wheelset components using symbolic functional elements

B. *Used Asynchronous Motor Modelling in dq0 frame and its disadvantages in control*

The AC motor is considered as the main component of the train's wheelset drive unit, as it generates the required power to the wheels which push the train forward on the rails. Here comes the importance of creating an accurate model of ASM that takes into account changing dynamic characteristics when a comprehensive model of the wheelset unit is established for the purpose of simulation

When modelling an ASM with torque control, a variety of modelling methods used to represent the mathematical model of the motor. One of the favourite modelling methods known as direct quadratic frame dq0, where it converts the measured physical quantities such as voltage, current, and torque in the natural reference frame to abstract quantities (from three to two quantities) within a rotating reference frame. dq0 transformations or Park transformation [6] are based on the space phasor theory to study the dynamic behaviour of an ASM. These converted quantities cannot be measured directly on the ASM, and they are used as controlled variables when designing the ASM control system, they provide the ability to control torque and magnetic flux independently of each other.

In Fig. 4, a block scheme of the control structure with a drive motor cross section is shown, where the natural measurable physical quantities, i.e. voltages u_{SA}, u_{SB}, u_{SC} of the three-phase motor supply, inverter DC supply voltage u_{DC} together with the current, the natural quantities are illustrated in blue color arrows. Other arrows and blocks, except torque setpoint representation, are in black because of their purely abstract character.

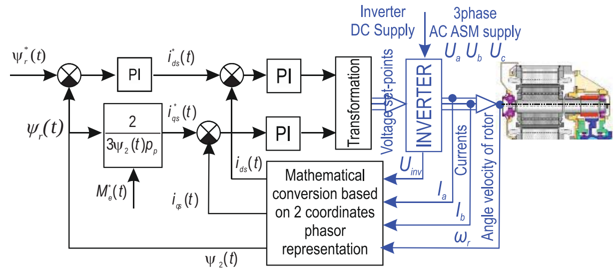

Fig. 4. A torque control scheme using abstract mathematical model based on dq0 frame representation and PI controllers.

The torque control set-point is defined, but the controlled variable is not directly measured, which results in disability in evaluating the topical control error. Also, the ASM should be equipped with an Inverter in order to generate control actions. The dq0 stand as converter between the physical reality, and abstract (mathematical) image of it, where the problems of controller design, optimal parameter setting are not easy to solve by standard time-domain methods. This has evoked our attention to study them in more detail, using the developed Simulink model.

Basically, indices dq express affiliation to orthogonal coordinate system, added index s linkage to the stator, r then to the rotor. For variables that are introduced only on the basis of the mathematically formulated definitions without any direct link to natural physical quantities common symbols of their physical counterparts are used, i.e. for currents *i* [A], voltages *u* [V]. Magnetic fluxes *Ψ* [Wb]. Also, the same physical units are assigned them because their values are computed according to the same formulas used for calculations in electrical circuit schemes with lumped parameters such as the resistance *R* in [Ω], the (mutual) inductance *L* in [H].

The Simulink model which we developed was based on the dq model equations as follows:

a. Stator voltage equations:

$$u_{qs}(t)=R_s i_{qs}(t)+\frac{d}{dt}\Psi_{qs}(t)-\omega_s(t)\Psi_{ds}(t) \quad (2)$$

$$u_{ds}(t)=R_s i_{ds}(t)+\frac{d}{dt}\Psi_{ds}(t)-\omega_s(t)\Psi_{qs}(t) \quad (3)$$

b. Rotor voltage equations:

$$u_{dr}(t)=R_r i_{dr}(t)+\frac{d}{dt}\Psi_{dr}(t)-(\omega_s(t)-\omega(t))\Psi_{qr}=0 \quad (4)$$

$$u_{qr}(t)=R_r i_{qr}(t)+\frac{d}{dt}\Psi_{qr}(t)-(\omega_s(t)-\omega(t))\Psi_{dr}(t)=0 \quad (5)$$

c. Flux linkages of the stator and rotor are expressed in terms of the stator and rotor current in dq axis:

$$\Psi_{ds}(t)=L_s i_{ds}(t)+L_m i_{dr}(t) \quad (6)$$

$$\Psi_{qs}(t)=L_s i_{qs}(t)+L_m i_{qr}(t) \quad (7)$$

$$\Psi_{dr}(t)=L_r i_{dr}(t)+L_m i_{ds}(t) \quad (8)$$

$$\Psi_{qr}(t)=L_r i_{qr}(t)+L_m i_{qs}(t) \quad (9)$$

c. Magnetizing fluxes are defined as:

$$\Psi_{dm}(t)=L_m i_{ds}(t)+L_m i_{dr}(t) \quad (10)$$

$$\Psi_{qm}(t)=L_m i_{qs}+L_m i_{qr}(t) \quad (11)$$

$$L_m=2/3\,L_{ms} \quad (12)$$

d. Electromagnetic torque expressed by:

$$M_e(t)=2/3\,P_p\left(\Psi_{ds}(t)i_{qs}(t)\text{-}\Psi_{qs}(t)i_{ds}(t)\right) \quad (13)$$

The stator and rotor winding are mutually coupled. Thus, when rotor angle changes, the mutual induction also changes i.e. as it is dependent on the rotor position.

The dq0 frame allows us to removes the time varying inductances position dependencies between the stator and the rotor, making it easier to model the motor, also, it decouples the magnetic flux linkage, and thus easier to control the motor torque. These advantages of dq0 representation may not be valid for many cases in which it is necessary to create a motor model in abc natural coordinates frame which takes into account transient dynamic changes and nonlinear components. This prompted us to propose a new ASM model based on the natural frame discussed in the next chapter.

III. New Modelling Method of Asynchronous Motor in ABC Frme

The process of delivering the optimal torque value from the ASM to the wheelset is subject to a variety of parameters and constraints such as degree of ASM model accuracy, control system stability and response, in addition to dynamical conditions influence the wheelset slip and adhesion such as weather conditions, and unpredicted changes in operation conditions.

When adhesion of the wheelset is lost, a significant transient changes in the motor voltage could be noticed [7] due to the fluctuation in the motor traction torque in order to reestablish the adhesion of the wheels to the rails. This unwanted situation affect the toque transmitted to the wheels. In transient conditions, a number of harmonic components which has a nonlinearity nature are produced [4] which results in the inability to directly obtain real values of the currents since those linearity components are located in space harmonic vector. These quantities affecting the relationship between the original current in abc natural frame and the transformed current in dq0 frame are difficult to be represented precisely based on dq analysis since it has a linear nature. In addition, dq transformation model deals with id current as a function of iq, which eliminates the possibility to do simulation independently from each other, and also the dq model is not able to identify the differences of the phase currents. Considering the above-mentioned reasons, attention is switched to developing a new ASM model that can accurately and precisely reflect the transient conditions and steady-state operation of the ASM.

Some of the literature work focused on modeling ASM in abc frame using Matrix partitioning was done by Dimitrovski and Luther [5]. We propose an ABC natural coordinate model Fig. 5 of which should improve the accuracy of the transient process and controlling the response of the parameters of the analysis more precisely knowing that in practice, the currents flow through phases are not equal.

The stator voltage differential equations are defined as follows

$$u_{sA}(t)=R_{sA}i_{sA}(t)+\frac{d}{dt}\Psi_{sA}(t) \quad (14)$$

$$u_{sB}(t)=R_{sB}i_{sB}(t)+\frac{d}{dt}\Psi_{sB}(t) \quad (15)$$

$$u_{sC}(t)=R_{sC}i_{sC}(t)+\frac{d}{dt}\Psi_{sC}(t) \quad (16)$$

Similarly, the rotor voltage differential equations are

$$u_{rA}(t)=R_{rA}i_{rA}(t)+\frac{d}{dt}\Psi_{rA}(t) \quad (17)$$

$$u_{rB}(t)=R_{rB}i_{rB}(t)+\frac{d}{dt}\Psi_{rB}(t) \quad (18)$$

$$u_{rC}(t)=R_{rC}i_{rC}(t)+\frac{d}{dt}\Psi_{rC}(t) \quad (19)$$

In real operation of the ASM, the magnetic flux of the stator and rotor are mutually connected, and the magnetic flux of the one winding depends on the magnetic fluxes of the rest of the windings. The magnetic flux equation of the new ASM model can be stated in matrix form as follows:

$$\begin{bmatrix}\Psi_A(t)\\ \Psi_B(t)\\ \Psi_C(t)\end{bmatrix} = [L_{ms}].[I_{sABC}] + [L_{mr}].[I_{rABC}] \quad (21)$$

$$= \begin{bmatrix} L_{sA} & L_{sAsB} & L_{sAsC} \\ L_{sAsB} & L_{sB} & L_{sBsC} \\ 0 & L_{sBsC} & L_{sAsC+L_s} \end{bmatrix}$$

Where is

$$[L_{mr}] = \begin{bmatrix} L_{sArA} & L_{sArB} & L_{sArC} \\ L_{sBrA} & L_{sBrB} & L_{sBrC} \\ L_{sCrA} & L_{sCrB} & L_{sCrC} \end{bmatrix} \quad (23)$$

$$[I_{sABC}] = \begin{bmatrix} I_{sA} \\ I_{sB} \\ I_{sC} \end{bmatrix} \quad (24)$$

$$[I_{rABC}] = \begin{bmatrix} I_{rA} \\ I_{rB} \\ I_{rC} \end{bmatrix} \quad (25)$$

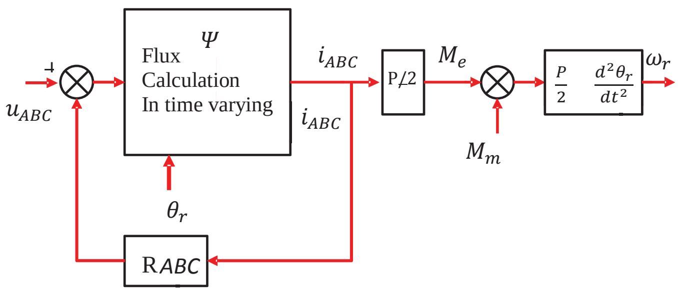

Fig. 5. ABC natural coordinate model proposal for ASM

Where in (14) – (25) symbols $i_{sA}, i_{sB}, i_{sA}, i_{rC}, i_{rA}, i_{rC}$ are the natural 3-phase currents. $u_{sA}, u_{sB}, u_{sC}, u_{rA}, u_{rB}, u_{rC}$ are the natural 3-phase stator and rotor voltages as follows.

IV. Proposal of Model Predictive Control for ASM

If an inadequate tractive torque is detected, it may lead to an inadequate wheel slip and a subsequent limiting vehicle dynamics. So far, a variety of vector modelling method like Field Oriented Control (FOC) and Direct Torque Control (DTC) [8] has been used in practice to control the ASM. These methods depend on two reference frames, stationery which is based on alpha and beta abstract quantities and known as Clark transformation [9], and arbitrary which based on direct quadratic abstract quantities that were used to simulate our ASM Simulink model.

FOC emulates the behaviour of ASM as if it is a DC machine by decomposed the stator currents into two-axis, d-axis correspond to (Flux) and q axis correspond to (Torque) which results in the decoupling of torque and flux control. Those separated quantities are then regulated using a two tuned PI controller, and good steady-state stability and fast dynamic response are obtained. On the other hand, DTC directly selects the best voltage vector using a predefined table based on stator flux position and error signals of the torque and stator flux. Thus, by eliminating the use of current control of the ASM, a faster dynamic response is achieved.

The features which FOC and DTC present, come with limitation represented in low-speed operation and computational effort and inability to handle constraints which influence the stability, in addition to difficulties in considering the nonlinear components in the ASM. It is also good to mention that based on some previous experience, the good tuning of the PI Controller in an untraditional control structure standardly used in the ASM torque is not a straightforward process, since the PI control loops work with signals computed in this model, not directly with physical quantities.

In order to approach a precise ASM model based on abc frame, we need to consider the nonlinearities nature of the stator flux which is not decoupled in abc frame due to harmonic components such as saturation. These nonlinear components are difficult to be represented in the dq0 frame.

Based on what previously mentioned, it is good to obtain a new control model based on Nonlinear Model Predictive Control (NMPC) [10] and replacing the implemented PI controllers in order to facilitate the adjustment. The benefits of the necessary state-of-the-art in-system order reduction, linearization for a computer simulation that is quite dependent on step size may be indispensable. In general, The MPC controller has a quick response, multivariable control, ability to handle various nonlinear constraints, also, MPC [11] can eliminate the use of the inner and outer loops and result in an increment of steady-state error. On the other hand, the computational effort, the requirements of the high sampling frequency, and the difference in the torque and stator flux amplitudes and units restrict the implementation speed rate of the traditional MPC in real application.

We propose a new control strategy based on the NMPC controller for voltage vector control and disturbance observing which caused by load torque variation and parameter deviation. The new control strategy will use an explicit nonlinear MPC, where an additional loop of current control will be neglected. Increasing the predicted instances of both torque and stator flux will help us in obtaining the best voltage vector come through minimizing MPC cost function J.

Developing such a new control method will result in a better stability and higher performance since the physical quantities will be directly measured in abc frame without using dq0 frame. The proposed MPC controller is depicted in Fig. 6.

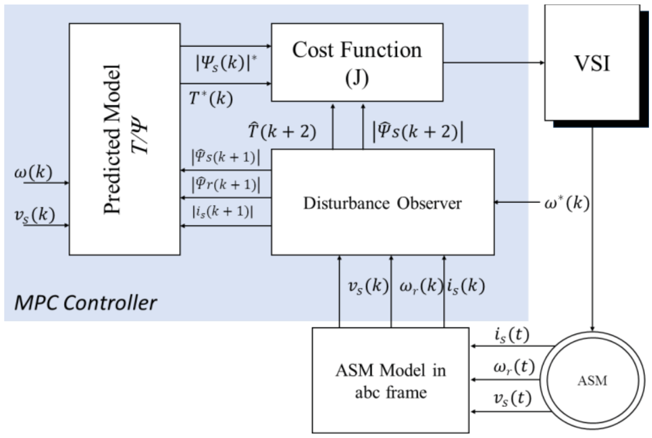

Fig. 6. Block scheme of proposed NMPC controller for ASM drive

The expected results of the MPC controller comparing with PI controller may include a better transient response, better robustness and improved stability in face of uncertainties including load disturbance, and torque fluctuating transmitted to the locomotive wheelset.

Conclusions

The urgent need, and the growing interest in obtaining an accurate model of ASM which consider the transient changes that affect the torque transmitted to the wheels under undesirable operating conditions, prompted us to propose a new model of an ASM based on its representation in the natural coordinate frame instead of the commonly used two-axis dq0 reference frame. In this paper, we have emphasized the importance of the proposed model in its ability to take into account nonlinear components that appear during motor operation. The conventional control method such as FOC and DTC cannot be employed with the proposed motor model, as it deals with torque and magnetic flux within a two-axis dq0 frame, so we proposed a new control system based on a nonlinear predictive controller. By predicting the motor variable within a predefined prediction horizon, taking into account all possible voltage vectors, it is possible to select the optimal voltage vector by minimizing the cost function of the controller.

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