STRIP THICKNESS ESTIMATION IN ROLLING MILLS FROM ELECTRICAL VARIABLES IN AC DRIVES

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***Abstract*— The large-scale utilization of steel in the modern society highlights the importance of the lamination process, and poses new demands for advanced technologies in the electromechanical equipments as well as for the control systems. Several process parameters, such as strip thickness, friction, tension, temperature, and rolling speed have a strong influence in the quality of the final product, and strategic importance in the control system. This paper introduces a method to obtain the torque and rolling mechanical power estimates in real time, without utilization of lamination process models. In contrast to existing techniques, in this work these estimates are derived from stator electrical variables, readily available in AC drives. This work also discusses the utilization of the torque and rolling mechanical power estimates to determine input and output strip thickness, by means of a neural network. Simulation results are presented and compared to real industrial data to demonstrate the validity of the proposed technique.**

***Keywords*— Strip thickness estimation, rolling drive system.**

I. INTRODUCTION

A rolling mill system is typically formed by rolls that reduce the strip dimension by lamination forces, and are commonly equipped with several instruments, actuators, and control devices.

Current rolling mills employ complex computer programs which require the knowledge of roll force, and rely on microprocessor control to provide several information, required for normal operation, as well as for inputs to new rolling mills design. Variables such as roll load, torque, power, and vibration are derived by mathematical models, and play a fundamental role in the process performance. Several operating parameters are monitored and controlled to warrant product quality.

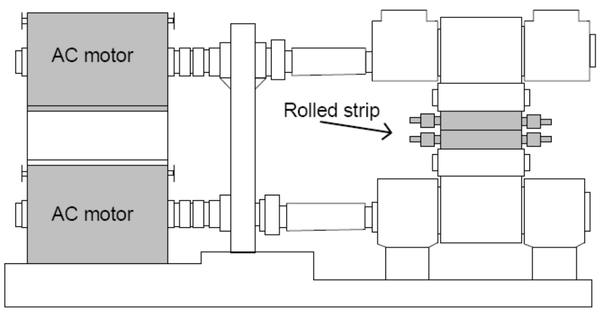

Fig.1:Rolling mill and motor drive.

Some variables such as strip thickness, yield stress, friction coefficient, strip tension between stands, temperature, and roll speed all have intense influence in the end product quality, and strategic importance in the control system performance. Roll force, torque, and mechanical power obtained by direct measurement or calculation are fundamental to process control system. The knowledge of the torque magnitude enables the identification of several process parameters, and can be decisive in the identification of fatigue efforts that the mechanical components are subjected to.

The rolls can present premature failure in their mechanical components even when the operating load is bellow the design limits. The solution to this problem normally involves a modification in the power transmission geometry and the selection of materials with better mechanical properties, which allows an improvement in the components lifetime. The lack of the knowledge of the torque magnitude in real time has prevented further development in this area. Engineering design normally utilizes safety factors larger that unity to warrant larger components lifetime. Even with all safety precaution in place, the drive component still fails prematurely (Chan, *et al*., 1999). This emphasizes the importance of a technique to obtain the roll torque in real time to warrant a safe operation.

This paper presents a methodology to obtain, in real time, the torque magnitude and rolling mechanical power, from an open loop observer, based on the machine dynamic model. Next, a neural network is trained to provide the input and output strip thickness from three inputs: torque magnitude, rolling mechanical power, and measured roll force. The synchronous machine dynamic model, converter model, and Orowan process model were initially utilized for simulations studies. Finally, real rolling stand data were utilized to validate the proposed methodology.

II. PROCESS DESCRIPTION

A. Rolling Process

A rolling mill is formed by several mechanicals components connected to produce the desired thickness reduction in a steel strip. A typical hot strip mill stand is present in Fig. 1. Two AC motors drive both sides of a roll strip. The material flows between the rolls to obtain the desired thickness, as show in Fig 2, at a temperature near 1000ºC. In hot rolling mills, the strip thickness is reduced, from an input thickness h_1 to an output thickness h_2 by the lamination force of the two parallel rolls while moving the upper work roll to achieve the desired

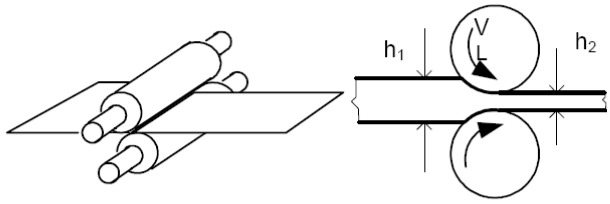

Fig. 2: Input and output thickness strip.

thickness.

B. Electro Mechanical Drive System

The rolling mill is a general structure of electromechanical drive system as shown in Fig. 3. The basic equipment can be divided into the following components: power source, converter, electric motor, and the mechanical components. The roll stand is the main process component. The motor control system is typically formed by a speed control loop with a secondary current loop (Monse, 1998).

The torque required by the material that is being rolled is transmitted to the electric motor shaft by the mechanical components composed of mass, gears, couplings, and joint shaft.

Cycloconverter synchronous or induction motor drives have been extensively utilized in modern rolling mills. They normally operate under vector control to deliver the high power and low speed required by these mills. The DC motor drives that were used for several decades have been gradually substituted for AC machine drives in news projects, as well as in retrofitting present plants.

C. Torque and Power Estimation

The Orowan Model was employed to represent the hot rolling strip process, and to demonstrate the possibility to obtain the torque magnitude and lamination power from the electric signals readily available in the power converter that feeds the AC machine in the drive system. The full order dynamic model of the AC synchronous machine was employed to demonstrate the feasibility of such scheme. Figure 4 shows a typical input rolling operating data, which are fed to the Orowan model, in order to obtain an estimate of the rolling power and torque. The lamination torque (T_q) from the Orowan model acts as the load torque that is fed to the synchronous motor model. The developed electromagnetic torque (T_{sinc}) and mechanical power (P_{sinc}) estimates form the output data. It is indispensable to verify if the magnitudes of the estimates from the machine estimator are in agreement with the values derived from the Orowan model. If so, these values can be employed to train a neural network, from which operating parameters such as thickness, yield stress, friction coefficient, strip tension between stands and others. Initially, in this paper, it is proved that the process variables such as torque and lamination power can be obtained from the electric variables. The models presented are simulated in MATLAB/SIMULINK.

D. Rolling Model

Several rolling process models are available in the literature. These models serve different purposes, and are suitable for specific applications, such as strip thickness computation, dynamic process studies, mechanical components specification, and control system implementation

Some models are employed to determine a rolling load P , the rolling torque Tq and rolling power Pot, which are related to the strip thickness. The load P can be related to several operating parameters, and can be expressed by nonlinear equations (Denti, 1994) such as:

$$P = f_p(\mu, S, t_1, t_2, h_1, h_2, \theta, v_L) \tag{1a}$$

$$Tq = f_{Tq}(\mu, S, t_1, t_2, h_1, h_2, \theta, v_L) \tag{1b}$$

$$Pot = Tq \cdot v_L \tag{1c}$$

where μ is the friction coefficient; S is the average yield stress; t_1 is the strip tension in the back stand; t_2 is the strip tension in the front stand; h_1 is the input strip thickness; h_2 is the output strip thickness; θ is the temperature and v_L is the rolling speed.

The Orowan model is adopted to obtain the rolling load P, rolling torque Tq and rolling power Pot, and makes use of the following input variables: h_1, h_2, t_1, h_2,

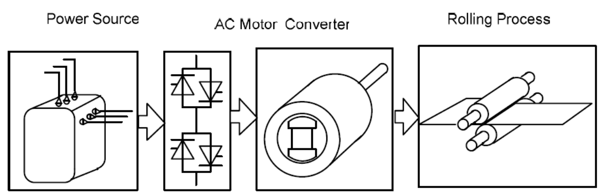

Fig. 3: Electro mechanical drive system.

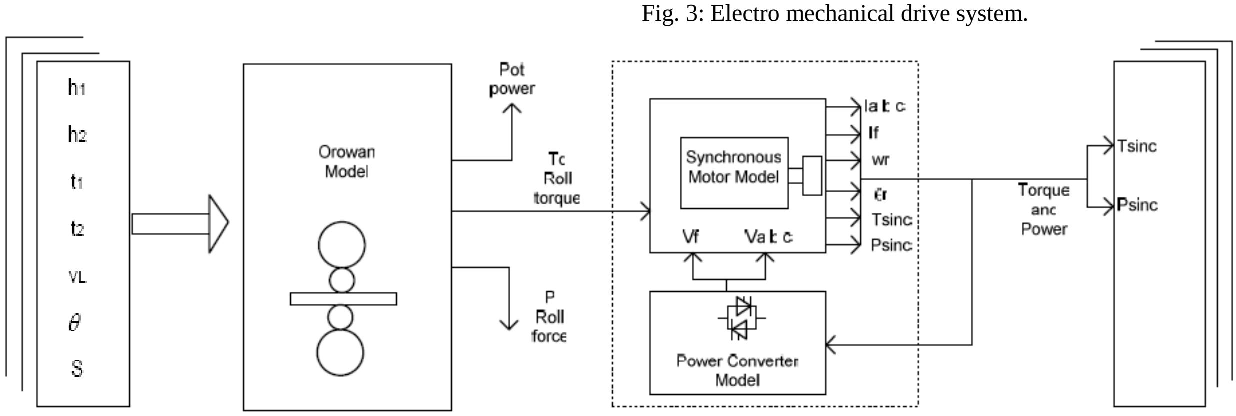

Fig. 4: Torque and rolling power estimation.

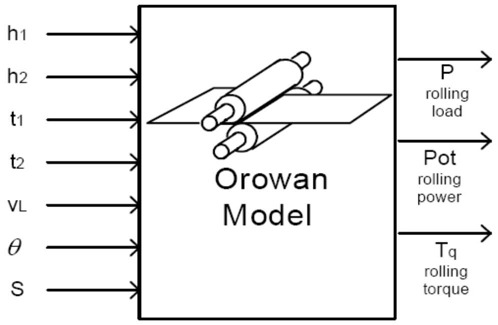

Fig. 5: Inputs and outputs in Orowan model.

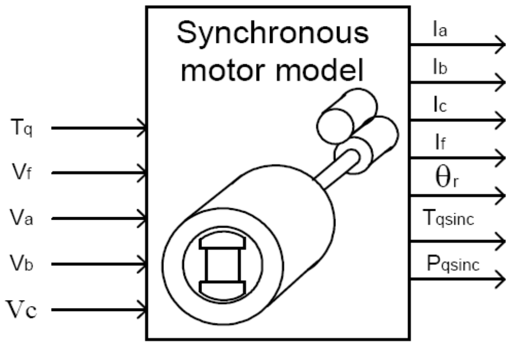

Fig. 6: Synchronous motor model: input/outputs variables.

S, V_L, θ as show Fig 5. The Eq. (3) is utilized to calculate the rolling load with application of strip tension between stands.

$$P = wR'\left(\int_0^{\alpha_N} p^+(\phi)d\phi + \int_{\alpha_N}^{\alpha} p^-(\phi)d\phi\right) \qquad (2)$$

where w is the strip width; R' is the rolling radius deformation; $p^+(\phi)$ ($p^-(\phi)$) is the strip vertical pressure in input (output) areas; α is the angle in strip and rolling contact and α_N is the angle in strip and rolling contact where $p^+(\phi)=p^-(\phi)$.

The rolling torque is determined by Eq. 3 bellow, which takes into account the rolling deformation and the input and output strip tensions.

$$Tq = w \cdot R \cdot R'\left(\int_0^{\alpha} \phi \cdot p(\phi)d\phi + \frac{t_1h_1 - t_2h_2}{2R'}\right) \qquad (3)$$

where t_1 is the strip tension forward; t_2 is the strip tension back; h_1 is the input thickness; h_2 is the output thickness.

E. Power Conversion and AC Motor Models

The electric motors applied in modern rolling mill drives have rated power in the MW range, and are predominantly AC motors, in substitution to the DC motors utilized in older rolling mill drives. One reason for such substitution is the maximum current limitation imposed by the DC machine commutator. In order to circumvent such limitation, older DC rolling mill drives were composed of many DC motors, assembled in the same shaft. As a consequence, these assemblies occupy a large space, and had a detrimental effect on the plant efficiency. In modern rolling mill drives, both induction and synchronous motors are utilized, and area fed by digitally controlled AC power converter.

The prime advantage of synchronous motors over induction motors in a cycloconverter drive system is its ability to operate at unity power factor in all operating conditions. With the minimum kVA requirement at the motor terminals, current requirements at the converter, transformers and motor cables are also reduced (Jackson, 1993).

The suitable representation of a synchronous motor to simulate its dynamic performance is done by means of the Park transformation. This transformation refers the stator variables to a rotor reference frame (d^r-q^r), which removes the time varying inductances present in the original voltage equations. The representation of a three-phase synchronous motor with its input and output variables is shown in Fig. 6. The equivalent circuit of a three-phase synchronous machine with the reference frame fixed in the rotor by the Park equations (Bose, 1986) is shown in Fig. 7.

Equations (4), (5) and (6) are derived from the d^r-q^r equivalent circuit. Equation (4) represents the electric dynamics, where flux linkages are the state variables. The various flux linkage definitions are presented in Eq. 5, whereas the electromagnetic torque Te is obtained from Eq. 6, where Pol is the number of poles. The variables indicated by v and i and subscript s, are associated with the stator windings. The terms L_{mq} and L_{md} represent the magnetizing inductance in the quadrature (*q axis*) and direct axis (*d axis*). The terms with subscript l represent the leakage inductances

$$\begin{aligned}
v^r qs &= -r_s \cdot i^r qs + w_r \cdot \lambda^r ds + p \cdot \lambda^r qs \\
v^r ds &= -r_s \cdot i^r ds - w_r \cdot \lambda^r qs + p \cdot \lambda^r ds \\
v'^r kq &= r'kq \cdot i'^r kq + p \cdot \lambda'^r kq \\
v'^r fd &= r' fd \cdot i'^r fd + p \cdot \lambda'^r fd \\
v'^r kd &= r'kd \cdot i'^r kd + p \cdot \lambda'^r kd
\end{aligned} \qquad (4)$$

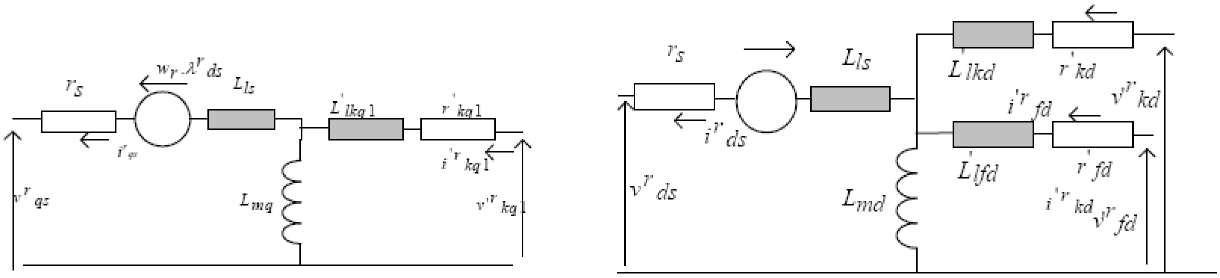

Fig. 7: Rotor frame equivalent circuit for a synchronous motor.

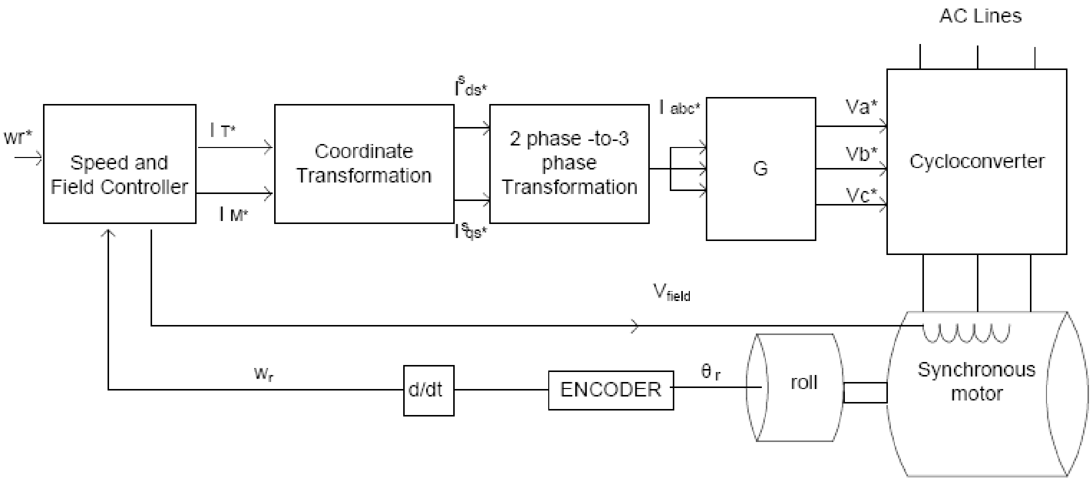

Fig.8: Vector controlled cycloconverter-fed synchronous motor drive.

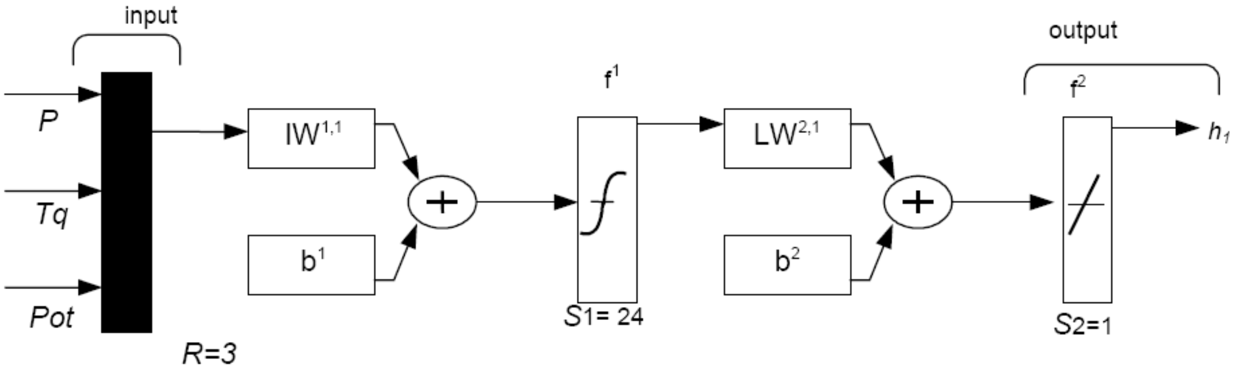

Fig. 9: Neural network with training variables

$$\lambda^r qs = -L_{ls} \cdot i^r qs + L_{mq}\left(-i^r qs + i'^r kq\right)$$
$$\lambda^r ds = -L_{ls} \cdot i^r ds + L_{md}\left(-i^r ds + i'^r kd + i'^r fd\right)$$
$$\lambda'^r kq = L'_{lkq} \cdot i'^r kq + L_{mq}\left(-i^r qs + i'^r kq\right) \qquad (6)$$
$$\lambda'^r fd = L'_{lfd} \cdot i'^r fd + L_{md}\left(-i^r ds + i'^r fd + i'^r kd\right)$$
$$\lambda'^r kd = L'_{lkd} \cdot i'^r kd + L_{md}\left(-i^r ds + i'^r fd + i'^r kd\right)$$
$$Te = \left(\frac{3}{2}\right)\left(\frac{Pol}{2}\right)\left(\lambda^r ds \cdot i^r qs - \lambda^r qs \cdot i^r ds\right) \qquad (7)$$

where *kq*, *kd* and *fd* denote the q and d damper winding variables, and field variables, respectively. These equations were employed to derive the Matlab/ Simulink dynamic model for the synchronous motor drive utilized in overall rolling mill model.

The electric variables necessary to implement the vector control are armature currents I_a, I_b, I_c, field current I_f, and rotor angle position θ_r. The output variables of interest are the electromagnetic torque and the mechanical power at the AC motor shaft (*Tqsinc* and *Pqsinc*).

The modern rolling mill drives are fed by cycloconverters or inverters, and utilize field-oriented control, also known as vector control. A simplified linear converter model was selected for convenience, as shown in Fig 8. The speed controller generates the current torque reference (I_T*) from the speed error, that is responsible for the torque production. During transients, a compensating flux reference is present (I_M*), to ensure fast dynamics, and to maintain the vector conditions between field flux and armature MMF (Bose, 1986). The currents are converted to stator reference d^s-q^s, and then to a,b,c stator reference frame. By proper current loop control (denoted by block G), the three phase currents are forced to follow the reference currents by action of the reference voltage vector v_{abc}^*. This reference voltage vector is then applied to the cycloconverter control.

F. Neural Network Based Thickness Estimation

As previously stated by Eqs. 1(a) and 1(b), the rolling force (*P*) and torque (*Tq*) are dependant on several operating parameters and process variables. It is thus necessary to establish a mathematical relation among these parameters variables. A neural network is well suited to represent such relation, since it can automatically derive the relation from measured data. The Multilayer Perceptron Backpropagation (MLBP) was chosen to provide values such as input and output thickness, as well as other parameters, if necessary. This choice of a MLBP can be seen as a practical tool to realize a non-linear input-output mapping between input and output variables. This network is shown in Fig. 9 and was used as a function approximator to replace Eqs. 1(a) and 1(b). In Fig 9 *R* represents the number of elements in the input vector, *S* is the output vector, *IW* and *LW* are, respectively, the input and hidden layer weights. The sum of the weighted inputs and the bias form the input to the transfer function *f.* A network of two layers, being the first layer with a sigmoid transfer function, and a second layer with a linear transfer function, can be trained to approximate any function (with a finite number of discontinuities) arbitrarily well. P, Tq and Pot were utilized to train the network, and the output S is equal the thickness h_1. These variables are obtained from the Orowan Model, as show in Fig. 5. After adequately trained, the inputs to the neural network were *P*, *Tqsinc* and *Pqsinc*, whereas these two last variables obtained by means of the dynamic model of the synchronous machine drive system, as shown in Fig. 10, and are the electromagnetic torque and mechanical power of the motor. The purpose here is to estimate the input thickness h_{1est} or other operation parameters.

G. Simulation Results

The rolling mill model presented in this paper was calibrated with measured data from in a real rolling process, and constructed with parameters provided by Siderar S.A. Company. The variables utilized to obtain the rolling load (P), rolling torque (Tq) and rolling power (Pot), were: h_1, h_2, t_1, t_2, V_L and temperature θ. Initially, the Orowan model was tuned by adjusting the yield stress S. Fig. 11 shows the input and the output strip thickness of the real rolling mill, that were applied to the model to test the proposed methodology. Figure 12 shows the roll force obtained from the Orowan Model, in comparison with the real force. It was next verified if the torque and mechanical power values of synchronous motor were well correlated with the corresponding torque and rolling power obtained from Orowan Model. In Figs. 13 and 14 can be observed, respectively, the electromagnetic torque and the mechanical power from the motor, compared with the values calculate from the Orowan Model. In Fig. 13 the peak torque occurred at t=2s, and corresponds to the synchronous motor start up, before the introduction of the strip in the roll gap. The electric variables are in accordance with the process variables in the time range above 4 s. These variables are utilized as input variables to the neural network in order to obtain the input and output thickness. The training data are obtained from Orowan Model as shown the Fig. 9. Then, the simulation results are compared with the real data process set as shown in Fig. 15. As shown in Fig. 16 and 17, the real data input thickness h_1 is quite close to the estimated value h_{1EST}. Fig. 18 shows the output thickness estimate h2EST along with the actual thickness (h_2). It can be seen that they are closely related, although not identical.

III. CONCLUSION

This paper demonstrates the possibility to obtain, in real time, the torque and rolling power from the readily available electric stator variables (stator voltages and currents) of the AC motor in rolling mill drives. The proposed technique makes use of a torque estimator, based on the electromagnetic torque dynamic Eq. (6).

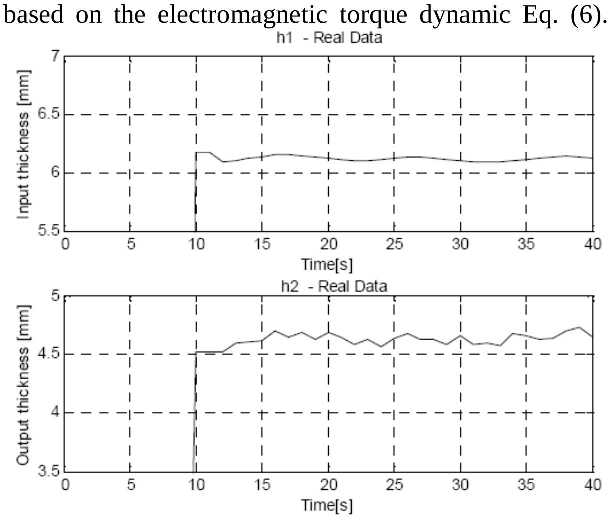

Fig. 11: Input operating variables for the simulation study (input and output thickness magnitudes).

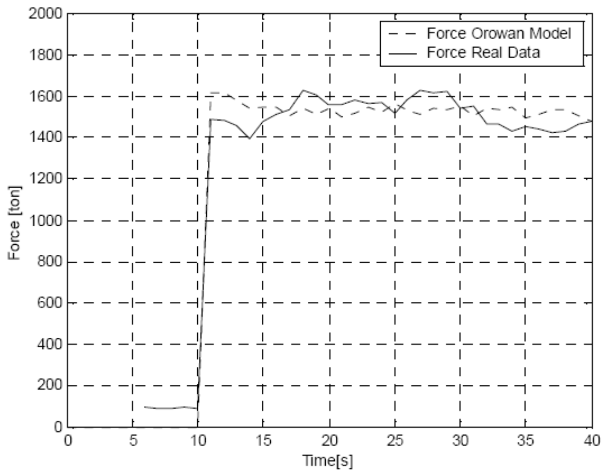

Fig. 12: Real data rolling force and rolling force from the Orowan model.

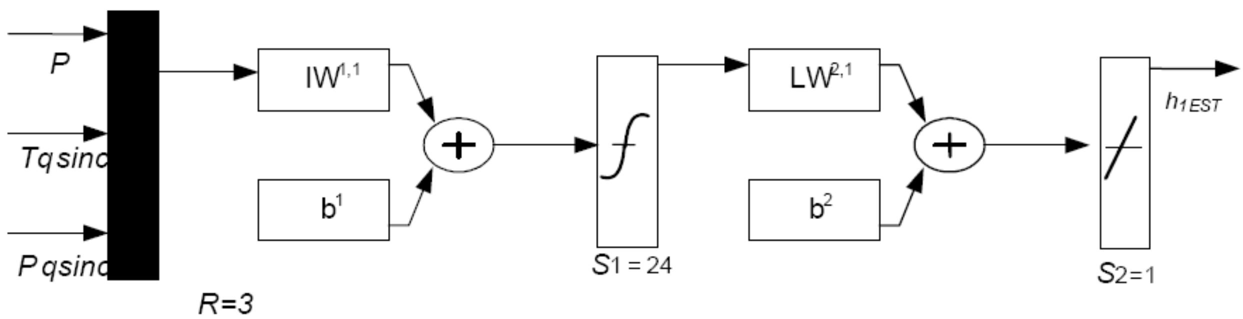

Fig. 10: Neural network with sampled variables.

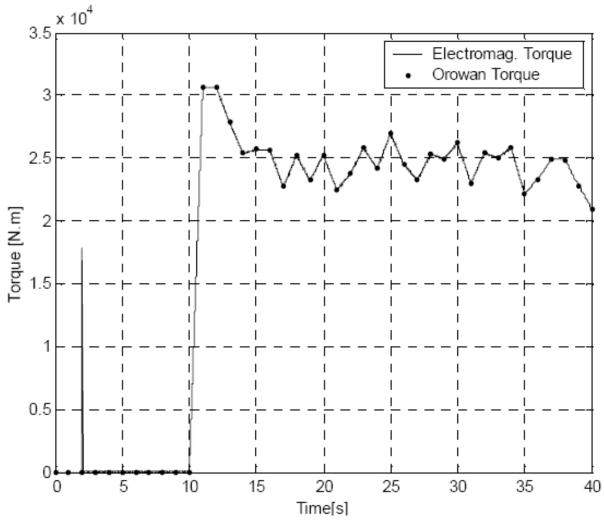

Fig. 13: Developed electromagnetic torque and rolling torque.

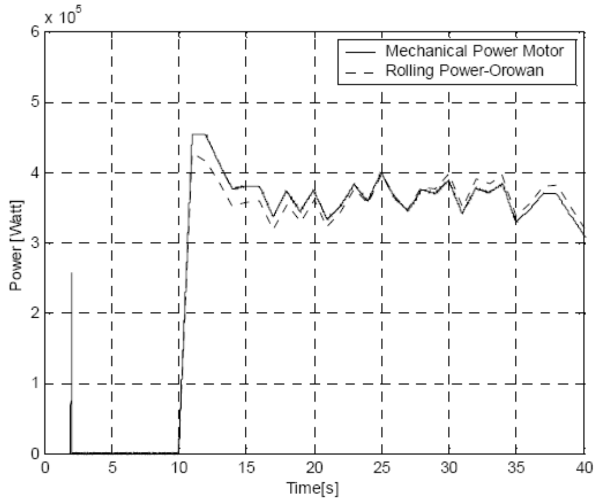

Fig. 14: Electromechanical power in AC motor and rolling power

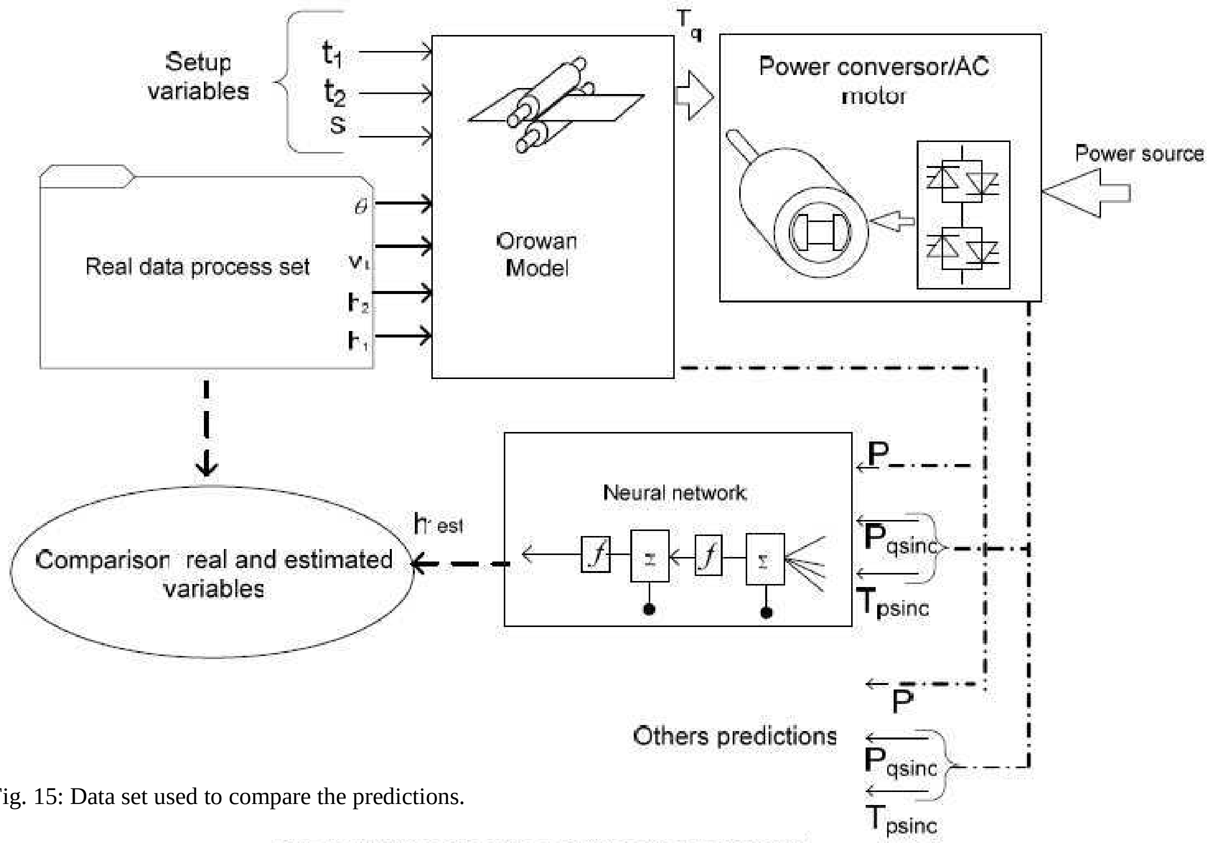

Fig. 15: Data set used to compare the predictions.

Another possibility to be probed the feature, is the utilization of the electromagnetic torque estimate provided by the drive processor, via serial port (suck as RS485).These variables can be used in on-line rolling control, in substitution to the values obtained from simplified models, avoiding additional computation efforts. Moreover,they avoid the use of torque sensors in the process. By means of electric variables and the roll force, and a neural network trained with operational conditions, relevant process variables such as input an output thickness can be obtained with necessary precision. Other variables can be similarly obtained to supervise the rolling process, if necessary.

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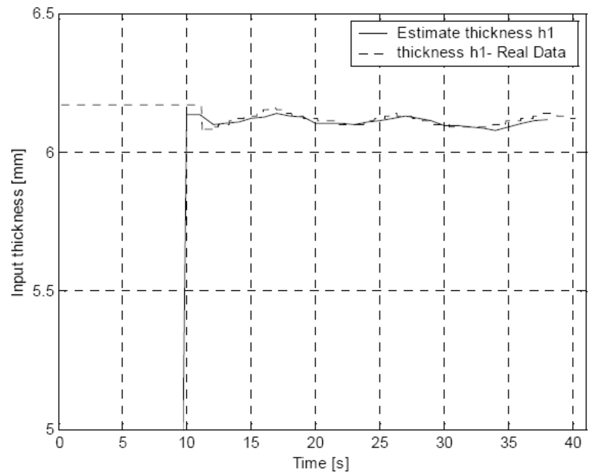

Fig.16: Estimate Thickness h1=h1EST.

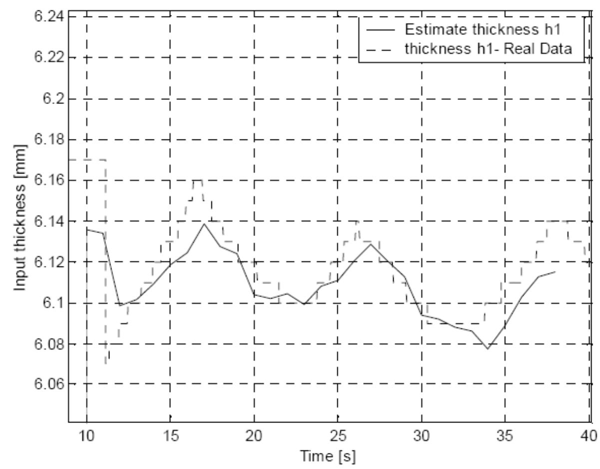

Fig. 17: Estimate Thickness h1=h1EST.

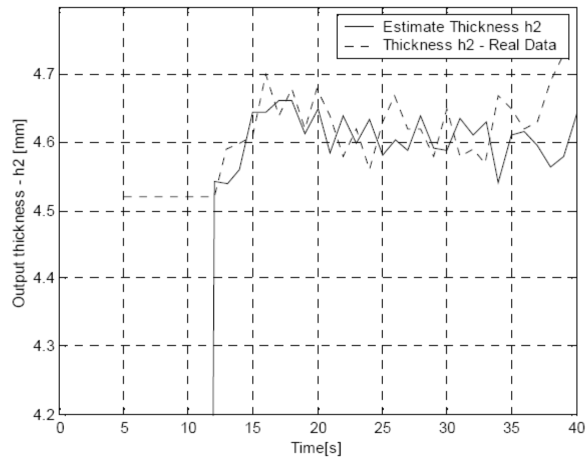

Fig. 18: Estimate Thickness h2=h2EST.

APPENDIX

A) Equivalent Circuit Parameter in rotor reference frame:

Rs=0.3 Ohm, stator winding resistance;

Rqr=2.2 Ohm, amortisseur rotor winding resistance direct axis quadrature axis;

Rdr=2.2 Ohm, amortisseur rotor winding resistance direct axis;

Rfr=0.064 Ohm, winding field resistance direct axis;

J=0.1 kgm^2, rotor inertia;

B=0.001, amortisseur coefficient;

Poles=4;

Llfr=0.0017 H, leakage inductance in field winding direct axis;

Lls=0.001H, leakage inductance in stator windings; Llqr=0.00086H leakage inductance in amortisseur rotor winding quadrature axis:

B) Roll's Phisiques Characteristics

Roll's diameter= 300 mm

Trip width= 500 mm

Roll's Poisson Coefficient = 0,305

Strip's Poisson Coefficient = 0.305

Roll's Young modulus=21000 kgf/mm^2

Stripl's Young modulus=21000 kgf/mm^2

Friction Coefficient=0.1

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