Approach to Estimate the Parameters of the Melded Cast-Iron Conveyance within the Electromagnetic Pumps

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Abstract: In this paper an analysis of the observer-based approach and the differential-algebraic approach used to estimate the parameters and the speed of the melded within the electromagnetic pumps for melted cast iron conveyance and dosage are presented. In the second part of the paper mathematical model of the electromagnetic pump is deduced. In the third and the fourth parts of the paper the basis of above parameters and speed estimation methods are described. The implementation results and conclusions are then presented at the end of the paper.

Key words: electromagnetic pump, speed estimation, observers

1 Introduction

The implementation of the Electro-thermal processes within foundries and forge departments is an important element to improve the products quality and to optimize the energy costs. A modern approach for the conveyance and dosage of melted metals, cast-iron, aluminum, copper and so is the usage of the electromagnetic pumps.

The electromagnetic pumps are used [1] to extract the melted metal directly from the basis of the induction furnace and to cast and dose the melted metals from the mobile melting pots. The advantages of the electromagnetic conveyance of melted metals are: (1) the control by electrical means of the liquid's flow-rate if the pump is supplied from controlled three-phased frequency converters, (2) costs reduction due to the elimination of purging the channel with tempered metal scraps, (3) the increase of the metal's pureness because the non-metallic elements aren't drawn by the electromagnetic forces, (4) the melting furnace and the melting pot may be at the same level thus their structure is much simpler, and (5) an improvement of the working conditions within the casting departments. The main disadvantage of the electromagnetic pump is the channel maintenance especially to the channel's basis where the material is highly solicited.

Basically, the electromagnetic pump is a linear induction motor with a two-sided or single-sided stator whose induced is the melted metal. The main technical characteristics of some widely used electromagnetic pumps are presented in Table 1.

Table 1. The main features of the electromagnetic pumps

Denomi-nation	Units	Lighte metals	Heavy metals	Cast-iron
Tempe-rature	^{0}C	650 – 750	900 – 1200	1450
Flow rate	kg/s	0,1 – 10	0,3 – 30	1,3 – 100
Level	mm	50 – 540	80 – 540	80 – 930
Length	mm	1080 - 2600	1800 - 2600	1800 - 4200

2 The Mathematical Model of The Single-Sided Stator Electromagnetic Pump

The stator winding of the electromagnetic pump supplied from a three-phased electric network produces a progressive electromagnetic field whose first harmonic is given by the following expression.

$$B_\delta(x,t) = B_{\delta m} \cdot sin\left(\omega_1 \cdot t - \frac{\pi}{\tau} \cdot x\right) \qquad (1)$$

where: $B_{\delta m}$ - the magnitude of the magnetic induction, $\omega_1 = 2 \cdot \pi \cdot f_1$ - the angular frequency and the frequency of the voltages at the stator windings, τ - the stator's winding polar step.

The speed of the first harmonic of the progressive wave, v_1 is:

$$v_1 = \frac{\Delta x}{\Delta t} = 2 \cdot \tau \cdot f_1 \tag{2}$$

The progressive magnetic field induces into the melted metal electric electrical currents due to the electromagnetic induction phenomenon.

The electromagnetic force that acts on the melted metal results from the interaction between the electromagnetic field and the induced currents.

The expressions of the physical variables of the progressive field and the electromagnetic force, respectively may be deduced through the Maxwell's equations into the space above the inductor's the air gap of the electromagnetic pump such as for the classical electric machines, [1].

In addition, the following phenomena have to be taken into account: the transversal edge effect, and the longitudinal edge effect (static and dynamic).

The transversal edge effect consists in the modification of currents distribution through the transversal cross-section of the massive induced because the currents paths freely encircle the magnetic field.

The electro-magnetic force results less than the classical machines provided with windings on both armatures. The decrease of the electromagnetic force depends on the ratio between the polar step and the geometrical dimensions of the induced cross-section within the field [1].

The static longitudinal edge effect is because the stator windings aren't balanced – linear stator. The phenomenon consists in a non-symmetrical currents sequence in the stator's windings. The dynamic longitudinal edge effect consists in the modification of the currents distribution along the longitudinal direction due to the induced motion with respect to the progressive magnetic field. If the induced reaction is weak then the static longitudinal edge effect on the non-symmetrical system of currents will be preponderant.

The equivalent electric diagram is obtained through cascade connection of equivalent elements corresponding to the air gap layers.

For the on-line computations i.e. adaptive control, the simplified electrical equivalent diagram in Figure 1, is to be used.

The significance of the components in Figure 1

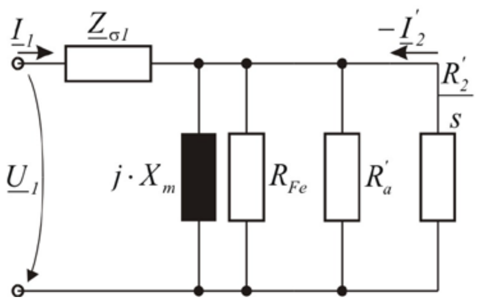

Fig.1 The simplified equivalent electrical diagram of the electromagnetic pump.

is as follows: $\underline{Z}_{\sigma 1}$ - the leakage inductance with respect to the induced, X_m - the linkage inductance, R_{Fe}, R_a' - the equivalent resistances corresponding to the cast-iron and channel losses respectively R_2' - the equivalent resistance of the induced and - the slip. The simplified diagram is only valid for larger polar step inductors at low frequencies.

3 The Extended Observer

In this approach, [3], the extended system is depicted by the following general set of equations with the unknown parameters θ.

$$\left| \begin{aligned} & \frac{dX(t)}{dt} = f\left(X(t), \theta\right) + B \cdot U\ (t) \\ & y(t) = h(X, \theta, t) = C \cdot X(t) \end{aligned} \right. \tag{3}$$

The expressions of the matrices $f\left(X(t), \theta\right)$, B, $h(X, \theta, t)$, C are lengthy and are not given explicitly given here.

The unknown parameters are obtained with a Luenberger observer given by the following expressions.

$$\hat{X}_{k+1} = f\left(\hat{X}_k, \hat{\theta}_k\right) \cdot \hat{X}_k + B \cdot U_k + K \cdot y_k \tag{4}$$

with the estimation error

$$\tilde{X}_k = X_k - \hat{X}_k \tag{5}$$

and

$$\tilde{X}_{k+1} = \left(A - K \cdot C\right) \cdot \tilde{X}_k \tag{6}$$

The implementation of the observer requires a DSP to perform the computations each 200 microseconds, [2]. The results accuracy is altered by the modifications of the parameters due to temperature.

4. The Differential-Algebraic Method to Speed Estimation

The expression of the algebraic speed estimator is obtained by differentiating the general space vector model, [3] of the induction motor as follows.

$$\begin{cases} \dfrac{d\underline{i}_1}{dt} = \dfrac{\beta}{T_R}\cdot\left(1 - j\cdot p\cdot\Omega\cdot T_R\right)\cdot\underline{\Psi}_2^{'} - \\ -\gamma\cdot\underline{i}_1 + \dfrac{1}{\sigma\cdot L_1}\cdot\underline{u}_1 \\ \dfrac{d\underline{\Psi}_2^{'}}{dt} = -\dfrac{1}{T_R}\cdot\left(1 - j\cdot p\cdot\Omega\cdot T_R\right)\cdot\underline{\Psi}_2^{'} + \\ +\dfrac{L_h}{T_R}\cdot\underline{i}_1 \\ \dfrac{d\Omega}{dt} = \dfrac{p\cdot L_h}{\underline{J\cdot L_2^{'}}}\cdot\operatorname{Im}\left\{\underline{i}_1\cdot\underline{\Psi}_2^{*}\right\} - \dfrac{M_W}{J} \end{cases} \tag{7}$$

Where: $\underline{u}_1$, $\underline{i}_1$, $\underline{\Psi}_2^{'}$ are the space vectors of the stator voltages, currents and the rotor flux linkage respectively, p is the number of pair poles of the pump, $R_1, R_2^{'}$ are the inductor and induced resistances, $L_1, L_h, L_2^{'}$ are the inductor inductance, the mutual inductance and the induced inductance respectively, $T_R = L_2^{'}/R_2^{'}$ is the induced time constant, $\sigma = -L_h^2/\left(L_1\cdot L_2^{'}\right)$ is the total leakage factor, Ω is the induced angular speed, is the load torque.

Differentiating (2) gives, [4]:

$$\begin{aligned} \frac{d^2\underline{i}_1}{dt^2} &= \frac{\beta}{T_R}\cdot\left(1 - j\cdot p\cdot\Omega\cdot T_R\right)\cdot\frac{d\underline{\Psi}_2^{'}}{dt} - \\ &- j\cdot p\cdot\Omega\cdot T_R\cdot\underline{\Psi}_2^{'}\cdot\frac{d\Omega}{dt} - \gamma\cdot\frac{d\underline{i}_1}{dt} + \\ &+ \frac{1}{\sigma\cdot L_1}\cdot\frac{d\underline{u}_1}{dt} - \\ &- \frac{j\cdot p\cdot T_R}{1 - j\cdot p\cdot\Omega\cdot T_R}\cdot\left(\frac{d\underline{i}_1}{dt} + \gamma\cdot\underline{i}_1 - \frac{\underline{u}_1}{\sigma\cdot L_1}\right)\cdot\frac{d\Omega}{dt} \end{aligned} \tag{8}$$

Where; $\beta = L_h/\left(\sigma\cdot L_1\cdot L_2^{'}\right)$and
$\gamma = R_1/\left(\sigma\cdot L_1\right) + \left[1/\left(\sigma\cdot L_1\right)\right]\cdot\left[1/T_R\right]\cdot\left[L_h^2/L_2^{'}\right]$.

Solving the equation above for $d\Omega/dt$ leads to a complex function depending on Ω, the machine's parameters, stator voltages, stator currents and their derivatives. It is proven in [4] that, in steady-state operation, the real part of the complex function is never stable and cannot be used as a speed observer. However, the imaginary part which is a second degree in Ω is stable and one of the two zeros is equal to the induced speed.

The expression of the observer is as follows.

$$\Omega = \frac{1}{D}\cdot\left[\frac{1}{A+B}\cdot\left(\frac{d^2\underline{i}_1}{dt^2} - C\right) - 1\right] \tag{9}$$

with: $A = -\dfrac{1}{T_R}\cdot\left[\dfrac{d\underline{i}_1}{dt} + \gamma\cdot\underline{i}_1\cdot - \dfrac{1}{\sigma\cdot L_1}\right]$,

$B = \dfrac{\beta\cdot L_h}{T_R^2}\cdot\underline{i}_1$, $C = -\gamma\cdot\dfrac{d\underline{i}_1}{dt} + \dfrac{1}{\sigma\cdot L_1}\cdot\dfrac{d\underline{u}_1}{dt}$,

$D = -j\cdot p\cdot T_R$.

The coefficients of this expression contain the second and the first order derivatives of the stator currents and the first order derivative of the stator voltage so there is noise concern.

5 Implementations and Results

5.1. The Parameters Estimation

The basic features of the electromagnetic pump taken into account are given in Table 2.

Table 2. The Technical Features of the Experimental Induction Electromagnetic Pump

No.	Denomination	Symbole	Units	Value
1	The rated supply voltage	U_{1N}	V	220
2	The rated frequency	f_{1N}	Hz	50
3	The rated flow rate	Q_{mN}	kg/s	22
4	No. of units	-	-	2
5	Total power of an unit	P_t	W	9500
6	The induced	-	-	cast-iron
7	The pump's slope	s	0	10

To estimate the pump parameters based on the extended observer a Matlab application has been implemented. The phase resistance of the inductor has been previously measured and the inductance coefficients have been separately calculated based on the pump's geometry. The parameters estimations are presented in Table 3.

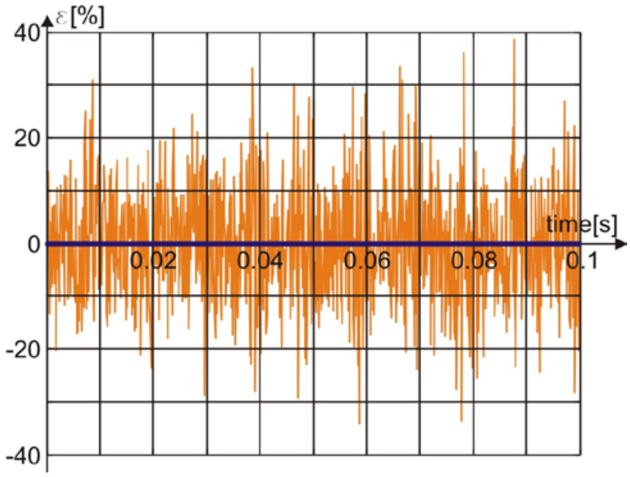

Fig. 2 The measurements errors and the their average value for a 0.01% corrupting noise.

Table 3. The estimated values of the electrical parameters of the experimental pump, [5]

Denomination	Symbol	Units	Value
Phase resistance of the inductor	R_1	Ω	0.042361
Total inductance of the stator winding	L_1	H	0.0038067
The equivalent resistance of the melted metal	R_2'	Ω	5.9419e-006
The linkage inductance	L_m	H	0.0028573
The inductancies coefficient	σ	-	0.75061

5.2. The Speed Estimation

To emphasize the behavior i.e. the stability of the speed observer and the influence of the corrupting noise over the estimate, a program in the MatLab environment has been implemented. In the first place, the general expression of the speed observer given in notation (9) has been adapted for the model of the linear induction motors. Afterwards, a normal distributed noise with zero mean and the variance $\lambda = 1$ has been added to the measured phase voltages and phase currents. The mean values of the measurements and their standard deviation with respect to the noise measurements conditions are presented in Table 4.

Table 4. The Mean Values and Standard Deviation of the Speed Observer with Respect to the Noise Conditions.

No.	Noise magnitude	Mean Value	Standard Deviation
-	[%]	[m/s]	$[m/s]^2$
2	0.10	0.0231	0.0258
3	0.05	0.0223	0.0127
4	0.04	0.0229	0.0098
5	0.03	0.0229	0.0074

The errors and the mean value of the measurements are presented in Figures 2.

As seen from Table 2 the statistical mean value of the speed observer are convergent to the theoretical value of the speed. These results prove that if the statistical characteristics of the corrupting noise are known then the sensor less algebraic speed observer is consistent in statistical sense.

6 Conclusion

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