Estimation of the Induction Motor Parameters of an Electric Vehicle

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***Abstract*-With the advent of the electric vehicles, one market niche can be the transformation of the internal combustion engine vehicles into electric vehicles equipped with induction motors. One of the challenges of this process is to establish simple and fast methods to estimate the parameters of the available induction motor. In this paper, a method to estimate unknown parameters of an induction motor equivalent electric circuit is presented and discussed. With the proposed method, the unknown electric parameters can be estimated knowing only the induction motor nominal voltage, current torque, frequency and speed. Knowing the induction motor equivalent circuit parameters, further studies and simulations can be conducted to design the complete traction system (namely the bank of batteries and power converter) to be installed in an electric vehicle.**

I. INTRODUCTION

During the last decades, electric vehicles have been under development and strong efforts have been made by the car manufacturers to get technically sound solutions. Year after year, car manufacturers have been presenting new prototypes not only of hybrid solutions but also purely electric versions. Some of the pure electric vehicles use induction motors to power their prototypes taking advantage of the characteristics of this type of motor (these machines are less expensive, require less space and are more reliable and efficient than other electric machines). In addition, the electric power chain can be implemented using efficient power converters and distinct control techniques. The versatility of such systems contributes to make the electric vehicles based on induction motors one of the common solutions adopted by the automotive industry.

Although being these machines may be the typical choice in industrial variable speed applications, the design of induction motor to be used in electric vehicles presents particular characteristics according to the requirements of the application, as for instance the power, the torque and speed range. Usually, electric car's induction motors conform to a specific design and have characteristics that are different from the typical industrial induction motors. Furthermore, the induction motor for an electric vehicle should contribute to meeting the expectations of a car driver.

Fig. 1. Photography of the induction motor and of the "Fiat Seicento Elletra".

Along with the launching of electric vehicles onto the market, it is expected that the transformation of internal combustion engine (ICE) vehicles into electric vehicles will mature. This will entail maintenance problems which will be different from those of combustion vehicles. To test and fix electric cars, it will be useful to estimate the motor parameters with the motor mounted in the car. In this situation experimental procedures to determine the motor' parameters cannot be performed easily and quickly [1], [2], [3], [4], [8], [9]. Some classical experiments could be difficult to perform because they require not only additional electrical equipment but also mechanical instruments. To overcome these constraints, in this paper, a process based on a computational algorithm developed to compute easily and quickly the parameters of the electric equivalent circuit of an induction machine is described. To use this algorithm one only needs to know the induction motor nominal voltage, current torque, frequency and speed, and to measure stator resistance. With this procedure, the open circuit and short circuit tests can be avoided. Using the proposed process the rotor's inductance, the stator's inductance, the rotor resistance and the magnetic inductance the induction motor equivalent electric circuit are estimated. After that, it is possible to use other tools to study the dynamic behaviour of the motor or to check the health of the motor. Knowing the induction motor equivalent circuit parameters, further studies and simulations

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can be conducted to design the complete traction system (namely the bank of batteries and power converter).

A difficulty that the authors had faced in this work was the need to estimate the electrical parameters of a commercial "Fiat Seicento Elettra" induction motor (Fig. 1) [6]. In the first section of the paper the basic and known information about the motor is presented and discussed. In the following sections the algorithm is presented and explained. The estimated parameters are presented and simulation results performed based on this induction machine are shown and discussed.

II. IMPLEMENTED ALGORITHM

A. Manufacturer standard parameters

As mentioned before, the main motivation to develop this algorithm was the difficulty of knowing the electrical parameters of the induction motor used in the commercially available electric "Fiat Seicento Elletra" [6]. A project involving the car is being conducted and additional information about the motor is required in order to investigate and develop new solutions to the traction system based on this electrical machine. The information that was already known and that was provided with car is reproduced in Table I. It is possible to find out from these data that the motor in question does not show linear behaviour with changes of supply voltage and frequency. As can be seen in Table I, the manufacturer only provided information about three nominal operation points. Therefore, to fully characterize the motor's behaviour it is necessary to estimate the electrical parameters according to the supply conditions, i.e., according to the supply voltage and frequency.

It is also known that the motor power is 30 kW manufactured by Siemens (Motor model/reference: 1LH5118-4AA9-Z) and supplied by a voltage inverter [4]. The motor is water cooled and has a length of 360 mm and a diameter of 196 mm.

TABLE I
STANDARD MANUFACTURER INFORMATION

Nominal values					
Operation Points	**Volt. (V)**	**Freq. (Hz)**	**Current (A)**	**Torque (Nm)**	**Speed (r.p.m.)**
A	76	76	157	65	2200
B	121	220	90	22	6500
C	121	305	88	16	9000

B. Algorithm steps

The main objective of this paper is to estimate the parameters of the induction motor equivalent circuit. The method proposed in this paper is based on the manufacturer information and on the electrical equations obtained from classical equivalent circuits of an induction machine.

As inputs, the algorithm uses the following parameters given by the manufacturer: torque, speed, power and frequency (in general, nominal values). Using the typical electrical equations representing the induction machine and the nominal point values, the motor slip and the stator flux can be calculated. However, to get all the parameters an additional input is needed. Using an ordinary DC low power source it is possible to obtain the stator resistance measuring the voltage and the current.

In order to use this algorithm for any induction machine class, the algorithm can be tested assigning a value to the stator reactance (in per unit values) and establishing a relationship between the stator and rotor reactance according to the standard "IEEE 112" [4].

Using a "©Matlab" computing program all parameters can be calculated according to the equations that are going to be shown in the coming sections.

In order to give an overview of the computing process, algorithm steps are summarized in the block diagram represented in Fig. 2.

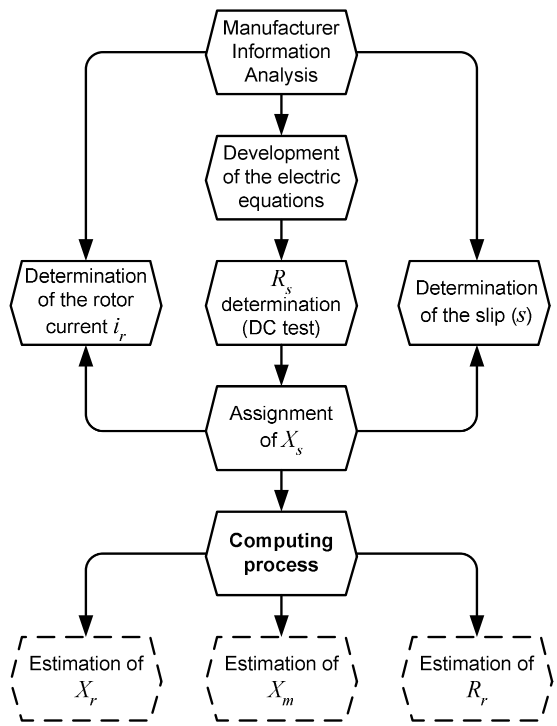

Fig. 2. Computing process.

C. Stator resistance determination

As was mentioned earlier, one of the inputs of the proposed algorithm is the stator resistance. According to the nominal values of the available machine (Table I) it is to be expected that a low value to the stator resistance would be difficult to measure with accuracy. Accordingly, two tests were performed to measure this parameter.

i) *DC test*:

The stator windings of the induction motor assembled in the "Fiat Seicento Elletra" are Y (star) connected. Using a DC voltage source and measuring the current and the voltage, the resistance of two stator windings is calculated applying the "Ohm law". After 20 measurements, the following average values were obtained:

$$\begin{cases} R_1 + R_2 = 0.067408\,\Omega \\ R_2 + R_3 = 0.062063\,\Omega \\ R_1 + R_3 = 0.068020\,\Omega \end{cases} . \quad (1)$$

Solving the equation (1):

$$\begin{cases} R_1 = 0.036683\,\Omega \\ R_2 = 0.030725\,\Omega \\ R_3 = 0.031337\,\Omega \end{cases} . \quad (2)$$

The average of the three previous values is the value calculated to the stator resistance:

$$R_s = 0.032999\ \Omega . \quad (3)$$

ii) *AC test*:

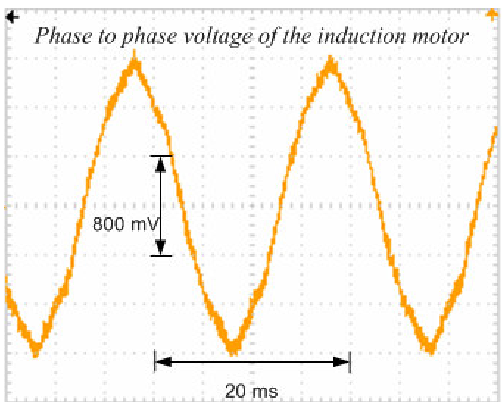

Fig. 3. Phase to phase voltage waveform.

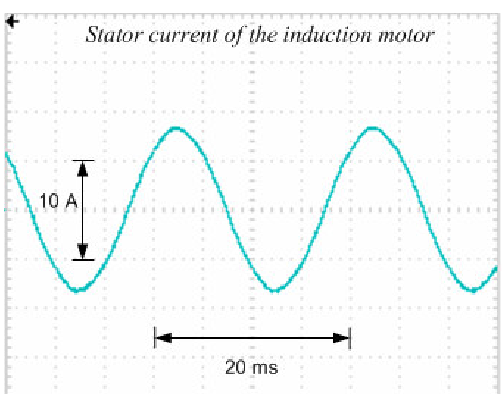

Fig. 4. Line current waveform.

The AC test is performed using an autotransformer connected to the motor. Using an oscilloscope, the current and voltage waveforms can be obtained, and using calibrated voltage and current probes, the stator resistance can be calculated with accuracy. Using as reference the Fig. 3 (phase to phase voltage) and Fig. 4 (line current) waveforms, the stator resistance obtained was obtained using the following values:

- V_{RMS} = 0.778 V (phase to phase)
- I_{RMS} = 11.6 A (line current)
- $\left|\bar{Z}\right| = 0.0387\ \Omega$
- $\varphi \cong 30^{\circ}$ (single voltage – current angle)

So,

$$R_s = 0.0335\ \Omega . \quad (4)$$

D. *Algebraic equations*

The developed algorithm is based on the equivalent circuit of the induction machine represented in Fig. 5 (iron losses were neglected) [1]-[3], [5], [8], [9].

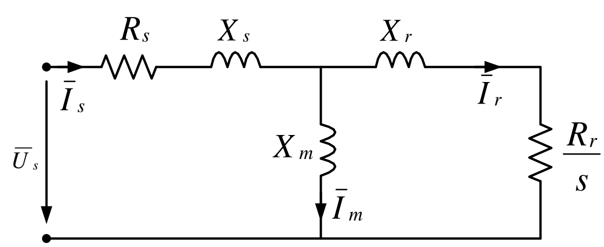

Fig. 5. Equivalent circuit of the induction machine.

Resistances and inductances of the equivalent electric circuit branches were grouped:

$$\begin{cases} \bar{Z}_s = R_s + j\,X_s \\ \bar{Z}_r = \dfrac{R_r}{s} + j\,X_r \\ \bar{Z}_m = j\,X_m \end{cases} . \quad (5)$$

In order to simplify the electric circuit, the global impedance is:

$$\bar{Z}_{eq} = \bar{Z}_s + \bar{Z}_m // \bar{Z}_r = \bar{Z}_s + \bar{Z}_{rm} . \quad (6)$$

Being,

$$\bar{Z}_{rm} = \bar{Z}_m // \bar{Z}_r \Leftrightarrow$$
$$\Leftrightarrow \bar{Z}_{rm} = \frac{\left(\dfrac{R_r}{s} + j\,X_r\right)(j\,X_m)}{\dfrac{R_r}{s} + j(X_r + j\,X_m)} = \frac{(j\,X_m)\left(\dfrac{R_r}{s}\right) - X_r X_m}{\dfrac{R_r}{s} + j(X_r + j\,X_m)} . \quad (7)$$

And,

$$\overline{Z}_{eq} = \overline{Z}_s + \overline{Z}_{rm} \Leftrightarrow$$

$$\Leftrightarrow \overline{Z}_{eq} = (R_s + jX_s) + \frac{(jX_m)\left(\frac{R_r}{s}\right) - X_r X_m}{\frac{R_r}{s} + j(X_r + X_m)} \quad (8)$$

The global impedance can be represented as following:

$$\overline{Z}_{eq} = \frac{A + jB}{C}. \quad (9)$$

Where:

$$\begin{cases} A = \left[\frac{R_r R_s}{s} - X_s(X_r + X_m) - X_r X_m\right] \\ B = \left[(X_s + X_m)\left(\frac{R_r}{s}\right) + R_s(X_r + X_m)\right] \\ C = \left(\frac{R_r}{s}\right) + j(X_r + X_m) \end{cases}. \quad (10)$$

According to the equations above, the stator current and stator voltage are given by:

$$\overline{U}_s = \overline{Z}_{eq} \overline{I}_s. \quad (11)$$

Expanding equation (11):

$$U_s\left(\left(\frac{R_r}{s}\right) + j(X_r + X_m)\right) = I_s(\cos\alpha + j\sin\alpha)(A + jB). \quad (12)$$

Where α is the angle of the stator's current (I_s).

The real and imaginary parts of equation (12) can be isolated. Doing the real/imaginary division of equation (12), four unknown variables can be identified: the stator reactance (X_s), the magnetic reactance (X_m), the rotor reactance (X_r) and the rotor resistance (R_r). To reduce the number of unknown variables, a "per unit" value is assigned for the stator reactance (X_s) and a relationship with the rotor reactance (X_r) is established fulfilling the standard "IEEE 112" standard [4]. With this restriction and using the following equations all the parameters can be computed.

$$\begin{cases} U_s\left(\frac{R_r}{s}\right) = I_s(A\cos\alpha - B\sin\alpha) \\ U_s(X_r + X_m) = I_s(B\cos\alpha + A\sin\alpha) \end{cases}. \quad (13)$$

Since the above equations (13) are non-linear, the solutions of these equations depend on the initial conditions and of the values assigned to the stator reactance and rotor reactance. To guarantee the convergence of the implemented algorithm, the following condition is imposed and verified:

$$\overline{I}_s = \overline{I}_m + \overline{I}_r. \quad (14)$$

To calculate the absolute value of the magnetic current and the angles of the magnetic current and the rotor current, the following equations are used:

$$\begin{cases} U_s = I_s[R_s\cos\alpha - X_s\sin\alpha] + I_r\left[\left(\frac{R_r}{s}\right)\cos\beta - X_r\sin\beta\right] \\ 0 = I_s[X_s\cos\alpha + R_s\sin\alpha] + I_r\left[\left(\frac{R_r}{s}\right)\sin\beta + X_r\cos\beta\right] \end{cases}. \quad (15)$$

Where β is the angle of the rotor's current (I_r).

Or:

$$\begin{cases} U_s = I_s[R_s\cos\alpha - X_s\sin\alpha] - X_m I_m \sin\gamma \\ 0 = I_s[X_s\cos\alpha + R_s\sin\alpha] + X_m I_m \cos\gamma \end{cases}. \quad (16)$$

Where γ is the angle of the magnetization current (I_m).

At the end of the algebraic process, five parameters were calculated: the magnetic reactance (X_m), the rotor reactance (X_r), the rotor resistance (R_r), the angle of the rotor current, the absolute value of magnetic current and the angle of magnetic current. Fulfilling the condition (14), and using another "©Matlab" routine the relationship between the stator reactance and the rotor reactance (k_x factor) was checked.

The steps of the last routine are summarized in the Fig. 5 diagram.

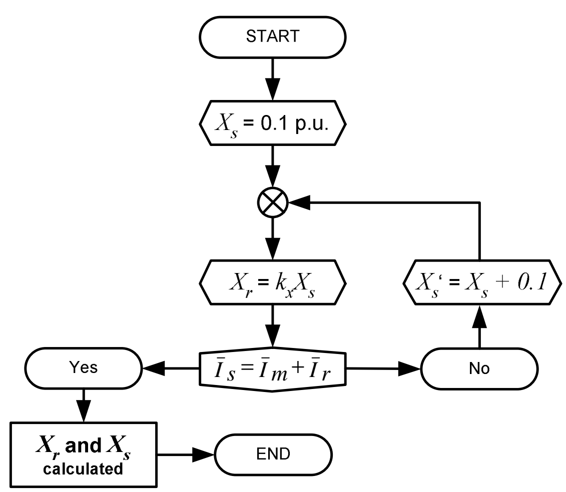

Fig. 6. Routine implemented to check X_s and X_r values.

E. Results

The routine illustrated in Fig. 6 can be used to compute X_s and X_r for different k_x factors. To analyse the variation of the output variables with the k_x factor in order to get the best fit, avariation of the rotor reactance between 50% and 100% was considered and applied to the three nominal points given by the motor manufacturer (Table I).

Based on the Table I nominal values and for different k_x factors, the parameters obtained are shown in Tables II to VII.

TABLE II
MOTOR PARAMETERS (K_x = 100%)

Parameters	Operation points		
	A	B	C
L_s (mH)	0.1333	0.0441	0.0305
L_r (mH)	0.1333	0.0441	0.0305
L_m (mH)	0.2141	0.3219	0.2418
R_r (Ω)	0.00692	0.01231	0.01334

TABLE III
MOTOR PARAMETERS (K_x = 90%)

Parameters	Operation points		
	A	B	C
L_s (mH)	0.13495	0.04425	0.03066
L_r (mH)	0.12146	0.03983	0.02759
L_m (mH)	0.23661	0.32053	0.240791
0.00692	0.00692	0.01231	0.01334

TABLE IV
MOTOR PARAMETERS (K_x = 80%)

Parameters	Operation points		
	A	B	C
L_s (mH)	0.13651	0.04438	0.03075
L_r (mH)	0.10921	0.03551	0.02458
L_m (mH)	0.23187	0.31916	0.23978
R_r (Ω)	0.00692	0.01231	0.01334

TABLE V
MOTOR PARAMETERS (K_x = 70%)

Parameters	Operation points		
	A	B	C
L_s (mH)	0.13801	0.04451	0.03085
L_r (mH)	0.09660	0.03115	0.02159
L_m (mH)	0.22717	0.31780	0.23877
R_r (Ω)	0.00691	0.01231	0.01334

TABLE VI
MOTOR PARAMETERS (K_x = 60%)

Parameters	Operation points		
	A	B	C
L_s (mH)	0.13931	0.04463	0.03092
L_r (mH)	0.08359	0.02678	0.01854
L_m (mH)	0.22354	0.31644	0.23776
R_r (Ω)	0.00691	0.01231	0.01333

TABLE VII
Motor parameters (k_x = 50%)

Parameters	Operation points		
	A	B	C
L_s (mH)	0.14046	0.04471	0.03099
L_r (mH)	0.07023	0.02235	0.01549
L_m (mH)	0.21803	0.31509	0.23676
R_r (Ω)	0.00692	0.01232	0.01334

III. RESULTS ANALYSIS

A. *Simulation Results*

In order to check the accuracy of the described algorithm, simulations using the obtained parameters (Table II to Table VII) were performed using the "©Matlab/simulink" [7].

In Fig. 7, the main blocks of model used to simulate the induction machine are represented ("©Matlab/simulink").

In the Fig. 8 the starting current transients are shown using the parameters calculated with the proposed algorithm.

The time evolution of the rotor speed is shown in Fig. 9, and electromagnetic torque in Fig.10, using the parameters of tables II to VII.

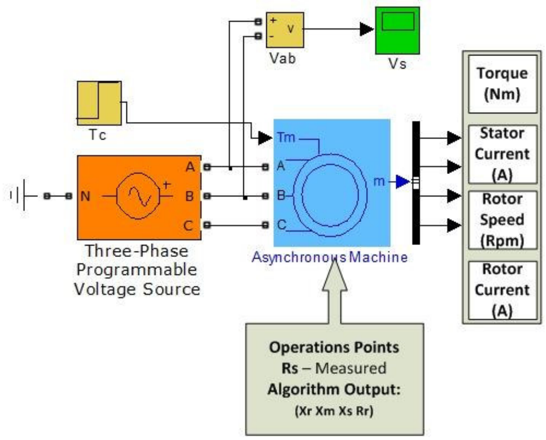

Fig. 7. Inputs and outputs of the estimation process.

B. *Remarks*

The algorithm was computed considering various relationships between the leakage inductance of the stator and the leakage inductance of the rotor. The parameters obtained for each of the k_x factor were then used in several simulations, which main results were presented in the previous section. For the available machine, the values of the parameters X_s and X_r should be within a narrow range, which makes it important to analyse the simulation results in order to determine the parameters X_s and X_r.

From the analysis of the simulation results obtained and considering the indications present in the standard "IEEE 112" [4], which describes basic procedures to test induction motors and estimate their parameters, the design class which fits best for this model is the class A induction machine. The classes of designed motors and their description are described in NEMA MG1 [B3] standard [4]. Class A is described as having a normal starting torque and a normal starting current. For this type of class the standard predicts that the stator will have approximately the same leakage reactance as the rotor's. So the best fit used in the simulations is the model for k_x = 100% (Table II).

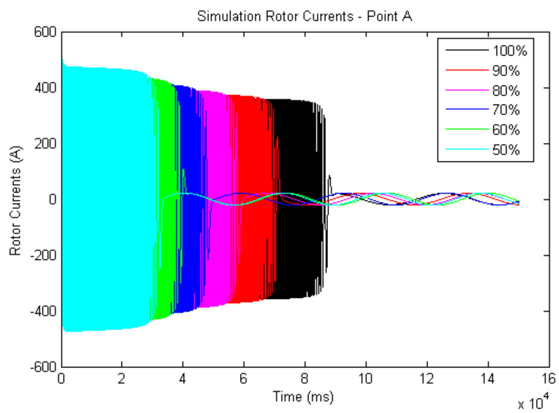

Fig. 8. Time evolution of the rotor starting current, $k_x \in [50,100]$ %.

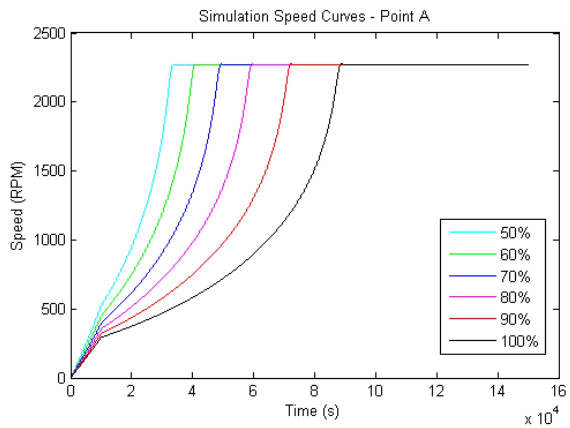

Fig. 9. Time evolution of the rotor speed, $k_x \in [50,100]$ %.

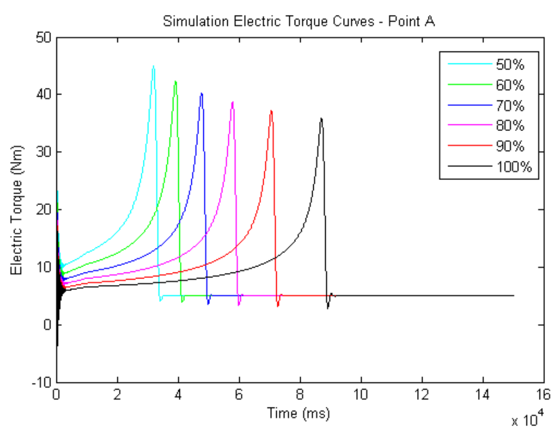

Fig. 10. Time evolution of the electromagnetic torque, $k_x \in [50,100]$ %.

IV. CONCLUSION

In this paper a mathematical algorithm used to estimate the parameters of an induction machine equivalent circuit is presented.

The described solution was developed in order to avoid to performing typical tests used to calculate these parameters.

This proposed method is a useful tool and can be used to determine the parameters of the induction motor when enough information about the machine is not available.

The algorithm starts out using only the typical parameters of an induction motor (typically a nominal point): torque, power, speed, voltage and frequency. Since the developed procedure needs an additional parameter, the rotor resistance was chosen because it can be measured easily as was described in section II.C of this paper. Performing the calculus based on the proposed algorithm, simulations were performed to check the accuracy of the obtained parameters. Using the parameters obtained for the available induction machine, the traction system of the "Fiat Seicento Elletra" electric vehicle is being re-designed based on sate-of-the art solutions.

As final remark, it is important to point out that the performed simulations predict well the behaviour of the motor available, being in accordance with the few data provided by the car manufacturer.

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