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# A Three-Step Procedure for Parameter Estimation of Induction Machines Considering Saturation Effect

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**Abstract:** The objective of this paper is identifying a nonlinear model for Induction Machine's parameters in offline mode considering saturation effect. Accordingly, first, the model of IM is simulated and then it is shown how saturation can be involved in this model. The results reveal that short-circuit current waveforms of machine are less sensitive to variations of the mechanical parameters. This concept is used to estimate electrical parameters regardless of mechanical equations in double-line-to-neutral short-circuit test. The obtained results are then used to compute the mechanical parameters from the starting test. It will be shown that with involving saturation in the proposed algorithm, we get closer to actual model results.

**Key words:** Identification of parameters · Induction Machine (IM) · MATLAB/SIMULINK · Nonlinear model · Offline mode · Saturation effect.

## INTRODUCTION

In recent decades, by increasing consumption of electrical energy and high production costs of fossil energy sources, made countries look for new methods of electricity production through renewable sources such as wind energy which has found a great interest. Considering the increasing number of wind power plants connected to distribution networks, extensive research on the plants and Induction Machines (IMs) which worked including generators and motors have been concentrated. Generally, these studies have been performed in stability analysis of fields, control and fault detection of IM. Furthermore, precise machine parameters are required for steady state analysis, dynamic operation and optimized control of IM and its protection relays adjustment. Hence, various methods have been utilized for IM parameter estimation so far. These methods can be categorized into two major groups: a) online and b) offline methods.

Great advances in the oriented control field of induction machines have brought parameter identification and online estimation methods into consideration [1,2]. However, offline parameter identification methods due to simplicity, low expenses and no need to additional hardware are still used so much [3].

So far, many attempts have been carried out to provide new solutions or to improve current solutions to optimize IM parameter identification accuracy. Reference [4], presents a method to estimate the electrical parameters of an induction motor fed by Voltage Source Inverter (VSI) using Recursive Least Squares (RLS) method. In this paper, four electrical parameters of the IM are simultaneously estimated with single-phase locked-rotor test at only one angular frequency of the stator current; however, all electric and mechanical parameters have not been identified. Moreover, only one mode of machine, known as standstill mode, has been considered. In [5], by combining "Maximum-Likelihood Identification" and "Kalman-Filter", a vector of optimized parameters is produced. In this paper, finite element simulation is used to find asymmetric machine's short circuit results. The results are then used as an input for a new algorithm for estimating machine's parameters. However, not considering iron saturation effect of machine is the most important problem that affects the estimated machine's parameters markedly. In [5], the significance of machine's

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parameters, especially the rotor time constant updating scheme for a rotor flux-oriented induction motor drive has been described. In this paper, a special technique called current-regulated pulse width modulation (CRPWM) is used to identify the rotor time constant. This technique poses some problems such as requiring additional equipment and hardware to control, limitation of using at low speeds and requiring an accurate calculation of slip frequency. In [6], two online and offline methods are used to identify induction machine's parameters, especially its 'time constant'. The problem of this method is its requirement for transient state of machine's speed. Moreover, using derivative in its flow control system causes significant disturbance. Also, other problems such as requiring extra equipments and hardware for flux production system, makes the method expensive and complicated. In [6], a technique has been introduced to approximate online resistance, inductance and the state or transient inductance, which is independent of the speed and rotor time constant. However, the parameters are not instantly identifiable. In [7], a new application of a chaos particle swarm optimization (PSO) algorithm for parameter estimation of an induction machine has been proposed. The algorithm used the measurements of the three-phase stator currents, voltages and the speed of the induction machine as the inputs of the parameter estimator. Experimental Results in this paper compare the estimated parameters with the induction machine parameters achieved using traditional tests such as the DC, no-load and locked-rotor tests.

In all previous methods, currents are used as a state variable. In this paper, however, fluxes play the role of currents and are used as state variables. This helps eliminating extra steps, which consequently will lead to simplify the process and reducing the required time. In this study, a suitable three-step method is used to approximate electromechanical parameters of an induction machine. Another important advantage of this method is that the rotor speed measurements are not required for identification. Moreover, implementing this method in offline mode will omit extra expenses and complexity of online mode. The main objectives of this paper are:

- To develop a block diagram of an electromechanical model with respect to the saturation effect on induction motor in state space form in MATLAB/SIMULINK. It is remarkable to say that the proposed model is taken into d-q state based on park transition and it has been expanded for a double-cage induction motor;

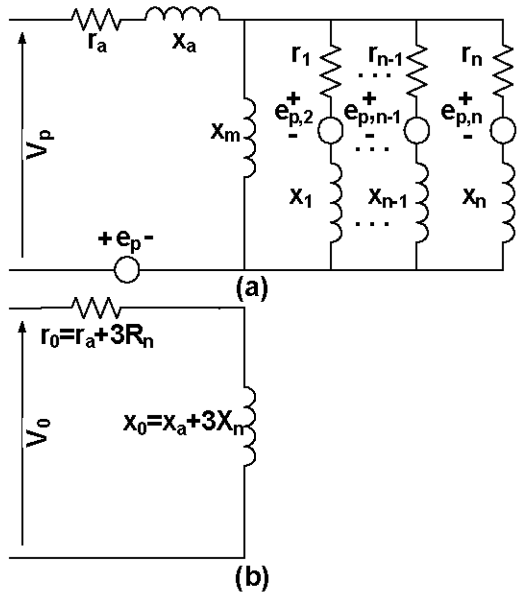


Fig. 1: (a) Generalized Park's equivalent-circuits of wye-Grounded-connected IM, $p = d$ for d-axis and $p = q$ for q-axis; (b) Zero-sequence axis; Rn and Xn are neutral resistance and reactance: $p = d$, $e_{d_k} = g\psi D_k$ , $e_d = -\omega_s \psi_q$ .

- To adapt the k-factor cross saturation approach of synchronous machines in order to analyze IM with the numerical computation method;
- To use induction machine model available in the MATLAB 7.6 instead of online model to obtain the initial parameters performing traditional tests;
- To express an example to show the efficiency of the proposed method for approximate parameters of a cage-type induction machine.

**Electromechanical State Models of IM:** Regarding the previous works of electromechanical state modeling of IM, a model of induction machine can be chosen. In reference [8], a complete model of induction machine is presented that can be easily simulated in MATLAB/SIMULINK environment. However, the used model in this paper is the general form of the number of cages, which is shown in Fig. (1). The model is the park generalized equivalent circuit for a three-phase induction machine. The classical single-cage and double-cage rotors are obtained by setting $n = 1$ and $n = 2$ respectively. Accordingly, a two-rotor windings model ($n = 2$) has been chosen in this paper to represent a double-cage IM. In [9], Matrix formulations of an accurate IM model, including the neutral connection for both balanced and unbalanced test analysis is given. Here we summarize relations used in previous works:

$$\begin{bmatrix}\psi_s\\ \psi_r\end{bmatrix}=\begin{bmatrix}X_s & X_{sr}\\ X_{sr}^t & X_r\end{bmatrix}\begin{bmatrix}i_s\\ i_r\end{bmatrix}\Leftrightarrow \Psi = Xi \qquad (1)$$

$$\begin{bmatrix}v_s\\ v_r\end{bmatrix}=\begin{bmatrix}R_s & O_{3,2n}\\ O_{2n,3} & R_r\end{bmatrix}\begin{bmatrix}i_s\\ i_r\end{bmatrix}+\left[\Pi+\Omega\right]\begin{bmatrix}\Psi_s\\ \Psi_r\end{bmatrix}\Leftrightarrow v = Ri+\Pi\Psi+\Omega\Psi \qquad (2)$$

$$\Pi=\frac{p}{\omega_n}I_{2n+3},\ \Omega=\begin{bmatrix}\omega_s\Xi & O_{3,2n}\\ O_{2n,3} & W\end{bmatrix}$$

$$,\Xi=\begin{bmatrix}0 & -1 & 0\\ 1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}, W = g\begin{bmatrix}O_{n,n} & -I_n\\ I_n & O_{n,n}\end{bmatrix} \qquad (3)$$

$$z_s=\begin{bmatrix}z_d & z_q & z_0\end{bmatrix}^t \qquad (4)$$

$$z_r=\begin{bmatrix}z_{D_1}...z_{D_k} & z_{Q_1}...z_{Q_k}\end{bmatrix}^t; z=i,v,\psi; k=1,...,n \qquad (5)$$

$$p(\omega_m)=\frac{1}{2H}\left(\left(T_e-T_m\right)-D\omega_m\right) \qquad (6)$$

$$T_e=\left(\psi_d i_q-\psi_q i_d\right)=i^t G_i i=\Psi^t G_\psi \Psi \qquad (7)$$

Where $z_{D_k}$ and $z_{Q_k}$ are the d- and q-axis rotor winding number $K$ for variable $Z$ respectively.

Equation (2) can be organized in the space-state form in which machine currents are state variables:

$$p\begin{bmatrix}z\\ \omega_m\end{bmatrix}=\begin{bmatrix}A_z & O_{2n+3,1}\\ \frac{1}{2H}z^t G_z & -\frac{D}{2H}\end{bmatrix}\begin{bmatrix}z\\ \omega_m\end{bmatrix}+\begin{bmatrix}B_z & O_{2n+3,1}\\ O_{1,2n+3} & -\frac{1}{2H}\end{bmatrix}\begin{bmatrix}v\\ T_m\end{bmatrix}\Leftrightarrow p\left(x_z\right)=Ax_z+Bu, z=i,\Psi \qquad (8)$$

The order of the system in Equation (8) is given by $h = 2n+4$, which yields to a 8*8 matrix in this paper. Finally, the electromechanical state model can be sorted in general matrix form (8) and also, y is as an output vector variable.

System (8) can be calculated using vector machine parameters defined in (10).

$$y=\begin{bmatrix}i_d & i_q & i_0 & \omega_m\end{bmatrix}^t=\begin{bmatrix}C_z & O_{3,1}\\ O_{1,3} & 1\end{bmatrix}\begin{bmatrix}z\\ \omega_m\end{bmatrix}=Cx_z \qquad (9)$$

$$\theta=\begin{bmatrix}\Re & \chi & H & D\end{bmatrix}^t; \Re=\begin{bmatrix}r_a & r_1 & r_2 & ... & r_0\end{bmatrix} \qquad (10)$$

$$\chi=\begin{bmatrix}x_a & x_1 & x_2 & ... & x_m & x_0\end{bmatrix} \qquad (11)$$

Machine model implementation in the MATLAB/ SIMULINK software is illustrated in Fig. (2).

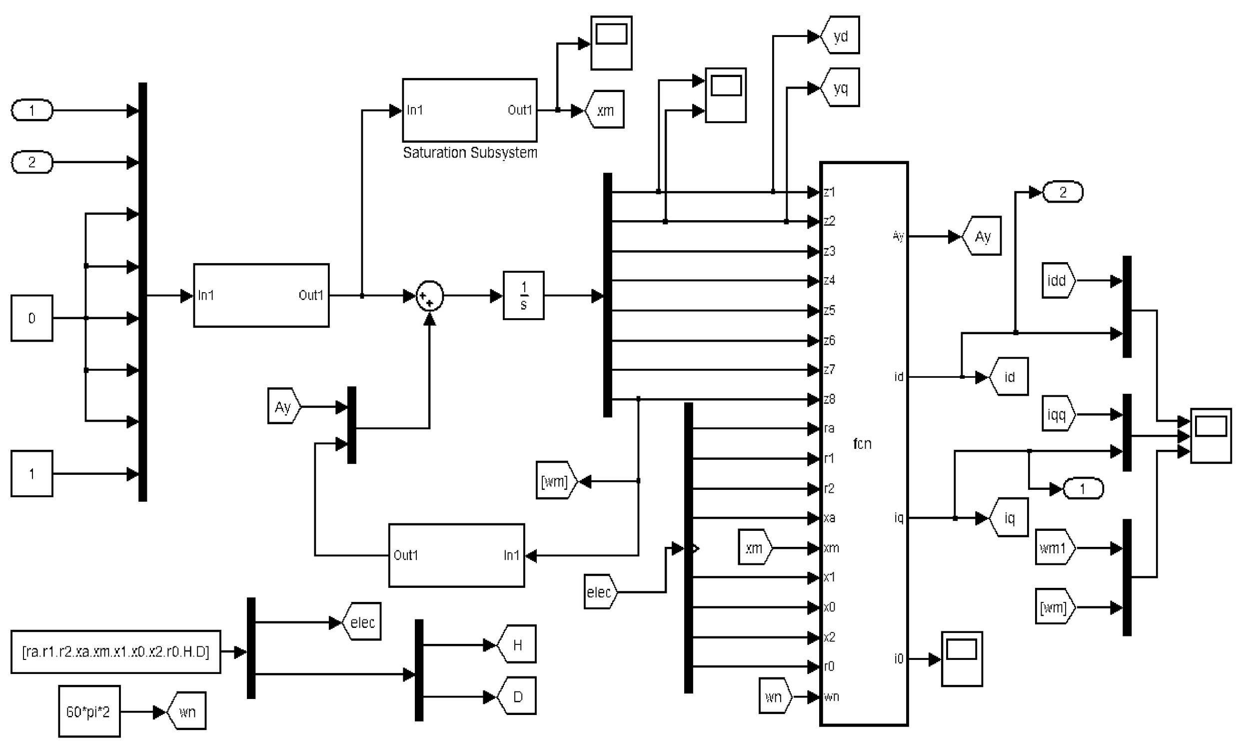


Fig. 2: Machine implementation model in MATLAB/SIMULINK software package

**Derivation of Nonlinear State Equations for IM:** In this section, first IM's differential equations are derived with respect to iron saturation. Then, using numerical method, saturation's factors are calculated and used to identify parameters in a three-step technique.

**The K-factor Cross Saturation of IM:** In order to present the cross saturation study used in this paper, the previous d- and q-axis equivalent circuits of IM can be combined in a single-phase circuit using the following complex variables [9]:

$$\bar{z}_t = z_d + jz_q; \bar{z}_k = z_{D_k} + jz_{Q_k}, z = i, v, \psi \quad (12)$$

$$\begin{aligned} \bar{i}_m &= i_{md} + ji_{mq} = i_d + \sum i_{D_k} + j\left(i_q + \sum i_{Q_k}\right) \\ &= \bar{i}_m + \bar{i}_m + \bar{i}_m + \cdots + \bar{i}_m, k = 1,\ldots,n \end{aligned} \quad (13)$$

$$\bar{v}_t = r_a \bar{i}_t + \frac{1}{\omega_n} p\left(\bar{\psi}_t\right) + j\bar{\psi}_t \quad (14)$$

$$\bar{\psi}_t = x_a \bar{i}_t + x_m \bar{i}_m; \bar{\psi}_k = x_k \bar{i}_k + x_k \bar{i}_k, k = 1,\ldots,n \quad (15)$$

$$\psi_{ml} = x_m i_{ml} = \psi_l - x_a i_l, l = d, q \quad (16)$$

$$\bar{\psi}_m = \psi_{md} + j\psi_{mq} = \bar{\psi}_t - x_a i_t = x_m \bar{i}_m \quad (17)$$

$$i_m = \sqrt{{i_{md}}^2 + {i_{mq}}^2};\ \psi_m = \sqrt{{\psi_{md}}^2 + {\psi_{mq}}^2} \quad (18)$$

Where, the index *m* denotes variables and parameters affected by magnetizing saturation. Subscripts *t* and *k* refer to terminal variables and rotor winding number variables, respectively. Similar to the analysis of the synchronous machine, the cross saturation factor $k_\Psi$ is defined by (19), where $x_m^0$ is the constant unsaturated value of the magnetizing reactance ($x_m$). Since loaded and unloaded machines saturate in steady and transient states similarly, the saturation factor (19) can also be expressed by (20):

$$K_\psi = \frac{1}{x_m^0}\frac{\psi_m}{i_m} \approx \frac{1}{x_m^0}\frac{\psi_{t0}}{i_{t0}} \approx \frac{1}{x_m^0}\frac{v_{t0}}{i_{t0}} \quad (19)$$

$$= \lambda_0 + \lambda_1\left(\omega_m \psi_m\right) + \lambda_2\left(\omega_m \psi_m\right)^2 + \cdots \quad (20)$$

Where $\left(v_{t0}, i_{t0}\right)$ is no-load IM data used to compute coefficients $\lambda_i$ , for $I = 1,\ldots,4$.

Table 1: Saturation factor model parameters

| $\lambda_6$ | $\lambda_5$ | $\lambda_4$ | $\lambda_3$ | $\lambda_2$ | $\lambda_1$ |
|---|---|---|---|---|---|
| 2.92 | -22.2 | -228 | 264 | -151 | 34.1 |

Using curve fitting, the values obtained for $\lambda_1$ to $\lambda_6$ are presented in Table (1). Also, $k_\Psi$ curve is shown in Fig. (3).

**Saturation with Currents or Fluxes as State Variables:** Using IM currents as state variables in Equations (1) and (2), in compact matrix form, yields:

$$p\left[X(i)i\right] = \omega_n v - \omega_n\left[R + \Omega X(i)\right]i \quad (21)$$

$$p\left[X(i)i\right] = p\left[X(i)\right]i + X(i)p(i) \quad (22)$$

$$p\left[X(i)\right] = \frac{d\left[X(i)\right]}{di}\frac{di}{dt} = X_{inc}\frac{di}{dt}. \quad (23)$$

$X_{inc}$ is the incremental inductance introduced by the current model, making the state model form (21) difficult to derive and time-consuming [10]. Selecting IM fluxes as state variables in (1) and (2) yields

$$p[\Psi] = \omega_n u - \omega_n\left[R\left(X(i)\right)^{-1} + \Omega\right]\Psi. \quad (24)$$

The state form (24) does not introduce the incremental inductance previously observed in the current mode, so the model with fluxes as state variables is selected for this paper.

**Numerical Method to Compute Saturated IM Model:** Knowing the saturation factor value $k_\Psi$ at each time instant $t_k$, the magnetizing level of the IM at $t_{k+1}$ can be adjusted in the parameter vector $\theta(t_k)$ which is introduced in the system model (8) for numerical resolution

$$\begin{aligned} &\theta(t_k) = \left[\Re \quad \chi(t_k) \quad H \quad D\right]; \Re = \left[r_a \quad r_1 \quad r_2 \quad \ldots \quad r_0\right]; \\ &\chi(t_k) = \left[x_a \quad x_1 \quad x_2 \quad \ldots \quad x_m(t_k) \quad x_0\right] \end{aligned} \quad (25)$$

The procedure shown in Fig. (4) is used for the numerical implementation of the saturated electromechanical model of the IM. Changes of $x_m$ during simulations in a sample circuit in starting time are shown in Fig. (5).

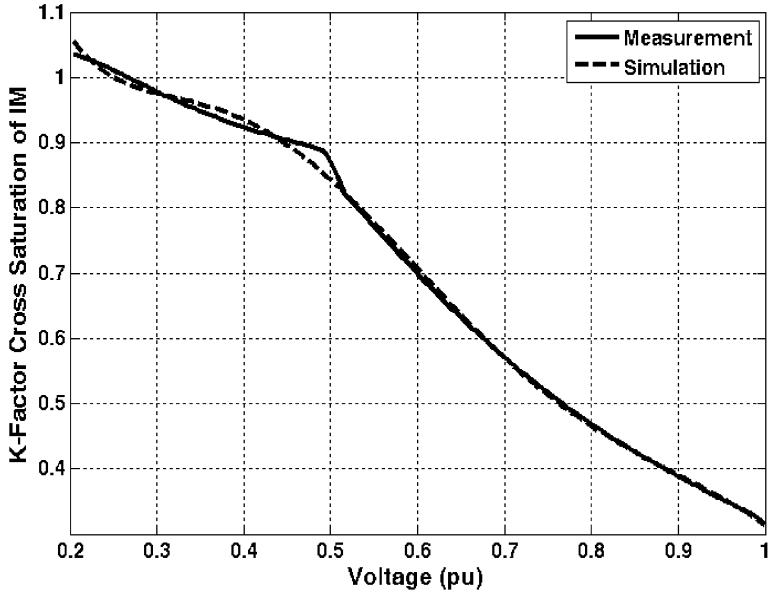


Fig. 3: $K_\Psi$ curve is shown according to the voltage

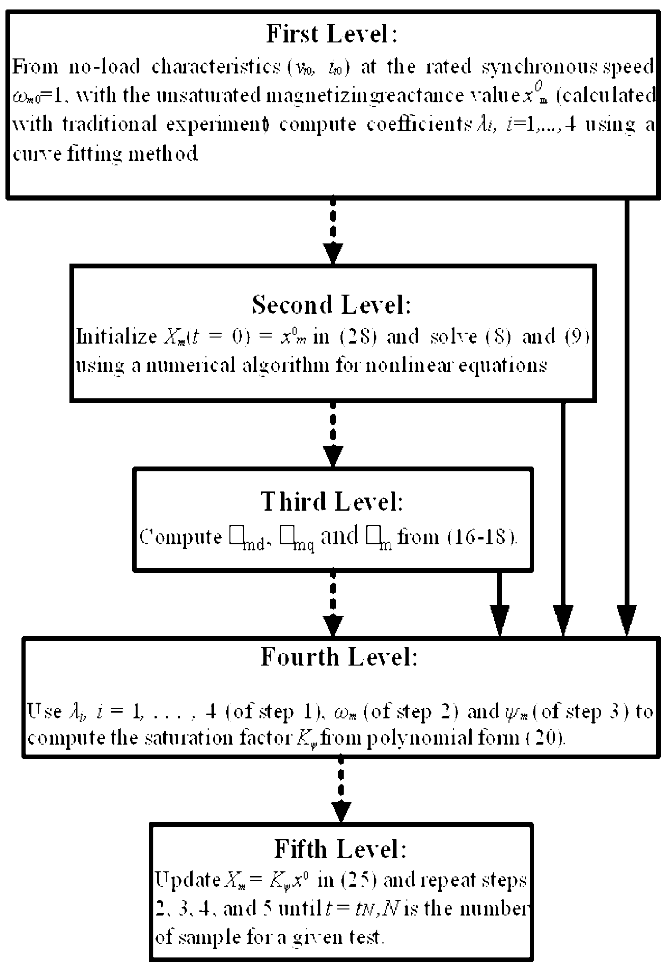


Fig. 4: The used algorithm for saturated IM's model in MATLAB/SIMULINK

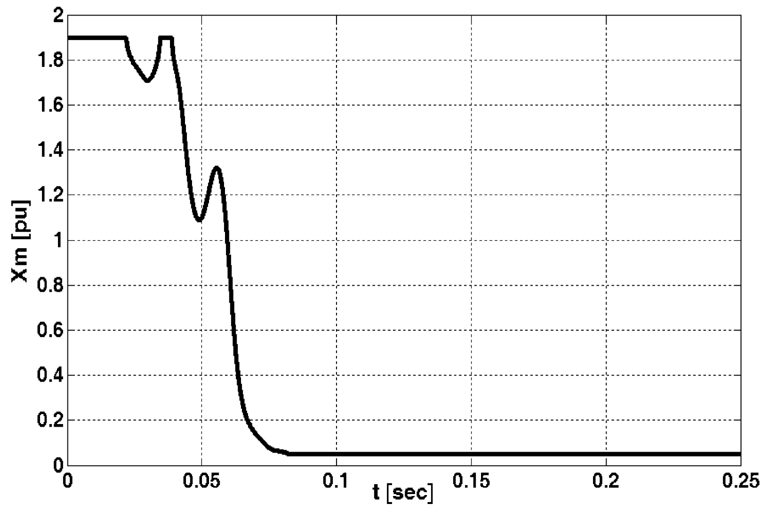


Fig. 5: The way of changes of $x_m$ during simulations in a sample circuit in starting time

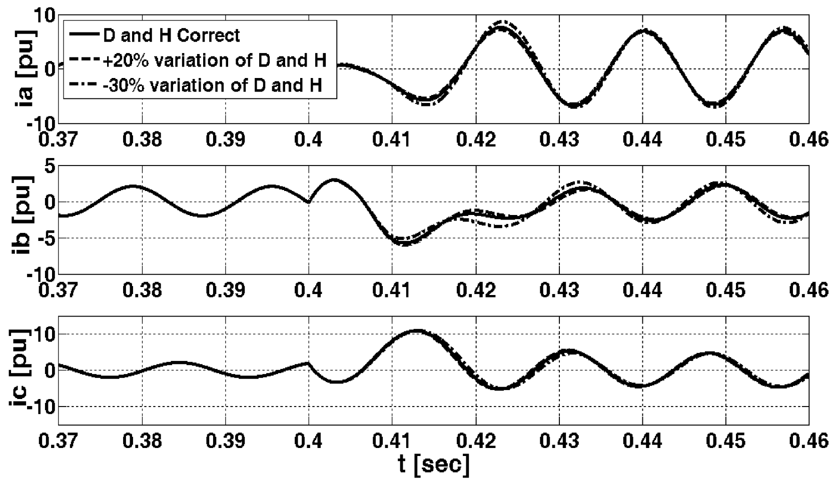


Fig. 6: Stator currents during a double-line-to-neutral short-circuit of an IM for three different values of mechanical parameters D and H: poor impact of D and H.

**Three-Step Identification Method of Saturated Model of IM:** Since large disturbance in online tests such as balanced and unbalanced short-circuits, load rejections, switching, starting and built-up tests severely excite all machine modes, they are good choices for the identification test of AC machines [5]. Accordingly, line-to-line-to-neutral short circuit and starting tests are used to estimate physical, electrical and mechanical parameters of IM. It is observed that when the induction motor operates with a weak slip (approximately zero), which corresponds to a quasi-constant rotor speed, balanced and unbalanced short circuit test waveforms are independent of the mechanical parameters and hence the motion Equation (6).

Fig. (6) shows armature currents during a double-line-to-neutral short-circuit of an IM for three different values of mechanical parameters, D and H. Armature current waveforms are less sensitive to the variation of mechanical parameters but as seen in Fig. (7), these parameters exert a strong influence on start-up current excursions.

The three-step estimation method has been shown in Fig. (8) can be summarized as follows:

***Step 1*:** Perform traditional locked rotor and no-load and DC tests and obtain initial parameters as inputs of the numerical algorithm.

***Step 2*:** First the double-line-to-neutral short-circuit test is used to estimate electrical parameter vector $\theta_{elec} = [\Re \quad \chi]$ without the motion equation (6). The motion equation is removed in the IM model (6) by setting, $H \to +\infty$.

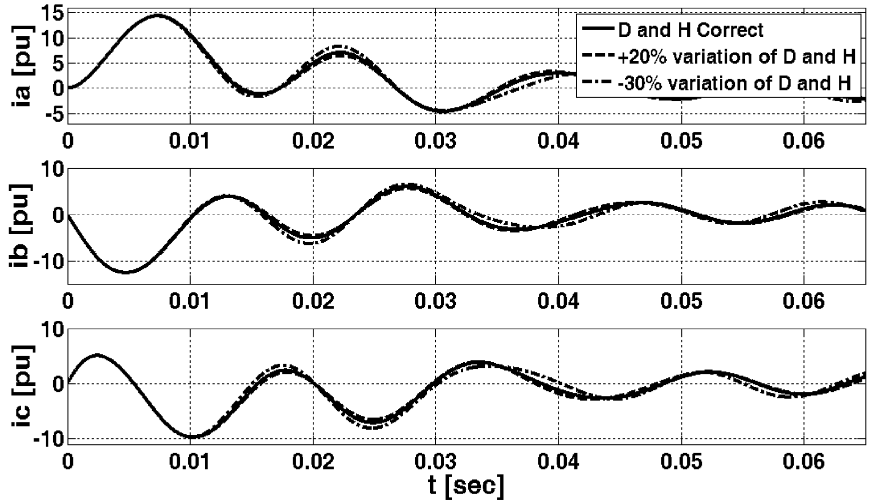


Fig. 7: Stator currents during a start-up of an IM with three different values of D and H: great impact of D and H on current waveforms

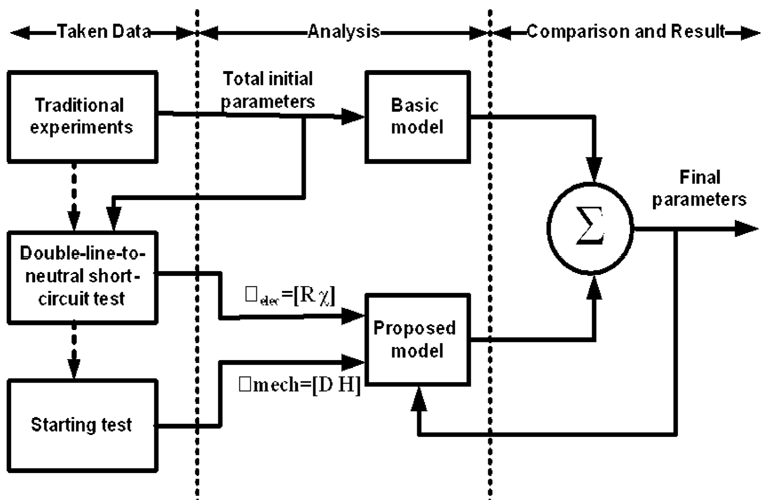


Fig. 8: Proposed three-step algorithm in this paper

***Step 3*:** Using estimated electrical parameter vector $\hat{\theta}_{elec}$ of step 2, mechanical parameter vector $\theta_{mech} = \left[D \quad H\right]$ is computed using the starting test data.

As it has been observed, the major advantage of this method is that the rotor speed measurements are not needed for the identification process and accordingly, $y_p = \left[i_d \quad i_q \quad i_0\right]^t$ .

**Experiments and Determination of IM Parameters:** Initial electrical parameters [12] were computed from a classical no-load test and a locked-rotor test, while mechanical parameters were obtained from the retardation test (Table 2).

Table 2: Initial parameters taken from locked rotor, no-load and DC tests - basic model

| Parameter | Value |
|---|---|
| $r_a$ [Ω] | 0.02 |
| $x_a$ [Ω] | 0.04 |
| $x_m$ [Ω] | 1.9 |
| $r_0$ [Ω] | 10 |
| $x_0$ [Ω] | 10 |
| D [Nm.s] | 0.1 |
| H [Kg.m$^2$] | 0.05 |
| $r_1$ [Ω] | 0.02 |
| $R_2$ [Ω] | 10 |
| $x_1$ [Ω] | 0.04 |
| $X_2$ [Ω] | 10 |

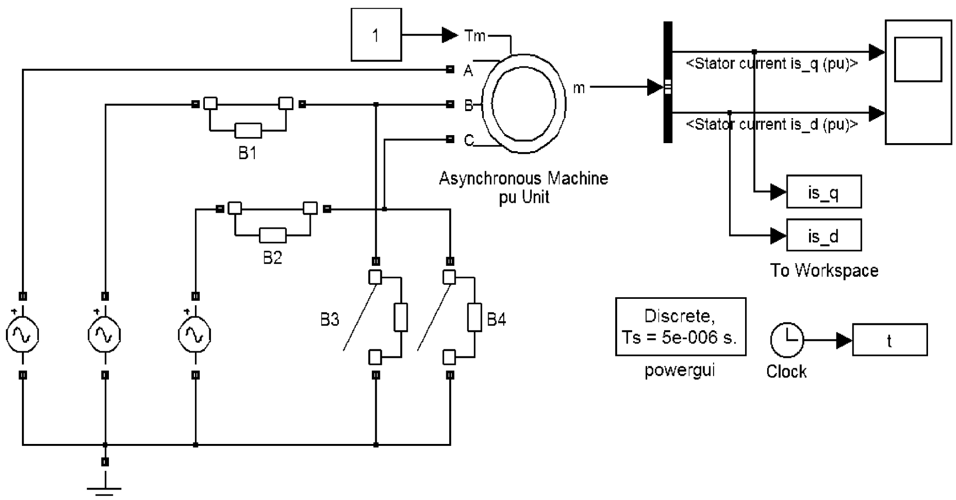


Fig. 9: Double-line-to-neutral short-circuit test in Matlab/SIMULINK

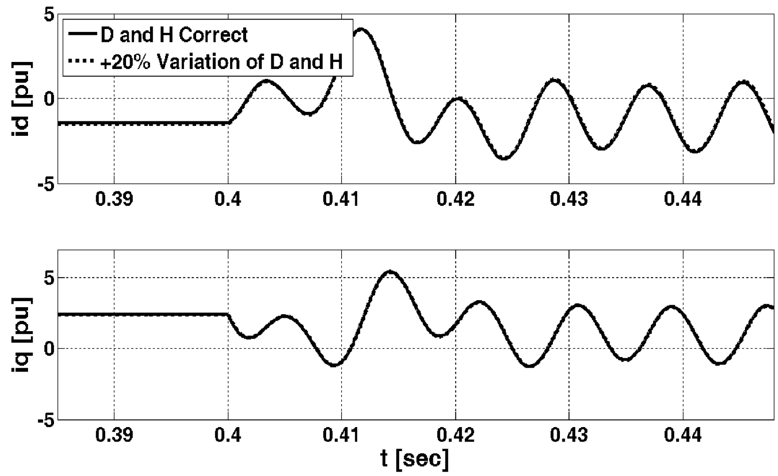


Fig. 10: Stator current waveform for d- and q- axis with two different values of D and H

The machine model existing in MATLAB/ SIMULINK has only one damper circuit per axis and its null is not connected to the ground, so in the proposed model for neglecting the second circuit and zero sequence circuit, the large amount of its parameters is selected.

Considering double-line-to-neutral short-circuit test setup according to Fig. (9) and comparing d- and q- current waveforms shown in Fig. (10), for two sets of values, ( H = 0.1, D = 0.05 ) and ( H = 0.11, D = 0.06 ), it can be easily concluded that the mechanical parameters of machine has a slight influence on short circuit current.

As seen before, the low effect of mechanical parameters on short circuit currents can be calculated. Input source voltage is 50 percent of rated value (if these tests were online, this reduction does not make restriction for stator currents) and source frequency is 60 Hz.

Table 3: The estimated electrical parameters reached by presented algorithm of proposed model

| $r_a$ | $x_a$ | $x_m$ | $r_1$ | $x_1$ |
|---|---|---|---|---|
| 0.0209 | 0.048 | 1.49 | 0.0208 | 0.35 |

Also, the switches will be open only for 0.4 seconds, i.e. the switches opening and closing operation time was about 0.4 second. According to Fig. (11) and low influence of q- and d-current axis of stator and also ignoring mechanical equations (considering H = ∞), putting the sample data which are achieved by short circuit test in proposed model using Control and Estimation Tools Manager control in MATLAB/SIMULINK the electrical parameters are estimated. In this paper, 61 sample data which are obtained from intervals with the size of 0.001 have been used to estimate parameters. The estimated parameters are shown in Table (3).

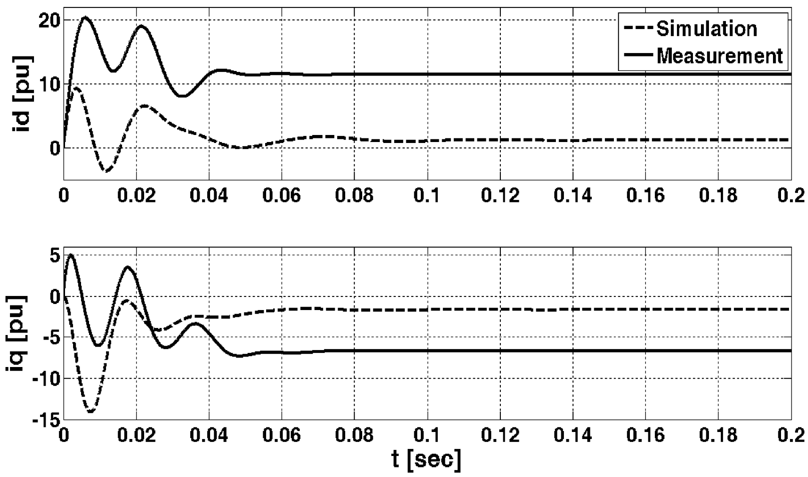


Fig. 11: Comparison between waveform of q and d stator current without approximation of saturation

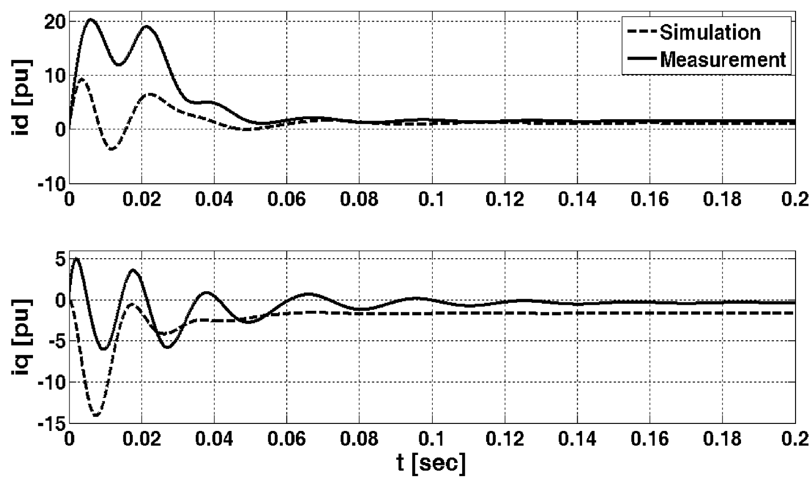


Fig. 12: Comparison between waveform of q and d stator current with one level advancing of approximation of saturation

The values of mechanical parameters, D and H, are 0.1 and 0.0085, respectively that have been estimated using Control and Estimation Tools Manager in MATLAB/SIMULINK.

**Analysis of Simulation Results:** The real and proposed model waveforms have been plotted in Figs. (11) and (12) for analysis of operation in this method. Comparison between these two figures shows the estimated parameters follow real current, more precisely. Moreover, it can be concluded that to decrease the fault existing between real current waveforms and the currents obtained from proposed model, more data must be used for estimating parameters. Also, the steps to estimate saturation could be increased. So, in each step, in order to improve the results, the outcome of previous step can be used as input for next step.

## CONCLUSION

In this paper, three-step method has been used to estimate parameters of the double cage induction machine in offline mode. First, the expanded Park transition model of induction machine in d-q axis has been presented. To make the model, flux has been used as state variable to eliminate incremental inductance variable and to reduce difficulty and simulation response time. By considering iron saturation effect, the model has been simulated in MATLAB/SIMULINK software package. Saturation effect has been introduced during a 5 step algorithm by cross saturation coefficient ($K_\Psi$). Then, during this three-step method, approximation of parameters has been performed. In first step, traditional tests (namely locked rotor, no-load and DC tests) have been performed to get basic model parameters (that is the same model presented in MATLAB/SIMULINK). Parameters resulted from this step have been used as inputs of second step. In second step, considering the fact that mechanical parameters are less sensitive to double-line-to-neutral short-circuit test, by omitting mechanical equation of machine and saving sample data from stator current, electrical parameters has been estimated by Control and Estimation Tools Manager in MATLAB/SIMULINK. Finally, in third step, mechanical parameters have been used in starting test. The accuracy obtained from comparison between waveforms of d- and q-current of stator has been evaluated and confirmed. Proposed model can be more accurate in final results by increasing the iteration of saturation algorithm.

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