An online nonlinear identification method for estimation of magnetizing curve and parameters of an induction motor *

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Abstract: A new method for the online parameter identification of an induction machine in standstill is proposed. In this approach the inverse of the mutual reactance of the induction motor is modeled by a simple polynomial of the magnetizing flux. Then, the unknown parameters are computed by employing the nonlinear recursive least square method. The identified parameters are particularly useful for field oriented control of the induction motor.

Keywords: Nonlinear system identification; Recursive identification; Systems with saturation; Induction motor parameters; Modeling and simulation of power systems; Electric machines.

1. INTRODUCTION

Parameter identification is a fundamental step for modeling dynamical behaviors and control of squirrel cage asynchronous motors, the most common type of motors in industry. More precisely, the accurate values of the motor parameters are required for all components of the field oriented control, such as the decoupling part and the rotor flux estimator, etc. Lack of this knowledge may significantly reduce the control performance and in the worst case scenario even cause instability of the closed loop system under control. For these reasons, developing appropriate identification methods which also consider the variation of motor parameters and their dependence to the measured variables are very crucial for a control design; see Tollyat et al. (2003) and the references therein.

The primary approaches for identifying the motor parameters were based on experimental tests, such as locked rotor and no load tests. Despite their simplicity, computation of the variables are achieved offline and thus does not take variation of the parameters during the operation into account. As alternatives to the experimental approaches, algorithms based on the linear Recursive Least Square (RLS) methods have been introduced which estimate the parameters from the measured signals and the errors between the measured and estimated variables; see for example Kertzsch (2003); Zhang et al. (2015); Koubaa (2004). These algorithms are executed online and are able to track the parameters under mild physical changes. The major drawback is that the RLS algorithms assume that the motor parameters vary slowly with respect to time, that is, their time derivatives are approximately zero. This assumption fails, however, for example for the mutual reactance which due to the effect of magnetizing flux saturation its derivative can instantly change. Motivated by this fact, developing online algorithms, which bring together the saturation phenomenon and parameter identification, is highly demanding. Our approach to tackle this problem is to model the inverse of the mutual reactance by a polynomial of the magnetizing flux with unknown coefficients. It turns out that the parameter identification gives rise to a nonlinear identification problem which can be solved by the Nonlinear Recursive Square (NRLS) algorithm. This idea distinguishes our work from the previous research including Levi et al. (2000); Terzic et al. (2012); Castaldi and Tilli (2005) which determine the magnetizing curve with offline techniques, and Aksoy et al. (2010); Kenné et al. (2008); Wamkeue et al. (2007) which do not explicitly take the saturation effect into consideration.

This paper considers an online parameter identification method of an induction motor in standstill. The principle of standstill identification consists in excitation of the induction motor by a voltage source in the direction of the α-axis, that is, \( u_{\alpha} = 0 \). It turns out that the motor generates no torque and consequently the rotor remains unrotated. This type of excitation can therefore highly simplify the derived equations for the identification algorithm. Another benefit of this method is that no speed sensor or no control loop for the motor are required. The disadvantage is, however, that due to non-existence of the electrical torque the mechanical parameters such as moment of inertial and load torque are not computable.

The contribution is structured as follows. In Section 2 we briefly explain the standard motor model in stator coordinate frame and in per unit system. In Section 3 we derive a convenient model for parameter identification in standstill. In this model we assume that the stator and the...
rotor leakage reactances are equal and the stator resistance is available via a DC measurement directly from the stator winding. The latter assumption allows us to compute the stator flux and therefore deal with it as a known signal in the identification model. We will then discuss the NRLS method for computing the unknown motor parameters. One special case of these results are when the mutual reactance is independent of the magnetizing flux. In this case the NRLS problem converts to the RLS one. That means our nonlinear identification method generalizes the existing one in Kertzscher (2003) with three unknown parameters. This is discussed in Section 4. In Section 5, by illustration of a simulation example we will demonstrate the usability of the algorithm and compare the results from RLS and NRLS algorithms.

2. MODEL OF A SQUIRREL CAGE INDUCTION MACHINE IN STATOR COORDINATE FRAME IN PER-UNIT SYSTEM

The model of a squirrel cage induction machine in stator reference frame \((\alpha, j\beta)\) and in per-unit system is expressed by

\[
\frac{1}{\omega_b} \frac{d\Psi_s}{dt} = u_s - R_s i_s, \tag{1}
\]

\[
\frac{1}{\omega_b} \frac{d\Psi_r}{dt} = -R_r i_r + j\omega\Psi_r, \tag{2}
\]

\[
\Psi_s = X_s i_s + X_m i_r, \tag{3}
\]

\[
\Psi_r = X_m i_s + X_r i_r, \tag{4}
\]

where \(R_s\) and \(R_r\) represent the stator and the rotor resistances, respectively, \(\omega\) represents the angular velocity of the rotational field. The vectors \(\Psi_s = [\psi_{s\alpha}, \psi_{s\beta}]^T\) and \(\Psi_r = [\psi_{r\alpha}, \psi_{r\beta}]^T\) represent the stator and the rotor fluxes, whereas the vectors \(i_s = [i_{s\alpha}, i_{s\beta}]^T\) and \(i_r = [i_{r\alpha}, i_{r\beta}]^T\) are the currents of the stator and the rotor, respectively. \(u_s = [u_{s\alpha}, u_{s\beta}]^T\) is the vector whose elements are the voltages of the stator. The base frequency \(\omega_b\) is a constant defined by \(\omega_b := 2\pi f_b\), where \(f_b\) is the nominal frequency of the induction motor. \(X_s\) and \(X_r\) are the stator and the rotor reactances, respectively. They are defined by \(X_s = X_m + X_{\alpha\sigma}\) and \(X_r = X_m + X_{\sigma\sigma}\), where \(X_m\) is the mutual (magnetizing) reactance and \(X_{\alpha\sigma}\) and \(X_{\sigma\sigma}\) are the phase leakage reactances of the stator and the rotor, respectively. Note that in this demonstration all variables except the time variable \(t\) are normalized by their corresponding base variables.

The torque and the rotational speed of the rotor are related through the mechanical equation:

\[
\tau_c - \tau_L = T_A \frac{dn}{dt}, \tag{5}
\]

where \(\tau_c = \psi_{s\alpha} i_s - \psi_{s\beta} i_{s\beta}\) and \(\tau_L\) represent the electrical and mechanical (load) torques, respectively. The time constant \(T_A\) is defined by \(T_A = J\omega_b^2/(3U_n I_n p^2)\), where in this expression \(p\) refers to the number of pole pairs of the stator, \(J\) is the moment of inertia, and \(U_n\) and \(I_n\) are the nominal voltage and current, respectively. \(n\) represents the angular velocity of the rotor.

![Fig. 1. Illustration of the dependencies: magnetizing flux-current (left) and magnetizing flux-reactance (right).](image)

In this model we assume that the mutual reactance \(X_m\) depends on the magnetizing flux \(\Psi_m\); see the illustrative diagrams in Fig.1. Similar to the proposed technique in Levi et al. (2000), we describe this relationship by a nonlinear function according to:

\[
X_m = \frac{\|\Psi_m\|}{\|i_m\|} = \frac{X_{m,s} a \|\Psi_m\|^b}{1 + a \|\Psi_m\|^b} = X_{m,s} - X_{m,d}, \tag{6}
\]

where \(X_{m,s}\) and \(X_{m,d} := X_{m,s} a \|\Psi_m\|^b (1 + a \|\Psi_m\|^b)^{-1}\) indicate the static and dynamic parts of the mutual inductance, respectively. The parameter \(a \in \mathbb{R}_{>0}\) is a constant number, \(b \in \{1, 2, \ldots\}\) is a fixed number that a priori has been chosen, \(\Psi_m = X_m i_m = \Psi_s - X_{\alpha\sigma} i_s\) and \(i_m = i_s + i_r\). The operator \(\|\cdot\|\) denotes the norm 2 of a signal. The interpretation of (6) is that for small magnitude of the magnetizing flux the mutual reactance almost remains constant, whereas for higher values due to the effect of saturation this reactance reduces. It follows from \(\Psi_m = X_m i_m\) and (6) that the following relationship between the magnetizing flux and current is valid

\[
i_m = \frac{\Psi_m}{X_{m,s}} (1 + a \|\Psi_m\|^b). \tag{7}
\]

Characterizing the magnetizing curve is usually achieved offline by carrying out a practical experiment called no-load test; see Levi et al. (2000). In this work we aim at determining the unknown variables by the NRLS algorithm.

3. PARAMETER IDENTIFICATION IN STANDSTILL

In this section we suggest the identification method in standstill. To begin, we assume that the stator resistance \(R_s\) is measurable and thus a known parameter. This implies that referring to (1) the stator flux \(\Psi_s\) is computable and can be treated as a measurable signal. Moreover, we use the common assumption that the total leakage reactance of the motor is equally divided between the rotor and the stator, that is, \(X_{\alpha\sigma} = X_{\sigma\sigma}\); see Yamamura (1986). This also implies that the reactances of the stator \(X_s\) and the rotor \(X_r\) are equal, that is \(X_s = X_r\). Next, note that (2) can be simplified if the rotor angular frequency \(\omega\) somehow is set to zero. This can be achieved by a convenient selection of the excitation voltage signal, for instance by a signal in the direction of \(\alpha\)-axis. As the rotor flux and current are not measurable, the proposed model for parameter identification must be independent of these variables.

In summary, the identification in standstill consists of three parts: i) excitation of the motor by an appropriate
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