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An identification procedure of electromagnetic parameters for an induction motor equivalent circuit including rotor deep bar effect

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Abstract: The paper presents an identification procedure of electromagnetic parameters for an induction motor equivalent circuit including rotor deep bar effect. The presented procedure employs information obtained from measurement realised under the load curve test, described in the standard PN-EN 60034-28: 2013. In the article, the selected impedance frequency characteristics of the tested induction machines derived from measurement have been compared with the corresponding characteristics calculated with the use of the adopted equivalent circuit with electromagnetic parameters determined according to the presented procedure. Furthermore, the characteristics computed on the basis of the classical machine T-type equivalent circuit, whose electromagnetic parameters had been identified in line with the chosen methodologies reported in the standards PN-EN 60034-28: 2013 and IEEE Std 112TM-2004, have been included in the comparative analysis as well. Additional verification of correctness of identified electromagnetic parameters has been realised through comparison of the steady-state power factor-slip and torque-slip characteristics determined experimentally and through the machine operation simulations carried out with the use of the considered equivalent circuits. The studies concerning induction motors with two types of rotor construction – a conventional single cage rotor and a solid rotor manufactured from magnetic material – have been presented in the paper.

Key words: induction motors, equivalent circuits, parameter identification, frequency-domain analysis, genetic algorithms

1. Introduction

The Induction Motor (IM) mathematical models are widely used in the realisation of various speed and torque control methods. Therefore, the knowledge on electromagnetic parameters of an IM Equivalent Circuit (EC) is indispensable in the case of implementation of these methods in variable frequency motor drives, and moreover, the accuracy of parameter identification has a significant impact on the motor drive static and dynamic properties. The knowledge on EC electromagnetic parameters is also essential in relation to algorithmic methods for IM speed estimation, which constitutes one of the fundamental signals in the control systems of a variable frequency motor drive.

The major problem associated with the use of IM mathematical models, basing on a classical machine EC with constant parameters, in control algorithms of a motor drive system is variability of machine electromagnetic parameters, conditioned by changes of machine winding temperature, ferromagnetic core saturation as well as rotor deep bar effect [1, 2].

As regards IM drive systems with the rotor flux oriented vector control, the information on actual values of rotor resistance and inductance, or rotor electromagnetic time constant is particularly important. Inaccurate tracking of IM rotor electromagnetic parameter variability introduces reconstruction errors of the rotor flux space vector, whose level depends on the discrepancy range between electromagnetic parameters of the considered machine and corresponding parameters of adopted ECs. Erroneous estimation of rotor flux space vector angular position affects in turn the deterioration of decoupling accuracy of the flux and torque control systems, thus the quality deterioration of the whole drive system operation [3–9].

IM mathematical models have been proposed in the literature, which allow to represent variability of rotor electromagnetic parameters of such a machine. These models have been elaborated basing on the classical T-type Equivalent Circuit (T-EC), in which the variability of rotor electromagnetic parameters is tracked by using the information derived from measured IM stator voltages and currents [5] or stator current responses to strictly defined additional voltage signals generated by frequency converters during motor drive operation [6] either the variability of these parameters is represented by the set of rotor resistances and leakage inductances determined as a function of slip frequency [10].

An alternative to the above mentioned IM mathematical models can be one elaborated on the basis of the expanded EC in relation to its classical counterparts. The variability of rotor electromagnetic parameters, in this case resulting from rotor deep bar effect, is approximated with the use of a parallel connection of two-terminal networks with constant lumped parameters [7–9, 11–17]. The usage of the Rotor Multi-Loop Equivalent Circuit (RML-EC) involves the necessity to identify a greater number of electromagnetic parameters of a rotor EC than in the case of the classical T-EC. An identification process of these parameters can be carried out with the aid of selected optimization methods through minimization of the errors between some types of time responses [11], instantaneous input impedances [12], impedance frequency characteristics [8, 9, 13–16] or torque-slip characteristics [17] of a considered machine and corresponding characteristics determined on the basis of IM mathematical models resulting from the RML-EC with the sought parameters.

In the paper, the identification procedure of RML-EC electromagnetic parameters has been presented, which is based on impedance frequency characteristics of the tested IM, determined with the use of machine physical quantities measured under the Load Curve (LC) test, described in the standard [18]. The considered characteristics represent the variability of rotor electromagnetic parameters, resulted from rotor deep bar effect, in the investigated range of slip frequency. The foregoing feature constitutes the fundamental argument standing for the use of these types of characteristics in an identification process of adopted EC electromagnetic parameters.

2. Identification of EC electromagnetic parameters based on IM impedance frequency characteristics

The identification procedures of EC electromagnetic parameters realised on the basis of IM impedance frequency characteristics are well known and their detailed description and usage can be found in the literature, for instance, [8, 9, 13]. In the quoted papers, the EC electromagnetic parameters have been determined as a result of an approximation of reference impedance frequency characteristics of the tested machines, obtained experimentally based on the standstill frequency response test [13] or calculated with the use of the finite element method [8, 9], by means of corresponding characteristics resulted from adopted ECs with the sought parameters. In the presented procedure, the main difference is the manner in which the impedance frequency characteristics of investigated IMs have been determined.

The procedures enabling the identification of machine T-EC electromagnetic parameters in the vicinity of a specified machine operating point, e.g. the rated one, have been described in detail in the standards [18, 19]. These procedures are based on measurement realised under the No-Load (NL), Locked Rotor (LR) or Reverse Rotation (RR) and load tests, where the latter is carried out at slip speed approximating the desired rotor slip frequency, preferably at rated load. If there is the possibility of coupling an examined IM to a controllable load, the LC test can be conducted as an alternative to the LR and RR tests. According to the LC test the measurement of stator power, voltages and currents is curried out at the fixed stator voltage parameters (amplitude and frequency) and under machine load conditions adjusted within the specified range. During the LC test, the measurement of rotor angular velocity is also suggested for each of machine load setpoints. Subsequently, basing on the tested IM physical quantities, measured under the NL and LC tests, the T-EC electromagnetic parameters are determined in the vicinity of a specified machine operating point [18].

For this reason, the usage of the measurement data derived from the LC test in order to determine the T-EC electromagnetic parameters only in the vicinity of a specified machine operating point seems to be little effective when taking into account the wide range of machine load setpoints indicated by the standard [18], which constitutes $(0.25 \div 1.25)$ of the load torque corresponding to the considered operating point of the tested machine. The foregoing conclusion concerns particularly machines, which are characterized by significant rotor deep bar effect (double cage, deep bar and solid rotor IMs).

The information included in the measurement derived under the LC test is sufficient for determination of the considered IM impedance variability as a function of slip frequency accordingly to the following equation:

$$\underline{Z}_1(f_2) = \frac{|\underline{U}_1|}{|\underline{I}_1(f_2)|}\left(\cos(\varphi_1(f_2)) + \mathrm{j}\sqrt{1 - [\cos(\varphi_1(f_2))]^2}\right), \tag{1}$$

$$\cos(\varphi_1(f_2)) = \frac{P_1(f_2)}{\sqrt{3}|\underline{U}_1||\underline{I}_1(f_2)|}, \tag{2}$$

where: $P_1(f_2)$, $|\underline{U}_1|$, $|\underline{I}_1(f_2)|$ are measured stator power, RMS values of stator voltages and currents, respectively, f_2 is a slip frequency $f_2 = f_1 s$, f_1 is a stator supply frequency, s is slip, $\cos(\varphi_1(f_2))$ is a power factor, j is the imaginary unit $\mathrm{j}^2 = -1$.

The impedance $\underline{Z}_1(f_2)$ can be described as a series connection of the stator phase winding resistance R_1 and the IM reactance $\mathrm{j}\omega_1\underline{L}_1(f_2)$. Separation of the stator phase winding resistance R_1 from the machine impedance $\underline{Z}_1(f_2)$ enables to determine the examined machine inductance $\underline{L}_1(f_2)$ according to the following equation:

$$\frac{\underline{Z}_1(f_2) - R_1}{\mathrm{j}\omega_1} = \underline{L}_1(f_2) = L_{1\sigma} + \underline{L}_{1\delta}(f_2), \tag{3}$$

where: ω_1 is a stator supply angular frequency $\omega_1 = 2\pi f_1$, $L_{1\sigma}$ is the stator leakage inductance, $\underline{L}_{1\delta}(f_2)$ is the inductance associated with the magnetic flux in the machine air gap.

The reactance $\mathrm{j}\omega_1\underline{L}_{1\delta}(f_2)$ in (3) can be represented in the form of a parallel connection of the magnetizing reactance $\mathrm{j}\omega_1 L_\mu$ and the rotor impedance $\underline{Z}_2^\bullet(f_2)$ (4) [14–16]. The stator leakage inductance $L_{1\sigma}$ and the magnetizing inductance L_μ appearing in (3) and (4) are treated as constant parameters due to the constancy of stator voltage parameters during the LC test.

$$\frac{1}{\mathrm{j}\omega_1\underline{L}_{1\delta}(f_2)} = \frac{1}{\mathrm{j}\omega_1 L_\mu} + \frac{1}{\mathrm{j}\omega_1}\left[\frac{\mathrm{j}\omega_2}{\underline{Z}_2^\bullet(f_2)}\right], \tag{4}$$

where: $L_\mu = \underline{L}_{1\delta}(f_2 = 0)$, ω_2 is a slip angular frequency $\omega_2 = 2\pi f_2$, superscript $^\bullet$ denotes rotor electromagnetic parameters and physical quantities referred to the stator.

The variability of rotor impedance as a function of slip frequency can be approximated through a parallel connected two-terminal networks of $R^\bullet_{2(n)}$, $L^\bullet_{2(n)}$ parameters (5), which leads to representation of the actual inductance frequency characteristic $\underline{L}_{1\delta}(f_2)$ (4) of a considered IM by means of an expanded rotor EC [14–16].

$$\frac{1}{\underline{Z}_2^\bullet(f_2)} \cong \sum_{n=1}^{N} \frac{1}{R^\bullet_{2(n)} + \mathrm{j}\omega_2 L^\bullet_{2(n)}}, \tag{5}$$

where: $R^\bullet_{2(n)}$, $L^\bullet_{2(n)}$ are lumped parameters of the n-th two-terminal network of an expanded rotor EC, $n = 1, 2, \ldots, N$, N is number of parallel connected two-terminal networks of an expanded rotor EC.

Taking into account the stator phase winding electromagnetic parameters R_1 and $L_{1\sigma}$ in the expanded rotor EC resulting from (4), the complete RML-EC of the tested IM is formulated (Fig. 1). The number N of parallel connected two-terminal networks of the rotor EC constitutes a compromise between desirable approximation accuracy of the actual IM inductance frequency characteristic $\underline{L}_{1\delta}(f_2)$ by the mathematical model based on this EC in the considered range of slip frequency [14] and a complexity level of drive system control algorithms, elaborated on the basis of the RML-EC. In turn, an approximation of the inductance frequency characteristic $\underline{L}_{1\delta}(f_2)$ by means of a single series connection of $R^\bullet_{2(1)}$, $L^\bullet_{2(1)}$ parameters in the rotor EC leads to the classical T-EC.

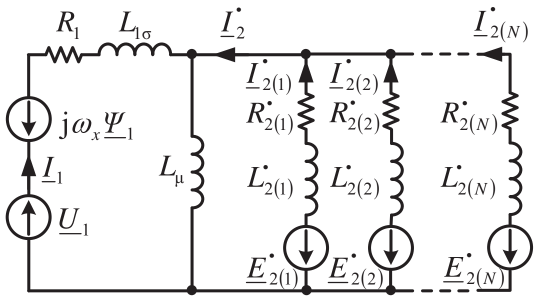

Fig. 1. The induction machine RML-EC. The particular symbols denote the following electromechanical quantities: $\underline{U}_1$, $\underline{I}_1$, $\underline{\Psi}_1$ are the stator voltage, current and flux space vectors, respectively, $\underline{I}^{\bullet}_2$ is the rotor current space vector, $\underline{E}^{\bullet}_{2(n)}$, $\underline{I}^{\bullet}_{2(n)}$ are the rotor electromotive force and current space vectors, respectively, related to the n-th two-terminal network of the expanded rotor EC, ω_x is the angular velocity of the coordinate system (the remaining symbols are denoted in the text)

The stator phase winding resistance R_1 is determined through measurement conducted according to the standards [18] or [19], whereas the remaining electromagnetic parameters $L_{1\sigma}$, L_μ, $R^{\bullet}_{2(n)}$, $L^{\bullet}_{2(n)}$ of the considered EC are subjected to an identification process, which can be conveniently carried out using selected optimisation methods.

3. Experimental studies

The studies have been conducted for the four-pole IM of type Sg 132S-4 with a single Cage Rotor (CR-IM). Due to the fact, that the main attention in the presented considerations is focused on IM mathematical models representing the variability of rotor electromagnetic parameters, resulted from rotor deep bar effect, the analogous studies have been carried out for the tested IM with the Solid Rotor (SR-IM) manufactured from magnetic material S235JR.

The examined IM-SR is marked by significant slip $s \approx 1$ corresponding to the breakdown torque at the stator supply voltage frequency of $f_1 = 50$ Hz. In order to reduce the breakdown slip of the IM-SR, while assuming the maintenance of approximately equal stator flux amplitudes of the tested IM with cage and solid rotors as well as bearing in mind the limitations resulting from rated parameters of the programmable AC source (AMETEK Model: 3001iX) powering the investigated motors, for the purposes of the conducted studies the new operating points have been adopted for the IM with both types of rotor construction. The operating data of the analysed IM with cage and solid rotors, corresponding to the considered machine operating points, have been set together in Table 1.

During the experimental studies, the NL, LR and LC tests have been conducted in conformity to the guidelines reported in the standard [18]. Under the NL and LR testes, the measurement of instantaneous values of the stator voltages and currents as well as stator winding temperature has been carried out in the adjustment range of stator supply voltage indicated by the standard [18]. Within the framework of the LC test, in addition to the above mentioned physical quantities of

Table 1. Operating data of IM of type Sg 132S-4 with cage and solid rotors corresponding to the considered machine operating points

Parameter	**Unit**	**CR-IM**	**SR-IM**
Stator voltage	(V)	400 Y	677 Y
Frequency	(Hz)	50	85
Stator current	(A)	4.536	4.495
Power	(kW)	2.358	1.992
Torque	(Nm)	15.53	9.39
Rotational speed	(rpm)	1450	2030
Power factor	(–)	0.8819	0.6698
Efficiency	(–)	0.8525	0.5641
Stator flux	Wb	0.973	0.995

the tested IMs, the instantaneous values of rotor angular velocity have been measured for each of machine load setpoints.

The investigated IMs have been coupled to the load DC machine fed by the 4Q thyristor converter (Parker DC590P). Such a solution has provided the wide adjustment range of considered IM load conditions, enabling the measurement of demanded physical quantities in the generating, motoring and ideal no-load modes of machine operation. The measurement of the aforementioned physical quantities has been carried out during steady-state operation of the examined machines. Additionally, the shaft torque of the tested IMs has been determined on the basis of the force measurement realised by means of the adequately mounted force sensor. Data acquisition has been performed with the use of a high-resolution, multi-channel measurement device equipped with a 16-bit AD converter. The view of the considered motor drive and measurement system has been presented in Fig. 2.

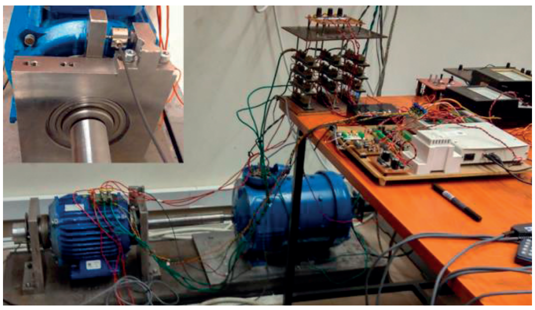

Fig. 2. The view of the considered motor drive and measurement system

The instantaneous values of stator voltages and currents registered under the NL, LR and LC tests, after conversion to the voltage and current space vectors, respectively, expressed in the stationary coordinate system $\omega_x = 0$, have been used to determine the stator power and RMS values of stator voltages and currents. In turn, the instantaneous values of rotor angular velocity measured within the LC test have served to calculate slip frequencies corresponding to the load setpoints of the tested IMs. The stator phase resistance, determined in compliance with the guidelines included in the standard [18], after correction to the reference winding temperature of 25°C has equalled $R_1 = 2.9597\ \Omega$.

In the first instance, based on the stator power and RMS values of stator voltages and currents derived from instantaneous values of the considered IM physical quantities measured under the NL and LC tests, the identification procedure of machine T-EC electromagnetic parameters has been executed accordingly to the standard [18] (marked in the article as T-EC Std 1), in the vicinity of the adopted machine operating points. Additionally, the T-EC electromagnetic parameters of the examined IMs have been identified on the basis of the procedure reported in the standard [19] – "Method 4" (marked in the article as T-EC Std 2). The T-EC electromagnetic parameters of the tested IMs, determined for comparative purposes in conformity with the abovementioned procedures, have been set together in Table 2 and 3.

Table 2. Electromagnetic parameters of the considered ECs of the tested CR-IM. Particular resistances are corrected to the reference winding temperature $T_{\mathrm{ref}} = 25°\mathrm{C}$

EC	$L_{1\sigma}$ (H)	L_μ (H)	$R^\bullet_{2(1)}$ (Ω)	$L^\bullet_{2(1)}$ (H)	$R^\bullet_{2(2)}$ (Ω)	$L^\bullet_{2(2)}$ (H)
T-EC Std 1	0.0153	0.4999	1.5687	0.0230	–	–
T-EC Std 2	0.0147	0.5041	1.6973	0.0219	–	–
RML-EC	0.0176	0.4875	2.0011	0.0143	6.7227	0.2145

Table 3. Electromagnetic parameters of the considered ECs of the tested SR-IM. Particular resistances correspond to the average temperature of stator winding $T_{\mathrm{ref}} = 55°\mathrm{C}$ registered under the LC test

EC	$L_{1\sigma}$ (H)	L_μ (H)	$R^\bullet_{2(1)}$ (Ω)	$L^\bullet_{2(1)}$ (H)	$R^\bullet_{2(2)}$ (Ω)	$L^\bullet_{2(2)}$ (H)	$R^\bullet_{2(3)}$ (Ω)	$L^\bullet_{2(3)}$ (H)
T-EC Std 1	0.0423	0.4613	11.5581	0.0741	–	–	–	–
T-EC Std 2	0.0268	0.5169	19.7569	0.0400	–	–	–	–
RML-EC	0.0356	0.5542	22.2571	0.0314	42.7071	0.06249	8.0260	1.2098

Subsequently, based on the stator power and RMS values of stator voltages and currents derived from the measurement conducted under the LC test, the variability of the considered IM inductance $\underline{L}_1(f_2)$ as a function of slip frequency have been determined in pursuance of (1), (2) and (3). The Inductance Frequency Characteristics (IFChs) $\underline{L}_1(f_2)$ of the tested IMs have been presented in Fig. 3.

The machine IFCh unequivocally represents the variability of rotor electromagnetic parameters, resulted from rotor deep bar effect, at any stator supply voltage frequency from the range enabling the machine operation at the constant flux range – below the field weakening point [15]. Taking the above feature into account, the IFCh can constitute a reference characteristic in an identification procedure of electromagnetic parameters of machine ECs, which can further be

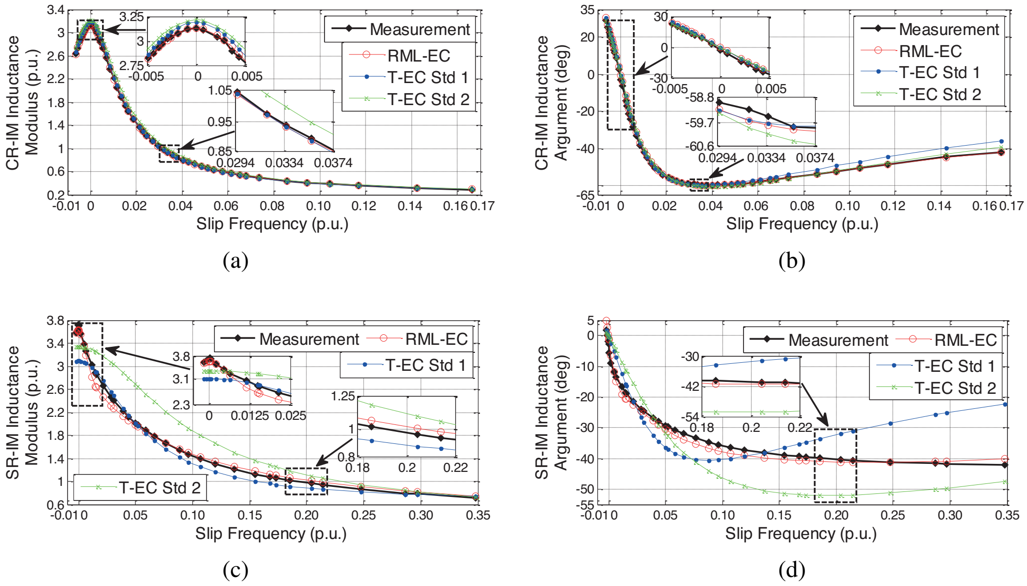

Fig. 3. The IFCh of the tested machines: CR-IM (a), (b) and SR-IM (c), (d), and the approximation characteristics resulted from the T-EC and RML-EC: modulus (a), (c) and argument (b), (d)

used in an elaboration process of various control algorithms of IM drive systems. An approximation problem of the IFCh by means of IM mathematical models resulting from adopted ECs with the sought electromagnetic parameters can be solved through minimization of the evaluation function defined as the sum of the mean squared errors of IFCh modulus and argument [14, 16]:

$$F\left(\left|\underline{L}_1(f_2)\right|, \arg \underline{L}_1(f_2)\right) = \sum_{f_{2\min}}^{f_{2\max}} k_{\text{mod}} \left(\frac{\left|\underline{L}_1(f_2)\right| - \left|\underline{L}_1^{(\text{EC})}(f_2)\right|}{\left|\underline{L}_1(f_2)\right|} \right)^2 + \\ + \sum_{f_{2\min}}^{f_{2\max}} k_{\arg} \left(\arg \underline{L}_1(f_2) - \arg \underline{L}_1^{(\text{EC})}(f_2) \right)^2, \tag{6}$$

where: $|\underline{L}_1(f_2)|$, $\arg \underline{L}_1(f_2)$ are the modulus and argument, respectively, of the IM impedance determined according to (3) basing on measured machine physical quantities, superscript $^{(\text{EC})}$ concerns the IM inductance determined with the use of machine mathematical models resulted from adopted ECs with the sought electromagnetic parameters, $(f_{2\min} \div f_{2\max})$ is the slip frequency range corresponding to the variation range of machine load conditions, k_{mod}, $k_{\arg}$ are the weighting factors of the particular components of the evaluation function.

The sets of EC electromagnetic parameters, leading to the evaluation function minimization, can be determined with the aid of various optimization methods, including evolutionary algorithms. The procedures have been presented in the literature, allowing for electromagnetic parameter identification of different structures of machine ECs employing Genetic Algorithms (GAs) [14, 16, 20–24]. The usage of a GA in an identification procedure of EC electromagnetic parameters involves the need to define the search space bounds for each of these parameters. Their ranges can significantly influence the final solution of evaluation function minimization process – representation accuracy of reference characteristics by machine mathematical models with determined electromagnetic parameters, as well as the rate of algorithm convergence. An excessive narrowing of the search space of potential solutions, without preliminary estimation of EC particular electromagnetic parameters, can in turn reduce the GA ability to find an optimal solution to the considered problem, and thereby diminish the efficiency of the parameter identification process.

The problem associated with specifying the search space bounds of sought EC electromagnetic parameters can be solved with the use of the search space reduction method quoted in [22]. According to this method the wide ranges of these bounds are initially assumed, then the ranges are restricted accordingly to the adequate formula under the information derived from introductory tests of parameter identification realised with the use of the GA.

In the presented studies, the search space bounds of particular electromagnetic parameters of the considered EC had been defined on the basis of the T-EC parameters, determined in conformity with the procedure reported in the standard [19] – "Method 4", which have been listed in Table 2 and 3.

The criteria, that have been adopted in the identification procedure of EC electromagnetic parameters of the tested IM with cage and solid rotors, assumed the representation of the IFCh modulus with an error not exceeding 5% in the considered range of slip frequency, while maintaining a possible minimum error of the IFCh argument representation and a minimum number N of two-terminal networks of the rotor EC. Fulfilment of the above criteria has been achieved with the use of the mathematical models basing on the machine RML-EC with the one and two additional two-terminal networks, comparing with the classical T-EC, in the ECs of the cage and solid rotors, respectively. The electromagnetic parameters of the machine RML-ECs, determined with the help of the Genetic Algorithm Optimization Toolbox implemented in the Matlab software [25], have been included in Table 2 and 3.

In Fig. 3, the reference IFChs have been set together with the approximation characteristics determined relying upon the IM mathematical models resulted from the T-EC and RML-EC with the identified electromagnetic parameters (Table 2 and 3), whereas in Fig. 4 the errors between the reference and approximation characteristics have been presented.

Adequacy of the determined electromagnetic parameters of the adopted machine ECs has been additionally verified through the comparison of the steady-state power factor-slip and torque-slip characteristics of the tested IMs, derived from the conducted measurement under the LC test and the simulations performed with the use of the mathematical models formulated on the basis of the machine T-EC and RML-EC, implemented in the Matlab software. The variability of the power factor and electromagnetic torque of the investigated IMs, presented in the following figures, have been expressed as a function of slip frequency.

In Fig. 5a and b the steady-state power factor-slip and the electromagnetic torque-slip (EM Torque) characteristics of the considered CR-IM have been included, respectively, whereas Fig. 5c and d present the relative errors between the characteristics determined on the basis of machine physical quantities measured under the LC test and the corresponding characteristics calculated with the use of the rotor angular velocity and space vectors of stator voltage, current and flux, received as a result of the machine operation simulations conducted at the specified load conditions.

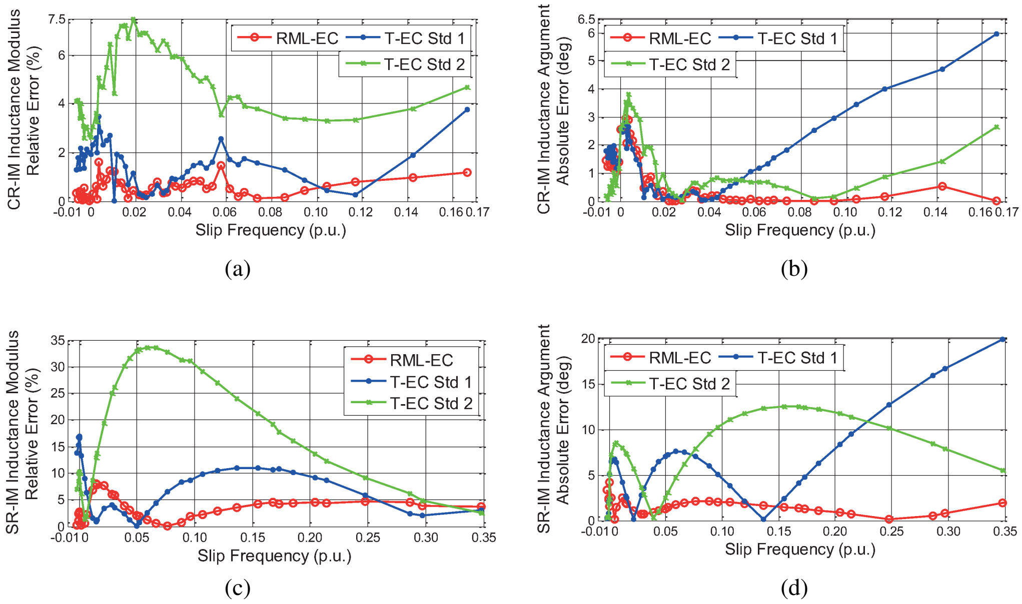

Fig. 4. The errors between the reference IFCh of the tested machines: CR-IM (a), (b) and SR-IM (c), (d), and the approximation characteristics resulted from the T-EC and RML-EC: modulus relative error (a), (c) and argument absolute error (b), (d)

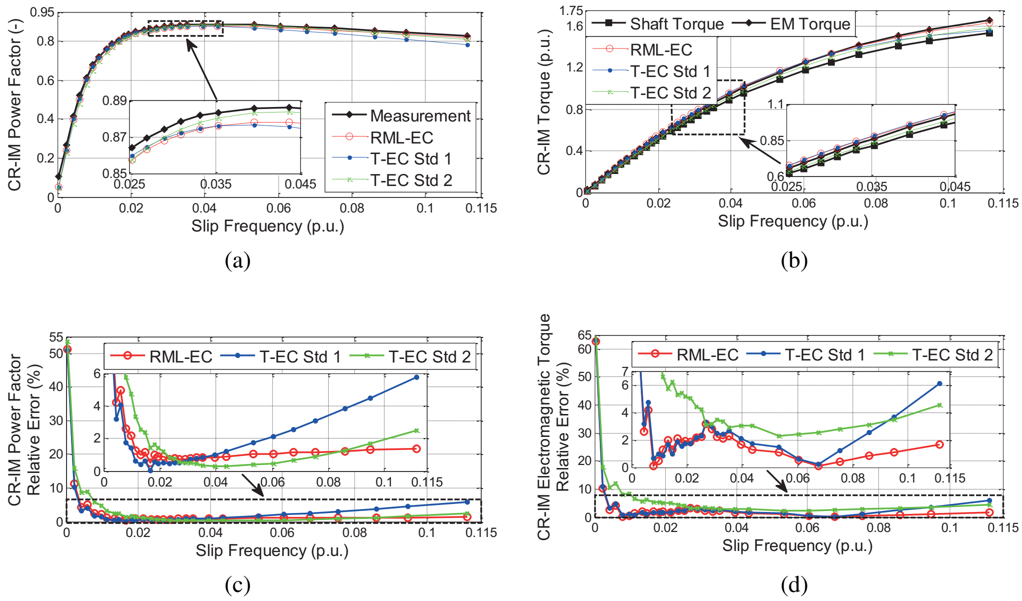

Fig. 5. The tested CR-IM steady-state power factor-slip and torque-slip characteristics (a), (b), and their relative errors (c), (d)

In turn, the analogous characteristics to those shown in Fig. 5, referring to the tested SR-IM have been presented in Fig. 6. Furthermore, in Fig. 5b and 6b the steady-state shaft torque-slip characteristic (Shaft Torque), determined on the basis of the force measurement (Fig. 2), have been compared with the corresponding characteristics of the IM electromagnetic torque calculated with the use of the investigated IM physical quantities obtained from the conducted experimental and simulation studies.

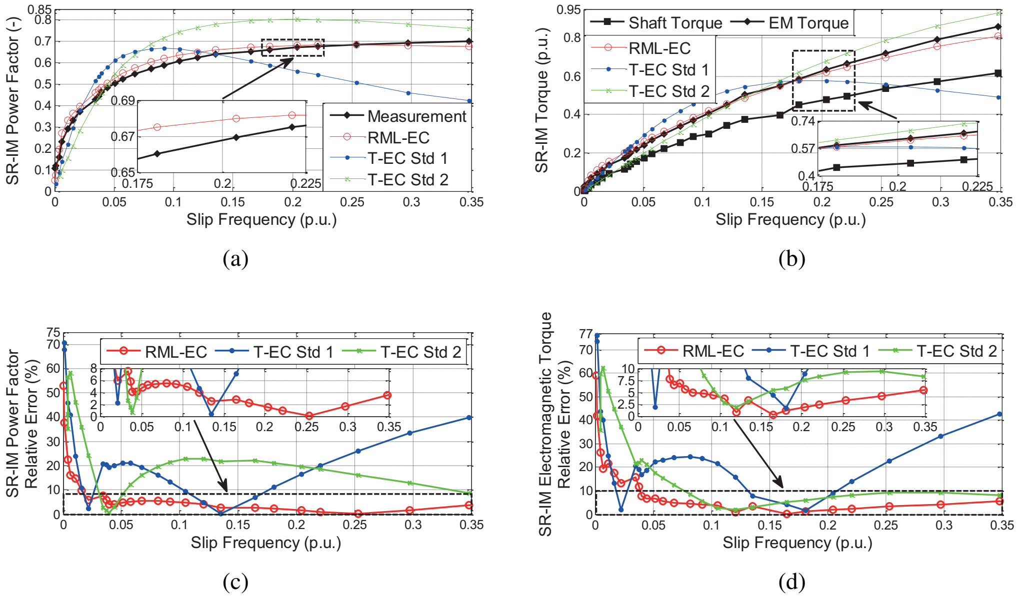

Fig. 6. The tested SR-IM steady-state power factor-slip and torque-slip characteristics (a), (b) and their relative errors (c), (d)

4. Conclusions

The presented procedure, founded on the approximation of reference IM impedance frequency characteristics, enables the electromagnetic parameters identification of a considered machine EC, including the one with an extended structure of the rotor EC, with the use of a selected optimization method, e.g. the GA. The reference IM impedance frequency characteristics are determined on the basis of the measurement conducted under the LC test. The mathematical model resulted from the machine RML-EC allows for representation of IM impedance frequency characteristics with assumed accuracy in the whole measured range of slip frequency, not restricting itself to the vicinity of slip frequency corresponding to the considered machine operating point as in the case of mathematical models formulated basing on the classical T-EC with constant parameters. Taking the above into consideration, the presented methodology enables the more efficient use of information included in the measurement executed under the LC test.

Satisfactory agreement of the steady-state power factor-slip and toque-slip characteristics of the examined IM, determined experimentally and through the machine operation simulations carried out with the use of the RML-EC with the identified electromagnetic parameters, confirms additionally the usefulness of the presented procedure.

Relying upon the conducted studies, it can be concluded that the presented procedure, elaborated for IMs characterized by significant rotor deep bar effect, can constitute an interesting alternative to identification methods of EC electromagnetic parameters reported in the literature, also in relation to standard squirrel cage motors.

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