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Estimation of Induction Motor Equivalent Circuit Parameters from Manufacturer's Datasheet by Particle Swarm Optimization Algorithm for Variable Frequency Drives

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ABSTRACT

In recent years, industrial developments have made it necessary to control induction motors, used in both industrial and household applications, over a wide range of speeds. Thanks to vector-control algorithms, in order to control the torque in high-performance operations over wide-ranging speeds, the equivalent circuit parameters of the induction motor have to be known precisely.

In this study, the equivalent circuit parameters of the induction motor are estimated only with the limited information shared by the manufacturer's datasheets. The estimation method is based on the principle of solving nonlinear equations derived from the equivalent circuit of an induction motor by the particle swarm optimization algorithm. The proposed equation set and the algorithmic solution have been tested for 20 different induction motors and presented in comparison with the experimentally obtained equivalent circuit parameters. Moreover, the speed–torque characteristics obtained experimentally and calculated from the estimated equivalent circuit parameters for ten different selected motors are compared and the performance of the proposed algorithm is examined.

***Index Terms*—**Equivalent circuit, induction motors, parameter estimation, particle swarm optimization algorithm, vector control.

I. INTRODUCTION

Due to the simplicity, low cost, and less maintenance, induction motors are indispensable in drive applications, both for industrial and simple household use. In recent years, speed control of the induction motor over a wide speed range has become critical as a result of developments in the manufacturing, transportation, and process industries. It has become quite popular in this respect, due to the decrease in the structural volumes of the newly developed electrical drive systems which can operate over a wide speed range, gearless, and without a belt–pulley assembly or with direct drive [1].

Many high-performance speed and torque control methods have been developed for induction motor drives in operations over a wide speed range [2]. Vector control is the most commonly used speed-control method in which the stator currents of the induction motor are identified as two orthogonal components that can be visualized with a vector. One component defines the magnetic flux of the motor; the other belongs to the torque. The control system of the drive calculates the corresponding current component references from the flux and torque references. Since these calculations are based on the motor model, the performance of the algorithms is sensitive to the equivalent circuit parameters of the induction motor [3]. Therefore, it is very crucial to know the equivalent circuit parameters of the motor for high-performance speed and torque control of the induction motor [4].

The equivalent circuit parameters of the induction motor are usually determined with the estimation algorithm embedded in variable frequency drives (VFD). In the literature, there are many studies about the estimation of the equivalent circuit parameters of the induction motor. According to these studies, the estimation of the equivalent circuit parameters of the induction motor can be examined in two parts, as offline and online estimation methods [5].

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Offline estimation methods are generally based on the no-load and the blocked-rotor tests. The equivalent circuit parameter estimation with this method is generally performed before the induction motor starts. The most commonly used methods for offline parameter estimation can be examined under two headings: by applying direct current to motor windings, and by applying single-phase alternating current. In the first method, a direct current not exceeding the rated current of the motor is applied to one phase of the induction motor through the VFD. Sometimes, the direct current can be applied while two of these phases are connected in series and the other one is connected in parallel to them. After this process, the stator current can be measured by a current sensor and the stator winding resistance (R_s) can be easily calculated. In the second method, currents at different frequencies are applied to two of the motor phases. This method corresponds to the locked-rotor test, since the motor will remain stationary. With the results obtained, rotor resistance, magnetization reactance, and leakage reactance can be roughly calculated.

Using the offline methods, the equivalent circuit parameters of the induction motor can be calculated with a small error. However, equivalent circuit parameters change due to operational quantities such as temperature rise, surface effect, and magnetic flux density. Therefore, in some applications, the parameters have to be estimated in real time. In the literature, there are several different methods for real-time-equivalent circuit parameter estimation. The iterative least-squares technique has advantages in terms of speed, efficiency, and ease of implementation. The least-squares technique is based on the principle of minimizing the square of the difference between the real value and the predicted value [6-8]. The model reference adaptive system (MRAS) is another method for online parameter estimation of the equivalent circuit parameters of the induction motor. This method has been used for many years, thanks to its advantages such as simplicity and ease of implementation. This method is based on the principle of reducing the error between the reference model and the adjustable model by an adaptive mechanism.

In addition to online estimation and offline estimation methods, the equivalent circuit parameters of the induction motor can also be estimated from the manufacturer's data. Lee et al [9] proposed an iterative method using rated power, rated voltage, efficiency, power factor, rated speed, and the number of the poles, from the manufacturer's datasheet. In [10, 11] a genetic algorithm-based metaheuristic method was proposed for the estimation of the induction motor's equivalent circuit parameters. Susanto and Islam [12] proposed a method that combines genetic algorithm and the Newton–Raphson Method for estimation of the equivalent circuit parameters of the double-cage induction motor. In [13], a modified Newton–Raphson method was proposed for estimation of the equivalent circuit parameters of the double-cage induction motor. In [14], both manufacturer's data and measurement data were used to estimate the equivalent circuit's parameters. Wengerkievicz [15] examined and compared nine different parameter-estimation methods in the study. In [16], three different metaheuristic methods were proposed for the equivalent circuit parameter-estimation problem and the results were compared on several induction motors. Al-Jufout et al [17] used equations from the equivalent circuit of the double-cage induction motor to obtain the motor parameters. However, the proposed method in this study was tested on different induction motors and the estimation error was high. It is possible to propose different numerical or metaheuristic methods for parameter estimation [18-25].

In this study, the equivalent circuit parameters of the induction motor are estimated by the particle swarm optimization (PSO) method for VFDs. Section II describes the PSO algorithm in the optimization problem. Section III discusses the effects of manufacturer's data on determination of the equivalent circuit parameters. In Section IV, the nonlinear equation systems in the equivalent circuit parameter-estimation problem are described, with an explanation on the method to solve this equation system by the PSO algorithm. In Section V, the parameter estimation results obtained for 20 different induction motors are presented and the errors between the estimated values and the experimental data are calculated with the well-known error metrics in the literature. Moreover, the performance of the proposed algorithm is examined by giving the estimated and experimental speed–torque characteristics of ten different induction motors selected from the given 20 motors.

II. PARTICLE SWARM OPTIMIZATION ALGORITHM FOR ENGINEERING OPTIMIZATION PROBLEM

Particle swarm optimization is a population-based heuristic optimization method developed by Kennedy and Eberhart in 1995, inspired by fish and insects moving in swarms [26]. The first version of the method could only be used for solving nonlinear continuous-time optimization problems. Later, the method was developed for use in globally optimal solutions of more complex engineering problems [27].

It has been observed that most of the time, random movements of animals that move in herds—in situations such as finding food—enable them to reach their goals more easily [28]. The PSO algorithm uses the social interaction between individuals, called particles, and adaptively guides these individuals to the most meaningful region [29]. The first of these interactions is moving to the best position among the past memories of each particle in the swarm. The second interaction is following the particle closest to the food in the swarm. These interactions create the basis of the PSO algorithm [30].

The PSO is initialized with a random solution set (particle swarm) and tries to find the optimal solution by updating this solution set. Each particle has its own position and flight speed. During each iteration in the optimization process, the particles protect these values unchanged. In the next iteration, the particle positions are updated relative to the two best particles. At each iteration, the particles move toward the optimal solution.

In the PSO algorithm, particles are initialized at random locations. At each iteration, their positions and flight speeds are changed. The new flight speed of each particle is determined by (1) and the new position of each particle is determined by (2):

$$v_i(k+1) = wfv_i(k) + c_1r_1(k)\left(XI_{besti}(k) - x_i(k)\right) + c_2r_2(k)\left(Xg_{best}(k) - x_i(k)\right), \quad (1)$$

$$x_i(k+1) = x_i(k) + v_i(k+1),\ v_i(0) = 0. \quad (2)$$

In these equations, k represents iteration number, M represents particle number (swarm population) in each iteration, $x_i(k)$, $i \in (1,\ldots, M)$ represents the position of particle i in iteration k, $v_i(k)$, $i \in (1,\ldots, M)$ represents the flight speed of particle i in iteration k, wf represents

the inertia weight factor, c_1 and c_2 are learning rates, and $r_1(k)$ and $r_2(k)$ are random numbers between 0 and 1. The best position of any particle in the swarm in their own memories is stored in the variable $XI_{besti}(k)$. In addition, the position of the particle in the swarm that is closest to the optimal solution is stored in the variable $Xg_{best}(k)$.

The linearly decreasing inertia weight factor controls the old flight speed and this value is calculated by (3), where wf_{max} and wf_{min} represent first and last inertia weight factors and *iter* and $iter_{max}$ represent the current iteration number and maximum iteration number:

$$wf = wf_{max} - \frac{wf_{max} - wf_{min}}{iter_{max}} iter. \quad (3)$$

To summarize the operation of the PSO method:

Step 1: Generate a swarm with randomly generated starting positions and flight speeds.

Step 2: Calculate the fitness values of all particles in the swarm.

Step 3: Calculate the $XI_{besti}(k)$ value for each particle in the swarm.

Step 4: Calculate the $Xg_{best}(k)$ value.

Step 5: Calculate new positions and flight speeds.

Step 6: Return to step 2 until stopping criteria have been ensured.

III. EQUIVALENT CIRCUIT MODEL OF THE INDUCTION MOTOR AND PARAMETERS SHARED IN MANUFACTURER'S DATASHEETS

A. Equivalent Circuit of the Induction Motor

The complex structure of the induction motor involves both very time-consuming and error-prone processes to calculate the currents flowing in the stator and rotor windings, torque, power factor, losses, and some other necessary parameters in variable operation conditions. Especially when the number of phases and shaft power are increased, it is too difficult to calculate the values of the phase quantities. In order to avoid these difficulties and to simplify the calculations of operation conditions, an equivalent circuit model of the induction motor is proposed [31]. The equivalent circuit of the induction motor has been used to understand operations and analyze the induction motor for a long time [32]. The single-cage and the double-cage equivalent circuit models of the induction motor are illustrated in Fig. 1.

In Fig. 1, V_s represents the stator voltage, I_s the stator current, I_r the rotor current, and *s* slip. In addition, the equivalent circuit parameters are named as follows:

R_s = stator resistance, R_r = rotor resistance referred to the stator, X_{sd} = stator leakage reactance, X_{rd} = rotor leakage reactance referred to the stator, and X_M = magnetizing reactance.

The equivalent circuit of the single-cage induction motor is given in Fig. 1a. It contains five different parameters: R_s, X_{sd}, R_r, X_{rd}, and X_M. On the other hand, the equivalent circuit of the double-cage induction motor includes seven different parameters: R_s, R_{r1}, R_{r2}, X_M, X_{sd}, X_{rd1}, and X_{rd2}. Since stator leakage reactance (X_{sd}) and rotor leakage reactance referred to stator (X_{rd}) are considered equal in practical applications, the equivalent circuit with five different parameters is reduced to four different parameters [33]. The double-cage induction motor has different equivalent circuits with six, seven, or eight parameters. The equivalent circuit with seven parameters shown in Fig. 1b. In this model, stator leakage reactance (X_{sd}) and rotor leakage reactance of the outer cage (X_{rd2}) are considered equal.

B. Parameters Shared in Manufacturer's Datasheets

Manufacturers share some information about their induction motors in datasheets, in order to assist in choosing the correct induction motors and to define the characteristics of the induction motor. Information shared in a manufacturer's datasheet of some mains-powered general-purpose motors is given in Table I. In this study, limited characteristic values in the datasheets shared by induction motor manufacturers were used. The characteristic data to be used are listed below, with their explanations.

P_n = rated power, V_n = rated voltage, I_n = rated current, F = frequency, P_f = power factor ($\cos\varphi$), N_r = rotor speed, poles = number of the poles, I_d/I_n = ratio of the starting current to the rated current, and M_d/M_n = ratio of the breakdown torque to the rated torque.

IV. IMPLEMENTATION OF THE PARTICLE SWARM OPTIMIZATION METHOD TO THE EQUIVALENT CIRCUIT PARAMETER ESTIMATION PROBLEM

In this section, using the equivalent circuit of the induction motor shown in Fig. 1, a set of equations including the equivalent circuit parameters and the experimental data shared in the manufacturer's data sheets has been obtained.

The number of equations and the complexities of the equations are reduced by assuming that the stator leakage reactance (X_{sd}) and the rotor leakage reactance referred to the stator (X_{rd}) are approximately equal. Four different equations with four equivalent circuit parameters were derived by using the equations of the active and the reactive components of rated current, rated torque, and breakdown torque. The first two equations for the PSO algorithm can be written as (4) and (5) by using rated current and power factor from the manufacturer's datasheet:

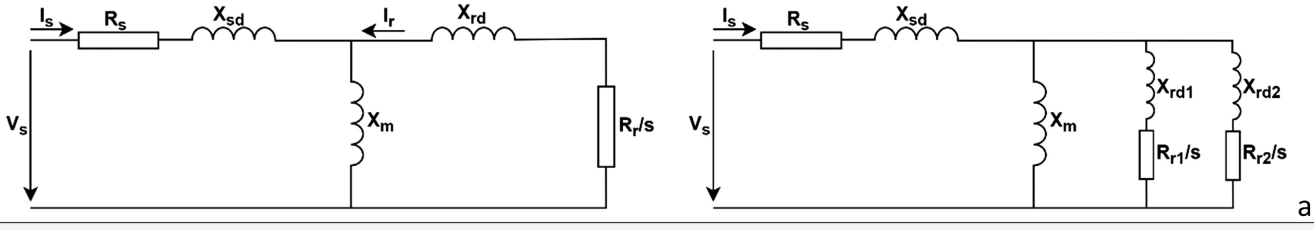

Fig. 1. Equivalent circuit of an induction motor (a) Single-cage model (b) Double-cage model.

TABLE I. ELECTRICAL AND MECHANICAL CHARACTERISTICS OF GENERAL-PURPOSE MAINS-POWERED INDUCTION MOTORS

Motor No.	P_n (kW)	N_r (rpm)	V_n (V)	I_n (A)	F (Hz)	Poles	T_n (N.m)	cosφ	M_d/M_n	I_d/I_n
1	3.72	1750	460	7.35	60	4	25.5	0.85	3.7	7.3
2	7.5	1760	460	13.3	60	4	48	0.89	2.9	6
3	15	1760	460	35	60	4	128	0.90	2.15	4.5
4	37	1780	460	54	60	4	192	0.86	3.7	7.4
5	74.5	1780	460	135.7	60	4	507.5	0.90	3.2	6.6
6	111	1785	460	140.6	60	4	497.5	0.85	4.43	8.75
7	149	1785	460	229.6	60	4	865	0.90	3.85	8
8	3.72	1750	575	5.38	60	4	22.8	0.83	4.38	8.59
9	7.5	1760	575	12.2	60	4	54.2	0.87	3	6.3
10	15	1765	575	22.5	60	4	102	0.88	3	6.44
11	37	1775	575	45.6	60	4	106	0.87	3.9	7.7
12	74.5	1780	575	113	60	4	533	0.91	2.9	6.1
13	111	1785	575	116	60	4	507.5	0.84	4.5	8.8
14	4	1430	400	8.3	50	4	28.8	0.83	3.18	6.1
15	7.5	1440	400	13.2	50	4	48.1	0.87	3.68	7.3
16	15	1460	400	29.2	50	4	112.8	0.90	4.97	10.5
17	37	1480	400	65	50	4	242.5	0.87	3.7	7.6
18	75	1484	400	124.4	50	4	475.1	0.88	4.18	8.6
19	110	1487	400	173.5	50	4	661	0.87	4.5	9.2
20	160	1487	400	270	50	4	1055	0.90	4.26	8.8

$$f_1(x)=\frac{V_n}{I_n}\cos\varphi-{}_e\{Z_{n_{est}}\}=0, \tag{4}$$

$$f_2(x)=\frac{V_n}{I_n}\sin\breve{}\ -{}_m\{Z_{n_{est}}\}=0. \tag{5}$$

The estimated total input impedance (Z_{n_est}) of the equivalent circuit is given in (6). In these equations, R_s represents stator resistance, R_r is rotor resistance referred to the stator, X_{sd} represents stator leakage reactance, X_{rd} represents rotor leakage reactance referred to the stator, X_m represents magnetizing reactance, and s_n represents the rated slip:

$$Z_{n_est}=\frac{\frac{jX_mR_r^2}{s_n}-\frac{X_mR_rX_{rd}}{s_n}+\frac{X_mR_rX_{rd}+X_m^2R_r}{s_n}+jX_mX_{rd}^2+X_m^2X_{rd}}{\frac{R_r^2}{s_n^2}+\left(X_m+X_{rd}\right)^2} \tag{6}$$

$$+R_s+jX_{sd}.$$

The input impedance of the equivalent circuit (Z_{n_est}) calculated with the estimated parameters have active (7) and reactive (8) components:

$${}_e\{Z_{n_est}\}=\frac{\frac{R_r^2R_s}{s_n^2}+R_s\left(X_m+X_{rd}\right)^2+\frac{R_rX_m^2}{s_n}}{\frac{R_r^2}{s_n^2}+\left(X_m+X_{rd}\right)^2}, \tag{7}$$

$${}_m\{Z_{n_est}\}=\frac{\frac{R_r^2\left(X_m+X_{sd}\right)}{s_n}+(X_m+X_{rd})\left(X_{rd}X_{sd}+X_{sd}X_m+X_{rd}X_m\right)}{\frac{R_r^2}{s_n^2}+\left(X_m+X_{rd}\right)^2}. \tag{8}$$

The other two equations for the PSO algorithm can be derived in (9) and (10) by using the rated torque (M_{n_test}) and breakdown torque (M_{D_test}) given in the manufacturer's datasheet:

$$f_3(x)=M_{n_test}-M_{n_est}, \tag{9}$$

$$f_4(x)=M_{D_test}-M_{D_{est}}. \tag{10}$$

The estimated rated torque (M_{n_est}) in (9) is derived from (11), (12), and (13) where P_{n_est} represents the shaft power calculated with the estimated parameters, I_{r_est} represents the rotor current, and n_r is rotor speed:

$$M_{n_est}=\frac{60\cdot P_{n_est}}{2\pi\cdot n_r}, \tag{11}$$

$$P_{n_est}=\frac{3\cdot\left|I_{r_est}\right|^2\cdot R_r\cdot(1-s)\cdot 60}{s_n\cdot 2\pi\cdot n_r}, \tag{12}$$

$$I_{r_est} = \frac{V_n - I_n\left(R_s + jX_{sd}\right)}{R_r / s_n + jX_{rd}}. \quad (13)$$

The breakdown torque (M_{D_est}) calculated with the estimated equivalent circuit parameters of the motor in (10) can also be calculated with the equations between (14) and (19), where P_{D_est} represents breakdown shaft power, I_{rD_est} is breakdown rotor current, I_{in_D} represents breakdown motor current, Z_{D_est} is breakdown motor impedance, and s_d represents breakdown slip:

$$M_{D_est} = \frac{60 \cdot P_{D_est}}{2\pi \cdot n_r}, \quad (14)$$

$$P_{D_est} = \frac{3 \cdot \left|I_{rD_est}\right|^2 \cdot R_r \cdot \left(1 - s_D\right) \cdot 60}{s_D \cdot 2\pi \cdot n_r}, \quad (15)$$

$$I_{rD_est} = \frac{V_n - I_{in_D}\left(R_s + jX_{sd}\right)}{R_r / s_D + jX_{rd}}, \quad (16)$$

$$I_{in_D} = \frac{V_n}{Z_{D_est}}, \quad (17)$$

$$Z_{D_est} = \frac{\frac{jX_m {R_r}^2}{s_D} - \frac{X_m R_r X_{rd}}{s_D} + \frac{X_m R_r X_{rd} + {X_m}^2 R_r}{s_D} + jX_m {X_{rd}}^2 + {X_m}^2 X_{rd}}{\frac{{R_r}^2}{{s_D}^2} + \left(X_m + X_{rd}\right)^2} + R_s + jX_{sd}, \quad (18)$$

$$s_D = \frac{s_n}{\frac{M_{D_test}}{M_{n_test}} - \sqrt{\frac{{M_{D_test}}^2}{{M_{n_test}}} - 1}}. \quad (19)$$

Then the derived nonlinear equation system is solved by the PSO algorithm. In order to find the equivalent circuit parameters of R_s, X_{sd}, R_r, X_{rd}, and X_m using the values from the manufacturer's datasheet, the PSO algorithm needs an aimed function named "fitness function." In this study, the fitness function is given in (20) where $x = (R_s, X_{sd}, R_r, X_m)$ is the equivalent circuit parameter vector:

$$F\left(x\right) = \sqrt{{f_1}^2 + {f_2}^2 + {f_3}^2 + {f_4}^2}. \quad (20)$$

Similar to all metaheuristic methods, the PSO algorithm also requires initial values. The proper selection of the initial values is critical to reach the result both quickly and accurately. In this study, the following initial conditions are used for the estimation of the equivalent circuit parameter problem of the induction motor given in (21)–(23). While the lower limit is determined as half of the values given in (21)–(23), the upper limit was chosen as twice these values:

$$X_m = \frac{3 \cdot {V_n}^2}{Q_n}, \quad (21)$$

$$X_{sd} = \frac{X_m}{20}, \quad (22)$$

$$R_s = R_r = \frac{X_{sd}}{20}. \quad (23)$$

The flowchart of the proposed optimization algorithm for estimation of the induction motor equivalent circuit parameters from the manufacturer's datasheet by PSO is given in Fig. 2.

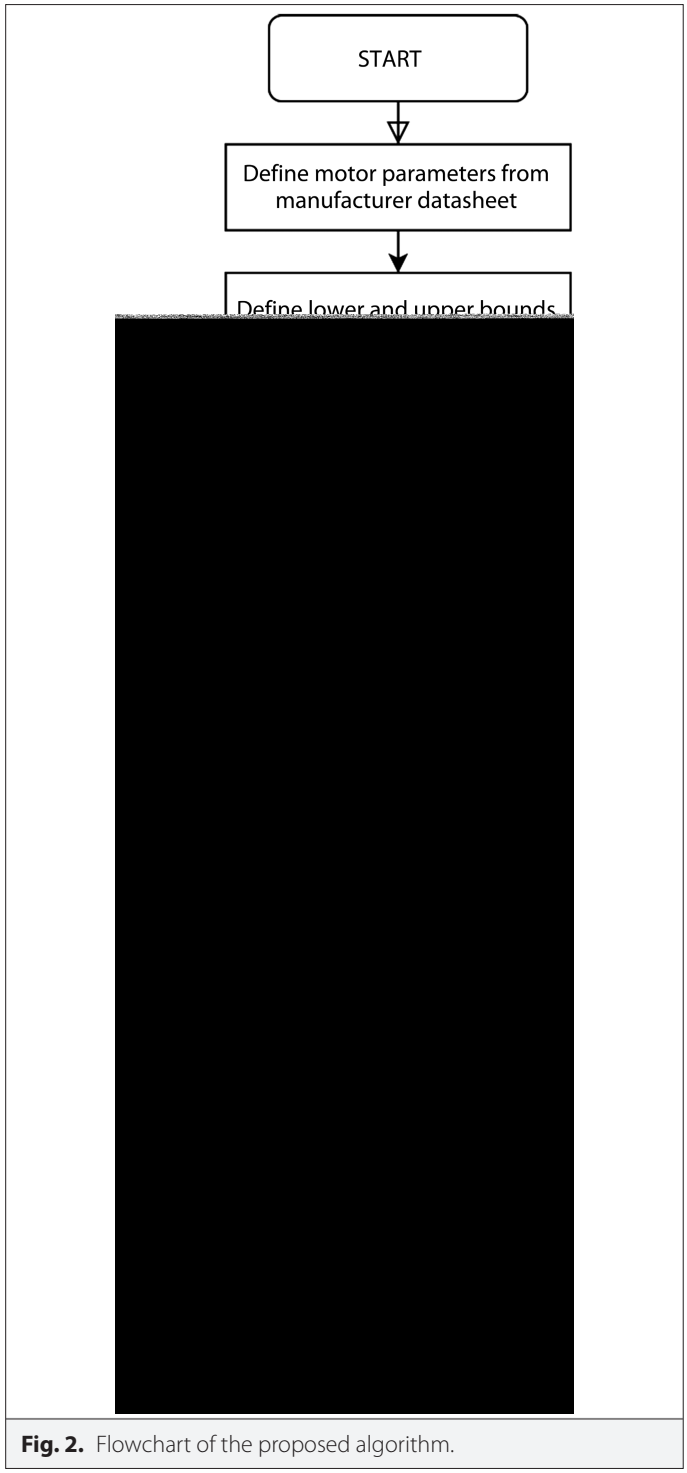

Fig. 2. Flowchart of the proposed algorithm.

TABLE II. COMPARISON OF STATOR RESISTANCE, STATOR, AND ROTOR LEAKAGE REACTANCE ESTIMATED BY THE PROPOSED ALGORITHM, AND THE EXPERIMENTAL RESULTS

Motor No.	R_s (Exp.)	R_s (Est.)	Estimation Error (%)	$X_{sd}=X_{rd}$ (Exp.)	$X_{sd}=X_{rd}$ (Est.)	Estimation Error (%)
1	1.115	1.122151	−0.64	2.2521	2.243695	0.38
2	0.6837	0.684712	−0.15	1.565	1.56277	0.16
3	0.2761	0.278571	−0.89	0.8259	0.824328	0.20
4	0.0996	0.0997	−0.09	0.3268	0.326305	0.17
5	0.0395	0.040778	−3.05	0.1466	0.146231	0.29
6	0.0302	0.029543	2.18	0.1066	0.106541	0.14
7	0.0181	0.017732	2.47	0.0716	0.071483	0.20
8	2.053	2.046149	0.33	3.0540	3.046752	0.24
9	0.9174	0.935301	−1.95	2.0632	2.053118	0.49
10	0.454	0.468523	−3.20	1.0989	1.094463	0.41
11	0.0987	0.099531	−0.83	0.4693	0.468155	0.26
12	0.0596	0.06446	−8.10	0.2386	0.237648	0.41
13	0.0458	0.04774	−4.08	0.1598	0.159217	0.39
14	1.405	1.41017	−0.37	1.8343	1.82385	0.57
15	0.7384	0.73871	−0.04	0.9566	0.952622	0.42
16	0.2147	0.227431	−5.93	0.3113	0.305227	1.96
17	0.0823	0.074988	8.92	0.2274	0.227756	−0.13
18	0.0355	0.034211	3.68	0.1052	0.105117	0.12
19	0.0215	0.021341	0.97	0.071	0.070928	0.10
20	0.0137	0.013764	0.19	0.0477	0.047717	0.07

V. NUMERICAL RESULTS

The proposed algorithm for the estimation of equivalent circuit parameters from the manufacturer's datasheet for the VFDs of induction motors has been tested for 20 different induction motors. For a better comparison of the performance of the algorithm, induction motors with significantly different nameplate values such as power, voltage, power factor, and frequency were chosen in the tests. The flowchart given in the previous section is programmed in the MATLAB environment. The equivalent circuit parameters of induction motors whose manufacturer's data are given in Table I were estimated by the proposed PSO algorithm. The estimated equivalent circuit parameters and experimental parameters have been given in Tables II and III. In order to examine the performance of the purposed algorithm, estimation errors have also been given in the tables.

Thanks to the proposed algorithm, the stator resistance was estimated with an average error of 2.40%, rotor resistance referred to the stator with an average error of 0.09%, the stator leakage reactance and rotor leakage reactance referred to the stator with an average of 0.36%, and the magnetization reactance with an average of 0.74% error. In addition to the results in the tables, the speed–torque characteristics of ten different motors were calculated with the equivalent circuit parameters estimated by the algorithm. The estimated characteristic and the experimentally obtained speed–torque characteristics are illustrated in Fig. 3.

It can easily be seen from Fig. 3 that the estimated results are in great harmony with the experimentally obtained results for ten motors. Although visual comparison gives satisfactory results, the mathematical success of the method is also calculated. Two different performance metrics were used to calculate the accuracy of the proposed algorithm with the experimental speed–torque characteristics. The first of the accuracy functions is derived from the definition of mean absolute percentage error (MAPE), which is given in (23), where k is the number of torque data. The MAPE, also known as mean absolute percentage deviation (MAPD), is frequently used to measure the accuracy of prediction methods [34]. The difference between the real and the predicted value is divided by the real value to determine how close the estimated value is to the real value. Then this value is divided by the number of data (k) and multiplied by 100 to find the percentage deviation from the real values:

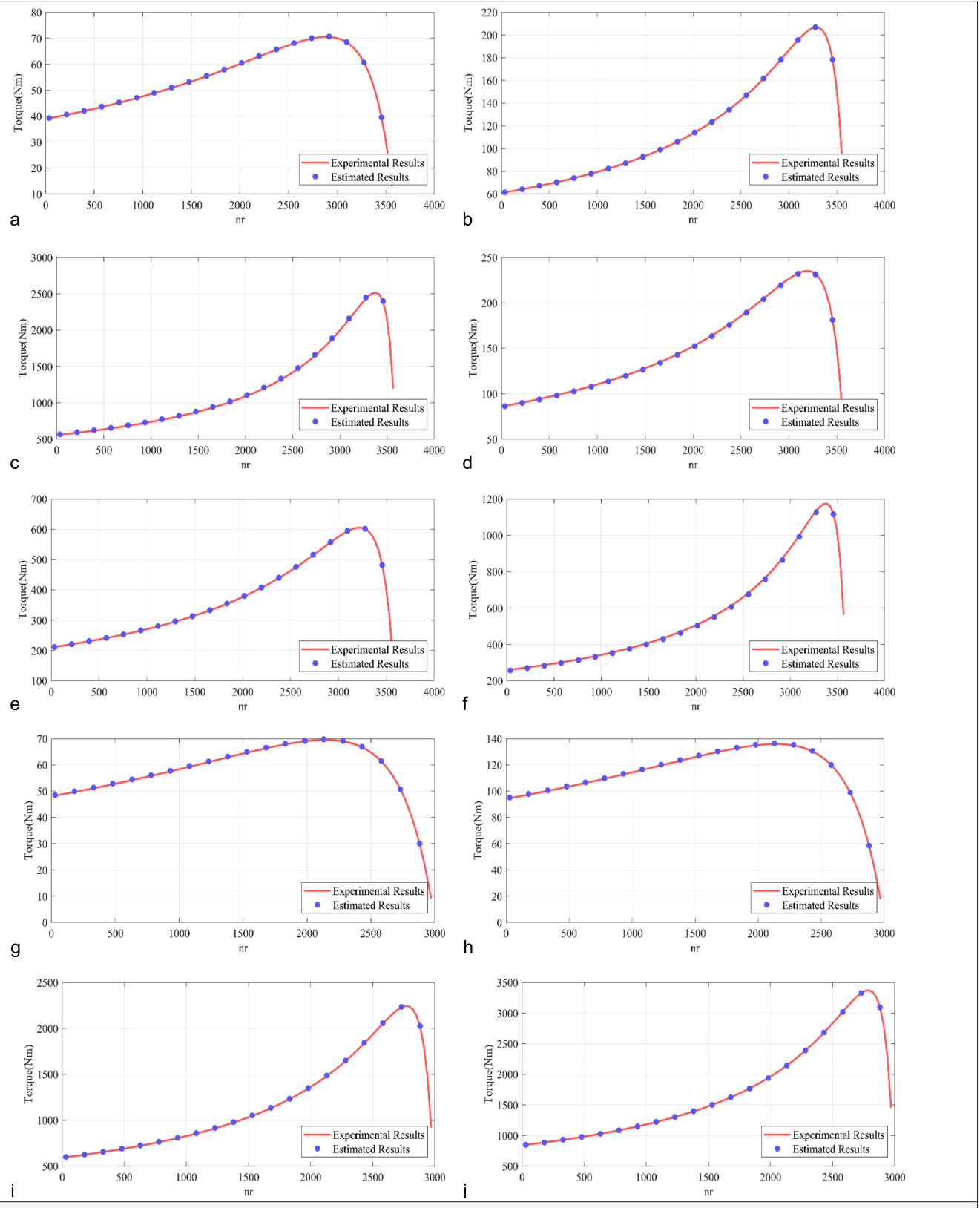

Fig. 3. Speed–Torque characteristics of ten different induction motors: (a) Motor 1, (b) Motor 3, (c) Motor 7, (d) Motor 10, (e) Motor 11, (f) Motor 12, (g) Motor 14, (h) Motor 15, (i) Motor 19, and (j) Motor 20.

TABLE III. COMPARISON OF ROTOR RESISTANCE, MAGNETIZATION REACTANCE ESTIMATED BY THE PROPOSED ALGORITHM, AND THE EXPERIMENTAL RESULTS

Motor No.	R_r (Exp.)	R_r (Est.)	Estimation Error (%)	X_m (Exp.)	X_m (Est.)	Estimation Error (%)
1	1.083	1.082547	0.04	76.7930	76.53754	0.33
2	0.451	0.451061	−0.01	56.0208	55.98997	0.06
3	0.1645	0.164309	0.12	28.7041	28.34671	1.25
4	0.05837	0.058377	−0.01	11.4567	11.42561	0.27
5	0.02215	0.02212	0.14	6.2731	6.221729	0.82
6	0.01721	0.017219	−0.05	4.1280	4.114918	0.32
7	0.009956	0.009961	−0.05	3.5493	3.509221	1.13
8	1.904	1.904406	−0.02	118.526	118.4565	0.06
9	0.6258	0.625061	0.12	69.8941	69.34056	0.79
10	0.2938	0.293357	0.15	40.6019	40.34188	0.64
11	0.1081	0.108064	0.03	17.7826	17.68628	0.54
12	0.03281	0.032698	0.34	10.3371	10.21255	1.20
13	0.02634	0.026307	0.13	6.0280	5.996128	0.53
14	1.395	1.394957	0.00	54.0982	53.96568	0.25
15	0.7402	0.740288	−0.01	38.9871	38.89323	0.24
16	0.2205	0.220485	0.01	20.1658	19.98934	0.88
17	0.0503	0.05048	−0.36	8.5168	8.501772	0.18
18	0.02092	0.020941	−0.10	4.7438	4.721447	0.47
19	0.01231	0.012313	−0.02	3.2609	3.249462	0.35
20	0.007728	0.007728	0.00	2.4158	2.307147	4.50

TABLE IV. ACCURACY RESULTS OF SPEED–TORQUE CHARACTERISTICS OF TEN DIFFERENT INDUCTION MOTORS

Motor No.	MAPE (%)	R^2
1	99.7956	0.9999
3	99.9509	0.9999
7	99.2125	0.9999
10	99.5669	0.9999
11	99.7997	0.9999
12	98.8310	0.9999
14	99.6342	0.9999
15	99.6596	0.9999
19	99.6393	0.9999
20	99.9567	0.9999

$$Accuracy(\%) = 100 - \left(\frac{100}{k}\right) \cdot \sum_{j=1}^{k} \frac{\left|Torque_{test}(j) - Torque_{est}(j)\right|}{Torque_{test}(j)}. \quad (24)$$

The second of the accuracy functions is the coefficient of determination. The coefficient of determination, denoted R^2 or r^2 and pronounced "R squared" is expressed in (24) where $Mean_{test}$ represents the mean of estimated torque values and $Mean_{test}$ represents the mean of the experimental torque values [34]:

$$MAPE(\%) = \frac{\sum_{j=1}^{k}\left\{Torque_{est}(j) - Mean_{est}\right\} * \sum_{j=1}^{k}\left\{Torque_{test}(j) - Mean_{test}\right\}}{\sqrt{\left\{Torque_{est}(j) - Mean_{est}\right\}^2} * \sqrt{\left\{Torque_{test}(j) - Mean_{test}\right\}^2}}. \quad (25)$$

The obtained accuracy values are given in Table IV. As can be seen from the accuracy results given in Table IV, the proposed algorithm is very successful in the estimation of the equivalent-circuit parameters of induction motors from the manufacturer's data.

VI. CONCLUSION

In order to obtain high performance control of wide-ranging speed and torque in induction motors, vector control algorithms are needed in VFDs. However, since vector control methods are generally based on the motor model, the performance of speed and torque control is sensitive to the equivalent circuit parameters of the induction motor defined in control algorithms. Therefore, the equivalent circuit parameters of the induction motor have to be determined as accurately as possible for a high-performance speed–torque control. In this study, the estimation of equivalent circuit parameters for vector-controlled drives of an induction motor was carried out with only limited information shared by manufacturers in their datasheets. First of all, non-linear equations derived from the equivalent circuit of the induction motor were obtained in accordance with the information given in the manufacturer's datasheets. The estimation method is based on the principle of solving nonlinear equations derived from the equivalent circuit by the PSO algorithm. The proposed equation system and solution algorithm have been tested for 20 different induction motors and presented in comparison with the experimentally obtained equivalent circuit parameters. According to the results obtained, the high accuracy of the information shared in the manufacturer's datasheets affects the performance of the algorithm. In addition, the proposed algorithm is highly dependent on initial conditions. In order to solve this problem, an algorithm can be proposed in which the initial conditions are adapted according to the motor's rated power. Owing to the proposed algorithm, the stator resistance is estimated with an average error of 2.40%, rotor resistance referred to the stator with an average error of 0.09%, the stator leakage reactance and rotor leakage reactance referred to the stator with an average of 0.36% error, and the magnetization reactance with an average of 0.74% error. In addition to the results in the tables, the speed–torque characteristics of four different motors were calculated with the equivalent circuit parameters estimated by the algorithm. It was seen that the accuracy of the torque data calculated from estimated equivalent circuit parameters is more than 99.5%, even for the most unsuccessful case.

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