Bilecik Şeyh Edebali Üniversitesi Fen Bilimleri Dergisi
Bilecik Seyh Edebali University Journal of Science
10(1), 153-161, 2023
DOİ: 10.35193/bseufbd.1200299
e-ISSN: 2458-7575 (https://dergipark.org.tr/tr/pub/bseufbd)

Araştırma Makalesi - Research Article

Investigation of Vector Control Applications for Asynchronous Machines Using Online Parameter Estimation Methods

Asenkron Makineler için Çevrimiçi Parametre Tahmin Metotları Kullanılarak Vektör Kontrol Uygulamalarının İncelenmesi

Nihat Pamuk[1*]

Geliş / Received: 07/11/2022 ***Revize / Revised: 19/02/2023*** ***Kabul / Accepted: 14/03/2023***

ABSTRACT

Two different methods are used in dynamic model vector control applications of asynchronous machines. The first of these methods is to use the derivative information of the state variables based on the system observability principle. The second is the use of instantaneous active and reactive power measurement results as a new method. The classical equivalent circuit model is used in steady-state studies of parameter estimation methods. In dynamic systems, methods based on nonlinear minimization of the cost function, different initial values, and giving more precise estimation results are used. In this study, the dynamic system structure is set up as the square sum of the difference between parameter estimate values. Different parameter estimation methods were used for asynchronous machine models, and test results under no load and full load were examined. The impedance measurement results in parameter estimation methods were compared with the measurement results obtained from the model. It has been shown that the test results performed in real time are very close to the offline and nonlinear parameter estimation values and their accuracy has been proven.

Keywords- Asynchronous Machine, Vector Control, Dynamic Model, Parameter Estimation Methods

ÖZ

Asenkron makinaların dinamik model vektör kontrol uygulamalarında iki farklı yöntem kullanılmaktadır. Bu yöntemlerden ilki sistem gözlenebilirlik ilkesine dayanan durum değişkenlerine ait türev bilgilerinin kullanılmasıdır.İkincisi ise yeni bir yöntem olarak önerilen aktif ve reaktif güç ölçüm sonuçlarının anlık olarak paylaşılmasıdır. Parametre tahmin yöntemlerinin kararlı durum çalışmalarında klasik eşdeğer devre modelikullanılmaktadır. Dinamik sistemlerde ise,maliyet fonksiyonunun doğrusal olmayan minimizasyonuna dayanan, başlangıç değerleri birbirinden farklı olan ve daha kesin tahmin sonuçlarıveren yöntemler kullanılmaktadır. Bu çalışmada, dinamik sistem yapısı parametre tahmin değerleri arasındaki farkın karesel toplamı olacak şekilde kurulmuştur. Asenkron makine modelleri için farklı parametre tahmin yöntemleri kullanılmış, yüksüz ve tam yük altındaki testsonuçları incelenmiştir. Empedans ölçümsonuçları ile, modelden elde edilen ölçüm sonuçları karşılaştırılmıştır. Gerçek zamanlı gerçekleştirilen deney sonuçlarının çevrimdışı olarak

*Corresponding Author Contact: nihatpamuk@beun.edu.tr (https://orcid.org/0000-0001-8980-6913)
Electrical Electronics Engineering, Zonguldak Bulent Ecevit University, Engineering Faculty, Farabi Campus, 67100, Zonguldak, Turkey

gerçekleştirilen ve doğrusal olmayan parametre tahmin değerlerineçok yakın oldukları gösterilmiş ve doğrulukları ispatlanmıştır.

Anahtar Kelimeler- Asenkron Makine, Vektör Kontrolü, Dinamik Model, Parametre Tahmin Metotları

I. INTRODUCTION

Numerous speed control applications of the asynchronous machine that were previously restricted to DC motors have now become viable because of the advancement of vector control theory, the more focused field-oriented method [1,2] and others. Comparing vector-controlled techniques to the conventional voltage frequency method can increase the dynamic response. The accurate real-time estimation of non-measurable variables is the focus of most of the research in vector control and field-oriented applications of the asynchronous machine. To address this issue, several estimating techniques have been presented by scientists [3-5]. The model parameters, which change throughout typical machine operation, are generally what these methods depend on. When the scientist-proposed vector control model is utilized, it is simple to compare the AC machine speed that controls the performance of asynchronous machines with the motor rotation speed of the DC machine [6]. By using mathematical formulas and matrix transformations, vector control can be used to identify the difference between the excitation current and torque current of an asynchronous machine [7,8]. The control approach to be applied in a comparable DC machine can significantly improve the control performance of the asynchronous machine. The majority of the asynchronous machine's parameter estimate techniques is either offline or live. Because the fundamental vector control parameter can be supplied and the operational steps are straightforward, the offline parameter estimate method is typically selected [9].

The asynchronous motor's traditional no-load and full-load rotor tests are connected to the initial concept in parameter estimation. An impedance function can be derived by using the balancing steady-state equivalent circuit for an asynchronous machine. The electrical frequency, the rotor slip, and the corresponding circuit parameters all influence this input impedance. An equivalent procedure for asynchronous machines can be carried out using the streamlined hypothesis set that was used in the transformer circuit parameter estimation technique. A simpler hypothesis can't be used in this situation. However, a preliminary and workable solution to this issue is provided by the transformer parameter estimate approach. A second approach involves building an error feature using the total of the rectangular impedance mismatch values between the size sections and the mathematical model, at least in three unbiased operational places [10]. The optimal parameter estimation results from the error function's absolute minimization. Due to its significant computational delay, non-linear regression is rarely used in real-time applications for minimizing quadratic functions mathematically.

When a constant or nearly constant rotor speed is considered, the instantaneous time response has a linear relationship with the machine parameters and the state variables while the impedance expression in the frequency domain is a non-linear function of the machine parameters. Based on the second and third derivatives of the stator currents and the second derivatives of the stator voltage, several researchers have developed a real-time parameter estimate method utilizing linear regression [11,12]. Equations for the quasi-stationary asynchronous machine are used in this identification technique. The noise that the large-order derivatives of the physical measurements introduce is the fundamental issue with this estimating technique. The scientist is using an adaptive control of the rotor time constant T_r based on the mismatch between the measured instantaneous machine active or reactive power, and the obtained by the mathematical model [13]. This approach is slower than derivative methods and assumes that only the rotor time constant is variable. Combining both ideas, an estimation method has been developed that reduces the derivative order and increases the number of parameters that can be estimated in real-time. This formulation is very simple. Using field-oriented equations or vector spatial theory, the active and reactive equations are derived. Simplifying these equations for steady state solution, one equation is obtained, with three unknown coefficients. A comparison between these four estimation methods was performed to find the electrical parameter of the asynchronous machine model in real-time applications.

II. METHODOLOGY

A. Classical Estimation Method

Using two independent asynchronous machine impedance measurements, one for load condition, and the other near the no-load condition (s→0), and the following procedure can be performed:

$$Z_i(s) = Z_s + Z_{sr} + Z_r \tag{1}$$

$$I_r(s) \approx I_s(s) - I_s(s \to 0) \tag{2}$$

$$R_r = \frac{s}{1-s} \cdot \frac{P_{shaft}}{|I_r(s)|^2} \tag{3}$$

$$X_{\sigma s} + X_{\sigma r} \approx 2X_{\sigma s} \approx \Im m(Z_i(s)) \tag{4}$$

$$X_{sr} = \Im m(Z_{i(s\to 0)}) - X_{\sigma s} \tag{5}$$

$$R_s = \Re e\left[Z_i(s) - (Z_{sr} + Z_r + jX_{\sigma s})_{s\to 0}\right] \tag{6}$$

where:

$$Z_s \equiv R_s + jX_{\sigma s}; Z_r \equiv R_r + jX_{\sigma r}; Z_{sr} \equiv jX_{sr} \tag{7}$$

In Equation 7, Z_S is the stator impedance, Z_r is the rotor impedance, R_S is the stator resistance, R_r is the rotor resistance, X_S is the stator admittance, and X_r is the rotor admittance.

B. Non-Linear Estimation Method

Building a least square cost function ψ, with the mismatch between the measured input impedance and the model's input impedance defined in equation (1), a non-linear regression can be performed. The cost function ψ is;

$$\psi = \sum_{k=1}^{n}\left[\frac{Z_m(s_k) - Z_i(R_s, L_{\sigma s}, L_{sr}, L_{\sigma r}, R_r, \omega_s, s_k)}{Z_m(s_k)}\right]^2 \tag{8}$$

Minimizing equation (8), using the Gauss-Newton method [14], descendent gradient method, or any other non-linear minimization method, the five parameters of the asynchronous machine model can be found [15].

C. Derivative Estimation Method

Spatial vectors $\vec{v}(t)$ and $\vec{i}(t)$ has been defined as;

$$\vec{x}(t) \equiv \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & e^{j\frac{2\pi}{3}} & e^{j\frac{4\pi}{3}} \end{bmatrix} \cdot \begin{bmatrix} x_a(t) & x_b(t) & x_c(t) \end{bmatrix}^t \tag{9}$$

In the stator reference frame, the asynchronous machine model can be expressed as;

$$\begin{aligned} \vec{v}_S &= R_S \vec{i}_S + L_S' p\vec{i}_S + L_{sr}' p\vec{i}_r \\ \vec{0} &= R_r \vec{i}_r + L_r'[p\vec{i}_r - j\theta \vec{i}_r] + L_{sr}'[p\vec{i}_e - j\theta \vec{i}_e] \end{aligned} \tag{10}$$

In Equation 10, θ represents the flux position and p represents the moment of inertia. In differential equations (10), the non-measurable variables $\vec{i}_r$ and $p\vec{i}_r$ can be reduced using the control observability method [16]. The new differential equations are independent of no-measuring variables but have dependence on the voltage derivatives as well as on currents, and their first and second derivative. The second derivative of the rotor position θ and the arbitrary reference position δ are neglected to make a linear model. The results obtained by substitution, explained above, might be written as the following linear problem [17].

$$p\vec{v}_S - j\theta\vec{v}_S = k_1\left[p^2\vec{i}_S - j\theta p\vec{i}_S\right] + k_2\left[p\vec{i}_S\right] - k_3\left[j\theta\vec{i}_S\right] - k_4\left[\vec{v}_S\right] + k_5\left[\vec{i}_S\right] \tag{11}$$

where:

$$k_1 = L_S'; k_2 = R_s + R_r\frac{L_S'}{L_r'}; k_3 = R_S; k_4 = \frac{R_r}{L_r'}; k_5 = R_s\frac{R_r}{L_r'} \tag{12}$$

In Equation 12, the k values represent the permeability coefficients. Linear equation (11) can be solved for each instant of time. An error function can be built with the sum of the square errors and minimized it. The error function can be written as:

$$\psi = \sum_{i=1}^{n}\left[\vec{fi}_{test} - \vec{fi}_{model}\right]^t \cdot \left[\vec{fi}_{test} - \vec{fi}_{model}\right] \tag{13}$$

Calculating the cost function minimum value (13) the following parameter vector can be found:

$$[k]=\left[\sum_{i=1}^{n}[w_i]^t.[w_i]\right]^{-1}.\left[\sum_{i=1}^{n}[w_i]^t.[h_i]\right] \tag{14}$$

where:

$$\begin{aligned}&[h_i]=\left[p\vec{v}_{si}-j\theta\vec{v}_{si}\right]\\&[w_i]=\left[p^2\vec{i}_{si}-j\theta p\vec{i}_{si}\quad p\vec{i}_{si}\quad j\theta\vec{i}_{si}\quad \vec{v}_{si}\quad \vec{i}_{si}\right]\\&[k]=\left[k_1\quad k_2\quad k_3\quad k_4\quad k_5\right]^t\end{aligned} \tag{15}$$

In Equation 15, h_i represents the friction of the motor and w_i represents the cavity diameter. Once the vector [k] is obtained, the electrical machine parameters can be evaluated in the following way:

$$R_s=k_3;L_s^{'}=\frac{k_2-k_3}{k_4};T_r=\frac{1}{k_4};\frac{L_{sr}^{'2}}{L_r^{'}}=L_s^{'}-k_1 \tag{16}$$

D. Active and Reactive Power Estimation Method

The phasor apparent power has been defined as:

$$\vec{S}=\vec{V}.\vec{I}^*=Ve^{j\alpha}.Ie^{-j\beta}=V.Ie^{j\varphi}=P+jQ \tag{17}$$

In the spatial vector representation, a similar expression can be obtained:

$$\vec{s}(t)=\vec{v}(t).\vec{i}^*(t)=v(t).i(t)e^{j\varphi(t)}=p(t)+jq(t) \tag{18}$$

From equations (18) and (9) the instantaneous active and reactive power can be written as:

$$p(t)=v_ai_a+v_bi_b+v_ci_c \tag{19}$$

$$q(t)=\frac{1}{\sqrt{3}}(v_{bc}i_a+v_{ca}i_b+v_{ab}i_c) \tag{20}$$

The instantaneous active power obtained in equation (19) agrees with the classical three-phase definition. Equation (20) defines the spatial vector concept of the instantaneous reactive power. It could be shown that these power definitions are closely related to the pointing vector on the air gap of the asynchronous motor. Definitions (19) and (20) are expressed in function of the original voltages and currents. Using the generic orthogonal coordinate system, with the arbitrary angular position δ as a reference, the spatial vectors in this frame are:

$$\vec{x}^{\delta}=e^{-j\delta}\vec{x}=x_d+jx_q \tag{21}$$

The instantaneous active and reactive power in the arbitrary and orthogonal reference frame can be expressed as:

$$\vec{s}=p+jq=\vec{v}^{\delta}.\vec{i}^{\delta*}=\vec{v}.\vec{i}^*=(v_di_d+v_qi_q)+j(v_qi_d-v_di_q) \tag{22}$$

From equations (19), (20), and (22), it follows that the instantaneous active and reactive power can be evaluated either on the primitive coordinate system or on the arbitrary reference frame. The field-oriented equations of the asynchronous machine can be written as [18]:

$$v_{ds}=R_si_{ds}+\tilde{L}s\,pi_{ds}-\delta\tilde{L}s\,i_{qs}+\frac{L_{sr}^{'2}}{L_r^{'}}pi_m \tag{23}$$

$$v_{qs}=R_si_{qs}+\tilde{L}s\,pi_{qs}+\delta\tilde{L}s\,i_{ds}+\delta\frac{L_{sr}^{'2}}{L_r^{'}}i_m \tag{24}$$

$$0=T_rpi_m+i_m-i_{ds} \tag{25}$$

$$0 = T_r i_m(\dot{\delta} - \dot{\theta}) - i_{qs} \tag{26}$$

where; T_r rotor time constant $L_r^{'} / R_r$, and $\tilde{L}s$ total referred stator inductance $L_s^{'} - L_{sr}^{'2} / L_r^{'}$. Replacing equations (23) and (24) into (22), the instantaneous active and reactive power equations in an oriented field frame can be written as [19]:

$$p(t) = R_s i_s^{2} + \tilde{L}s(i_{ds} pi_{ds} - i_{qs} pi_{qs}) + \frac{L_{sr}^{'2}}{L_r^{'}}(\dot{\delta}\, i_m i_{qs} + i_{ds} pi_m) \tag{27}$$

$$q(t) = \tilde{L}s i_s^{2} + \tilde{L}s(i_{ds} pi_{qs} - i_{qs} pi_{ds}) + \frac{L_{sr}^{'2}}{L_r^{'}}(\dot{\delta}\, i_m i_{ds} - i_{qs} pi_m) \tag{28}$$

Equations (27) and (28) have three different parameters $R_s, \tilde{L}s$, and the coefficient $L_{sr}^{'2} / L_r^{'}$. The magnitude of the stator current i_s, can also be measured in the machine terminals. The field-oriented variables i_{ds}, i_{qs}, i_m, and their derivatives are strongly dependent on the rotor time constant T_r. The rotor field-oriented equations (25) and (26) can determine these relations. In the steady state operating condition of the asynchronous machine, the angular speed reference $\dot{\delta}$ of the magnetization current i_m, and the mechanical rotor speed $\dot{\theta}$ are constants. The magnetization current i_m is also constant during the steady-state operation. From the field-oriented equations (23) - (26), the following relations are obtained:

$$i_m = i_{ds} \Rightarrow pi_{ds} = 0 \tag{29}$$

$$i_{qs} = T_r(\dot{\delta} - \dot{\theta}) i_m \Rightarrow pi_{qs} = 0 \tag{30}$$

Replacing (29) and (30) into expressions (27) and (28), the steady state active and reactive power can be written from equations (27) - (30) the power expression in the function of the parameters $R_s, T_r, \tilde{L}s, T_r$, and the variables $i_s, q(t), \dot{\delta}$ and $\dot{\theta}$ becomes:

$$p(t) = R_s i_s^{2} + T_r(\dot{\delta} - \dot{\theta}).q(t) - \tilde{L}s T_r\, \dot{\delta}(\dot{\delta} - \dot{\theta}) \tag{31}$$

All variables in expression (31) can be measured in steady-state operation. The magnitude of the stator current i_s, the active power $p(t)$, and reactive power $q(t)$ can be evaluated from the instantaneous voltages and currents in the machine terminals [20]. A steady-state condition is reached when the active and reactive power are constant. The fundamental frequency of the primitive stator currents is a good estimation of the angular reference derivative $\dot{\delta}$. The solution to the steady-state problem can be found using linear regression. The ψ cost function can be built with the sum of the square errors measured and the model active power. The estimation can be performed by equation (31). The absolute minimization of the least square function represents the best possible parameter estimation from the given measurement set. The least-square function can be written as:

$$\psi = \sum_{i=1}^{n} \left[p_m(t_i) - p(t_i) \right]^2 = \sum_{i=1}^{n} \left[p_m(t_i) - [w_i].[k] \right]^2 \tag{32}$$

The parameter estimation that minimizes the least square function (32) can be obtained as:

$$[k] = \left[\sum_{i=1}^{n} [w_i]^{t} . [w_i] \right]^{-1} . \left[\sum_{i=1}^{n} [w_i]^{t} . p_m \right] \tag{33}$$

Once the vector [k] has been found using at least three independent operational conditions, the electrical parameters of the asynchronous machine can be evaluated as:

$$R_s = k_1; T_r = k_2; \tilde{L}s = k_3 / k_2 \tag{34}$$

The torque coefficient $L_{sr}^{'2} / L_r^{'}$ can be obtained as [21]:

$$\frac{L_{sr}^{'2}}{L_r^{'}} = \frac{q_i - \delta_i \tilde{L} s i_s^2}{\delta_i i_{ds}^2} = \frac{p_i - R_s i_s^2}{\delta_i i_{ds} i_{qs}} \tag{35}$$

Since the stator resistance has a secondary influence in the estimation process, the steady state method can be simplified by neglecting the stator resistance R_s or using a previously obtained value of this parameter. In that case, only two parameters need to be found by linear regression, and the proposed method can be accelerated. The stator resistance R_s and the stator inductance L_s can be obtained directly from the non-load test using equations (27) and (28). In that condition, the quadrature current i_{qs} is zero, and the stator current corresponds with the direct component of the stator current i_{ds}.

III. ONLINE PARAMETER ESTIMATION ANALYSIS

Four estimation methods have been used to calculate the parameters for a 5.5 kW industrial squirrel cage motor, 208 V, 50 Hz, wye connected, four poles, 0.8 p.f., 1760 rpm. The voltages and currents were measured through the Hall Effect transducers, and the mechanical shaft speed was measured through a digital encoder. The H-bridge module was created by using 6MBP30RH060-50 smart power modules of Fujitsu Company in the experimental set. The H-bridge module is composed of a 3-phase 6-level cascaded inverter group and the input voltages of each H-bridge module are isolated from each other as 160 V. Hall-effect transducers MCR-S10-50-UI-SW-DCI-NC from Phoenix Contact Company were used. RIM Tach NexGen RT1 encoder of 1250 pulses of Dynapar Company was used to measure the motor speed and evaluate it by the digital signal processor. Figure 1 shows the picture of the main control board module together with the block diagram.

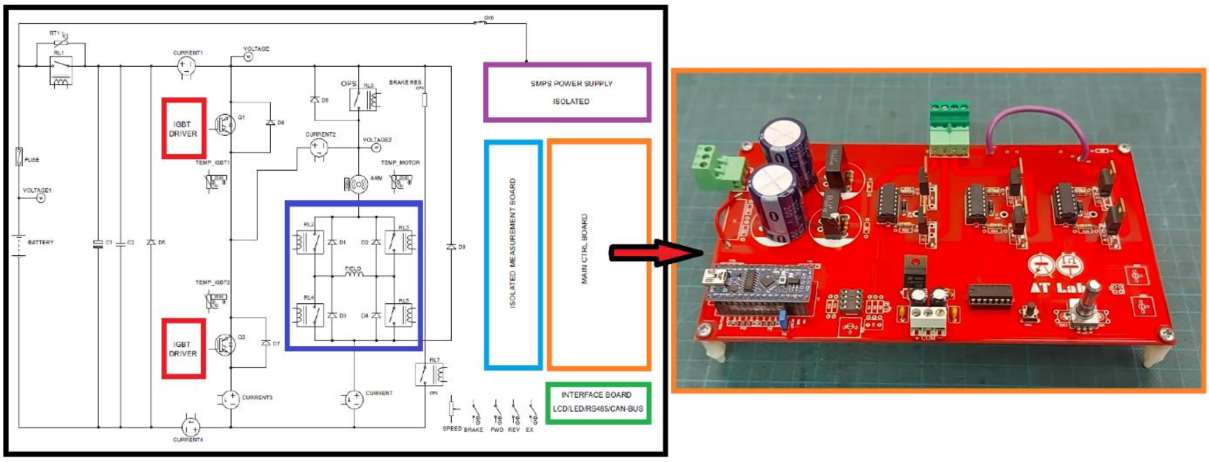
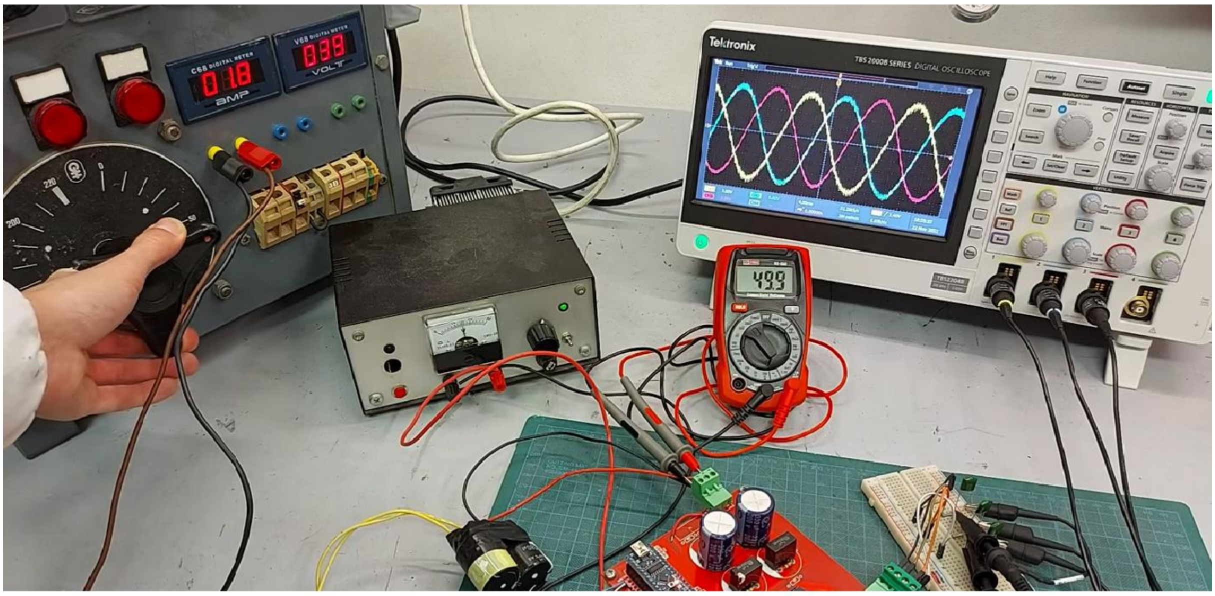


Figure 1. The picture of the main control board module together with the block diagram

A direct starting of the asynchronous machine, using nominal voltages was performed. The line voltages, the phase currents and the shaft speed were measured and digitized using a fast A/D (350 kHz) acquisition card with a sample and hold input. Digital signals were sent to a PC through the DMA channels. These variables were registered for three different mechanical load steps in the rotor shaft. Figure 2 shows the picture of the experimental setup.



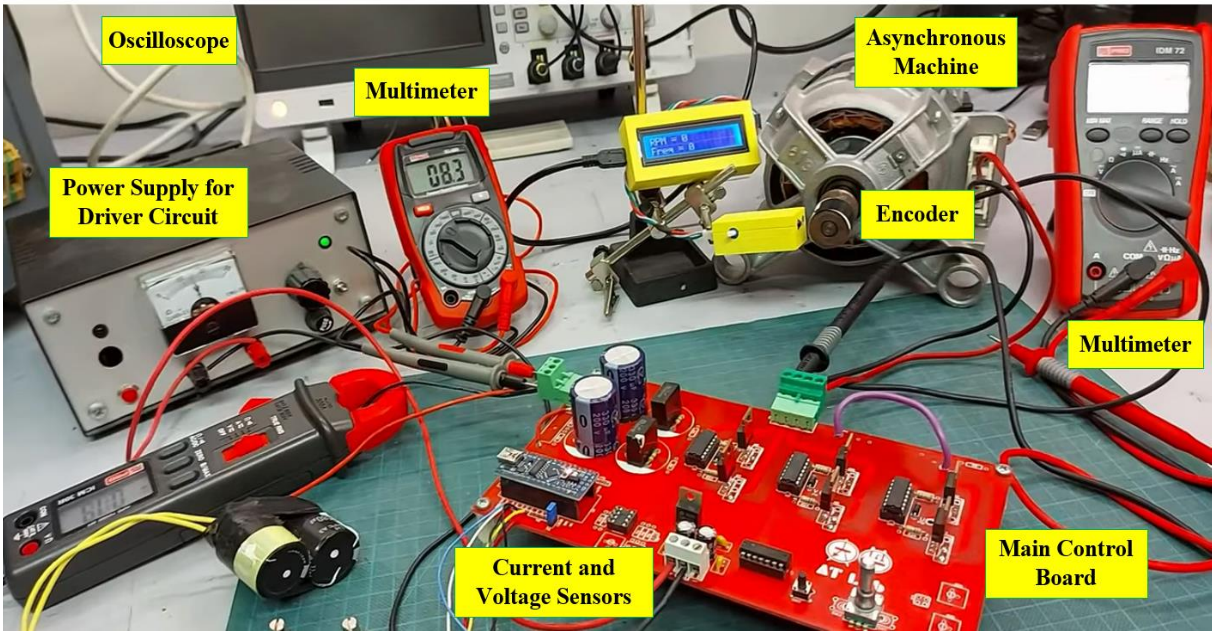


Figure 2. The picture of the experimental setup

Table 1 shows the test data obtained from three independent operating conditions and the obtaining values for the slip, impedance, current, and voltages related to the three operating conditions. The per-unit (pu) bases used in the calculations are S_{Base} = 5.5 kVA and V_{Base} = 208 V.

Table 1. Asynchronous machine testing data

	Real Values							Per-Unit Values					
Variables	V_{ab} [V]	V_{bc} [V]	i_a [A]	i_b [A]	n [rpm]	P [kW]	T [Nm]	s	$\Re e(Z_i)$	$\Im m(Z_i)$	$\lvert V_s \rvert$	$\lvert I_s \rvert$	$\angle I_s$
Condition 1	196.5	195.3	18.24	17.57	1768	5.02	24.51	0.0284	0.6361	0.4543	0.9501	1.1751	0.5916
Condition 2	203.8	203.1	11.27	10.46	1790	2.83	10.49	0.0068	0.8004	1.0224	0.9943	0.7835	0.9148
Condition 3	209.1	207.2	9.93	8.28	1803	0.88	0.21	0.0003	0.3017	1.7519	1.0108	0.5341	1.4205

IV. TEST RESULTS

Table 2 shows a comparison of the parameter estimation values using the four estimating methods. For the fourth method, calculations were performed with and without the stator resistance R_s. The classical estimation method is fast but has poor accuracy. The cost function with this estimation procedure is 0.2542. Nevertheless, the time required to solve this problem is less than that used by the non-linear method and derivative method. The best accuracy was obtained with the non-linear estimation method (ψ = 0.0029). However, the estimation algorithm was the most time-consuming (251.43). The derivative estimation method was accurate (ψ = 0.0087) and faster than the non-linear method (23.18) but was more noise sensitive. The active and reactive power estimation method was the fastest method (1.1380 or 1.0002). When the stator resistance R_s, is estimated from direct measurements, the accuracy of the non-linear method is practically reached. If the resistance is included in the estimation procedure, accuracy is reduced but speed is almost the same.

Table 2. Comparison of the parameter estimation per-unit values

Techniques	Classical Method	Non-linear Method	Derivative Method	Power (w-R_s)	Power (w/o-R_s)
R_s	0.2418	0.1703	0.2207	0.2112	0.1699
$L_{\sigma s}$	0.2386	0.1409	0.1398	0.1327	0.1203
L_{sr}	1.5113	1.5608	1.5405	1.6421	1.5182
$L_{\sigma r}$	0.2319	0.1235	0.1406	0.1386	0.1204
R_r	0.0297	0.0146	0.0139	0.0173	0.0151
T_r	80.11	115.37	130.04	107.59	113.44
$L_{sr}{}^2 / L_r$	1.3159	1.4110	1.4081	1.5004	1.3816
ψ	0.2542	0.0029	0.0087	0.0371	0.0038
$t_{exe}^{(*)}$	1.3963	251.43	23.18	1.1380	1.0002

(*) In per-unit of the fastest estimation

V. CONCLUSIONS

The analyzed parameter estimation methods of the asynchronous machine model have an accurate mathematical behavior according to the results presented and can be easily implemented in real-time applications. The accuracy of the classical estimation method leaves its application only for the initial solution used by the non-linear procedures. The non-linear estimation method is the most accurate, but the time required for this technique makes it difficult to use this algorithm in real-time applications. The derivative estimation method is accurate and fast. The main problem using this procedure can be the noise influence in the external variable measurements. The numerical derivative of these noisy signals introduces big errors in the estimation solution. Due to the adaptive and durable nature of the online parameter estimation method, the speed and torque current monitoring performance of the drive to be used is better than other controllers. With the method, a fast response characteristic was obtained against the driver load change. This has given the drive system a dynamic response characteristic. In addition, with the control of the inverter power switches, minimum switching transitions are provided in the space vector diagram. The active and reactive power estimation method is the fastest and one of the most accurate estimation methods. For these reasons, it is recommended for real-time applications in vector control drives. In the future, the improvement effect of compact machines based on gear brush DC machines and low-cost magnetic encoders on different mobile robot controls can be examined. The fluctuation and variation prediction values of the instantaneous angular rotation speed provided by the low-cost magnetic rotary encoder can be increased. This will improve the precision of angular rotational velocity estimation to be used in mobile robot applications based on a low-cost magnetic rotary encoder connected to asynchronous machines.

REFERENCES

[1] Rengifo, J., Aller, J. M., Bueno, A., Viola, J., & Restrepo, J. (2012). Parameter Estimation Method for Induction Machines Using the Instantaneous Impedance During a Dynamic Start-Up. *VI. Andean Region International Conference*. 7-9 November, Cuenca, Ecuador, 11-14.

[2] Barambones, O., & Alkorta, P. (2011). A Robust Vector Control for Induction Motor Drives with an Adaptive Sliding-Mode Control Law. *Journal of the Franklin Institute*, 348(2), 300-314.

[3] Adamczyk, M., & Orlowska-Kowalska, T. (2022). Postfault Direct Field-Oriented Control of Induction Motor Drive Using Adaptive Virtual Current Sensor. *IEEE Transactions on Industrial Electronics*, 69(4), 3418-3427.

[4] Elmahfoud, M., Bossoufi, B., Taoussi, M., Ouanjli, N. E., & Derouich, A. (2019). Rotor Field Oriented Control of Doubly Fed Induction Motor. *5th International Conference on Optimization and Applications (ICOA)*. 25-26 April, 1-6.
[5] Mondal, A., Sarkar, P., & Hazra, A. (2020). A Unified Approach for PI Controller Design in Delta Domain for Indirect Field-Oriented Control of Induction Motor Drive. *Journal of Engineering Research*, 8(3), 118-134.
[6] Gamazo-Real, J. C., Vázquez-Sánchez, E., & Gómez-Gil, J. (2010). Position and Speed Control of Brushless DC Motors Using Sensorless Techniques and Application Trends. *Sensors*, 10(7), 6901-6947.
[7] Mishra, A., & Choudhary, P. (2012). Speed Control of an Induction Motor by Using Indirect Vector Control Method. *International Journal of Emerging Technology and Advanced Engineering*, 2(12), 144-150.
[8] Robyns, B., Francois, B., Degobert, P., & Hautier, J. P. (2012). *Vector Control of Induction MachinesDesensitisation and Optimisation Through Fuzzy Logic.* Springer, London, 75-121.
[9] Peretti, L., Zigliotto, M. (2012). Automatic Procedure for Induction Motor Parameter Estimation at Standstill. *IET Electric Power Applications*, 6(4), 214-224.
[10] Ando, K., Takahashi, S., Ieda, J., Kurebayashi, H., Trypiniotis, T., Barnes, C. H. W., Maekawa, S., & Saitoh, E. (2011). Electrically Tunable Spin Injector Free from the Impedance Mismatch Problem. *Nature Materials*, 10(9), 655-659.
[11] Subasri, R., Meenakumari, R., Panchal, H., Suresh, M., Priya, V., Ashokkumar, R., & Sadasivuni, K. K. (2022). Comparison of BPN, RBFN and Wavelet Neural Network in Induction Motor Modelling for Speed Estimation. *International Journal of Ambient Energy*, 43(1), 3246-3251.
[12] Saad, K., Abdellah, K., Ahmed, H., & Iqbal, A. (2019). Investigation on SVM-Backstepping Sensorless Control of Five-Phase Open-End Winding Induction Motor Based on Model Reference Adaptive System and Parameter Estimation. *Engineering Science and Technology, An International Journal*, 22(4), 1013-1026.
[13] Soliman, M. A., Hasanien, H. M., Al-Durra, A., & Alsaidan, I. (2020). A Novel Adaptive Control Method for Performance Enhancement of Grid-Connected Variable-Speed Wind Generators. *IEEE Access*, 8, 82617-82629.
[14] Cartis, C., & Roberts, L. (2019). A Derivative-Free Gauss–Newton Method. *Mathematical Programming Computation*, 11(4), 631-674.
[15] Burgers, K. C. (2014). *The Non-linear Resonant Pole Soft Switching Inverter with Induction Machine Load*. University of Johannesburg, South Africa, 49-98.
[16] Tilli, A., & Conficoni, C. (2014). Induction Motor Sensorless Observer Aligned with Rotor Flux Derivative. *IEEE Conference on Control Applications (CCA)*. 08-10 October, Juan Les Antibes, France, 1722-1728.
[17] Pamuk, N. (2018). Numerical Method for Calculations of the Multi-Dielectric Fields Based on Flux Density in High Voltage Power Transformer Apparatus. *Balkan Journal of Electrical and Computer Engineering*, 8(4), 342-347.
[18] Tang, J., Yang, Y., Blaabjerg, F., Chen, J., Diao, L., & Liu, Z. (2018). Parameter Identification of Inverter-Fed Induction Motors: A Review. *Energies*, 11(9), 2194.
[19] Teja, A. R., Verma, V., & Chakraborty, C. (2015). A New Formulation of Reactive-Power-Based Model Reference Adaptive System for Sensorless Induction Motor Drive. *IEEE Transactions on Industrial Electronics*, 62(11), 6797-6808.
[20] Tohidi, S. (2016). Analysis and Simplified Modelling of Brushless Doubly - Fed Induction Machine in Synchronous Mode of Operation. *IET Electric Power Applications*, 10(2), 110-116.
[21] Kim, J. G. (2022). Soft Start Analysis of Induction Motor Using Current Phase Angle. *Journal of Electrical Engineering & Technology*, 17(2), 1475-1480.