Adaptive Control and One-line Identification of Sensorless Permanent Magnet DC Motor

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***Abstract*—Permanent Magnet PMDC motors have outstanding performance for use in many modern applications like automated manufacturing systems, automobiles, office machine drives, tools and medical equipment.To control these motors, speed sensors are indispensable. A sensorless control scheme using an observeris proposed. However, this sensorless control method uses motor parameters to estimate speed, and hence estimation error is caused by parameters variations. That is why,an effective and simple on-line parameter identification scheme is proposed to estimate armature resistance and inductance of the motor. The identification method is developed based on the fact that, in practice PM flux-linkage is constant. An adaptive control method is proposed to control PMDC motor speed to maintain speed estimation accuracy. Simulation results are included to prove the effectiveness of the overall control system under different operating conditions.**

***Keywords* —Permanent Magnet DC motor, Sensorless control, On-line parameter identification, Adaptive control.**

I. NOMENCLATURE

The symbols used in this paper are as follows:

R_a : Stator armature resistance, Ω.
ϕ_f : Flux linkage due to rotor permanent magnet, Wb.
i_a, v_a :Armature current, A and voltage, V.
L_a :Armature inductance, H.
p : Differential operator.
T_e : Electromechanical torque, Nm.
$\widehat{\omega}$, ω^* : Estimated and reference motor speed, rad/sec.
e : Instantaneous induced e.m.f, V.
K_E :Back e.m.f constant.

II. INTRODUCTION

DC motors were used for variable speed applications as they offer various control features of simplicity to control due to the decoupled nature of the field and armature magneto motive force (mmf). DC motors have variable torque/speed characteristics and can provide a high starting torque and it is also possible to obtain speed control over a wide range. The methods of speed control of DC drives are normally simpler and less expensive than those of AC drives [1], [2]. It might be a few decades before the DC drives are completely replaced by AC drive. Due to their ability to supply a continuously variable DC voltage, controlled rectifiers and DC-DC converters made a revolution in modern industrial control equipment and variable-speed drives, with power levels ranging from fractional horsepower to several megawatts [3].

Improvement of Permanent Magnet (PM) materials is widening the application of PMDC motors. Recently, with the advent of high performance (PM) with high coactivity and high residual flux, it has been possible for the PM motors to be superior to conventional DC motors in power density, torque-to-inertia ratio, performance and efficiency.Therefore, PMDC motors have become widespread in many industrial applications. These motors typically exhibit greater stability of operation, linearity, higher maximum speeds, straightforward design, and higher efficiency [4], [5].However, PMDC drive system is dependent on speed and current sensors for control. Since these speed sensors or rotational transducers not only increase cost, maintenance, and complexity of the drive, but also impair robustness and reliability of the drive system, elimination of both types of sensors is desirable in many applications, particularly in low-cost but high-volume applications, for cost and packaging considerations. Between the two sensors, the current sensor is easier to accommodate in the electronic part of the system; the speed sensor requires a considerable labor and volume in the motor for its mounting. That makes it all the more important to do without the speed sensor for the control of the drive system. Therefore, many researchers have been studying the sensorless drive of the PM motor in view of the robustness, reliability, cost, and so on [6]-[13].In this paper the speed estimation is obtained using an observer.

On-line identification of the motor parameters is essential to enhance the performance of the proposed sensorless schemes for PMDC motor. To solve this problem, several parameter identification methods under sensorless control have been proposed [8]-[14]. Some methods identify motor parameters using special signals at a standstill state [12] or under certain load condition [9]. In these cases, it is difficult both to identify motor parameters under motor control and to respond to changes in these parameters. Other methods can identify motor parameters depends on the estimation accuracy because rotor position and velocity are used to identify motor parameters. In [11] the stator resistance is identified but inductances cannot be identified. Therefore, in this paper, an effective and simple on-line parameter identification method for identifying both armature resistance and inductance is proposed and then applied to the sensorless control scheme based on the recursive least-squares (RLS) estimation technique. Finally, the effectiveness of the proposed identification system is verified simulation results.

Adaptive control method is proposed to control the position of a DC motor [15]. This method adjusts feedback gains of the states and feed forward gain of the closed loop plant, and equalizes its transfer function to the models. This way adaptation law becomes simpler andeasily implemented by computer [16].Adaptive gain is chosen by trial and error in order toachieve a good rate of convergence. The choice of small gain mayresult in slow convergence rate whereas large gain may make thedifferential equations stiff and difficult to solve numerically onthe computer. The choice of the gain is not based on mathematicalfoundation. This is evaluated as the weakness of the method [17].The basic idea is explained and control strategy is illustrated. The drive is simulated using MATLAB SIMULINK and theoretical results are obtained to show the transient and steady state performance of the machine.

III. SENSORLESS CONTROL

In PMDC machines, movement of the magnets relative to the armature windings causes a motional e.m.f to be induced. Since the instantaneous magnitude of the e.m.f is a function of rotor speed, information about speed is contained in the e.m.f waveform.Thus by measuring the e.m.f e, the speed ω can be obtained.

Equations describing the characteristics of PMDC motor can be concluded as follows:

$$v_a = R_a i_a + L_a p i_a + e \quad (1)$$

$$T_e = K_E \Phi_f i_a \quad (2)$$

$$e = K_E \Phi_f \omega \quad (3)$$

Therefore, the state-space equation for estimating the e.m.f for PMDC motor is obtained when it is assumed that the differentiation of the time of the e.m.f is zero ($pe = 0$). Rearranging "(1)", the state-space equation for estimating e.m.f is concluded as follows:

$$p i_a = -\frac{R_a}{L_a} i_a - \frac{e}{L_a} + \frac{v_a}{L_a} \quad (4)$$

The e.m.f can be estimated by an observer. Fig. 1 shows the equivalent block diagram of the observer for estimating $\hat{e}$, where g_γ represents the gain of the observer. From the estimated e.m.f, the estimated speed$\hat{\omega}$is concluded from "(3)", which is filtered through a low-pass filter to reduce the influence of noise. The estimated speed $\hat{\omega}$ is used to motor control.

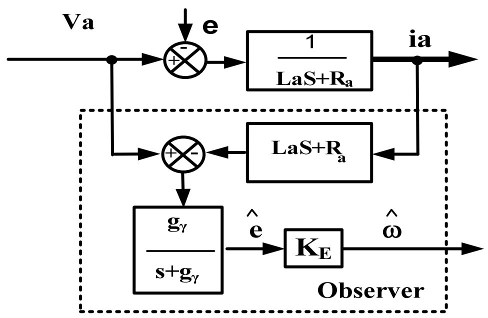

Fig. 1.Equivalent block diagram of the observer for estimation of e.m.f.

IV. ON-LINE IDENTIFICATION SCHEME

Most sensorless methods use motor parameters to estimate speed, and hence estimation error is caused by parameters variations. That is why, sensorless control schemes require information of electrical parameters to obtain accurate estimation of speed to guarantee the stability of the overall system over a wide range. The aim of the identification process is to find an adequate model structure of a practical process and an acceptable parameter values [7]. In as much as motor parameters are changed, an estimation error is generated when there are differences between actual motor parameters and ones used in the estimation system. Therefore, these parameters should be measured in all driving areas, in order to maintain the accuracy. However, parameter measurements are cumbersome and difficult.

The proposed identification scheme is based on recursive least-squares (RLS) estimation technique.This is usually accomplished by assuming a discrete time form for the mathematical motor model and then using a recursive estimation algorithm to obtain estimates of the parameters of the motor as it is more convenient to do the estimation recursively, i.e. taking the observations one at a time and updating the estimate each time. The reason of choosing the RLS technique is that it allows on-line estimation as a part of an adaptive control scheme and permits a time-varying model to track behavior which is too complicated to be described adequately by a constant-parameter model. The proposed identification method will identify the unknown motor parameters via a mathematical model using known values such as voltages and currents. The first order mathematical model of PMDC motor is simple and can be easily implemented without additional hardware because of the reduced calculations. Moreover, it requires less sampling time to be implemented on-line. In addition, prior parameter measurements are not necessary using this proposed method. Also, the method can use any signal that satisfies the condition of persistent excitation. Consequently, convenient signals for motor control can be used.

The flux-linkage of PM (which is equal toK_E) is found to be constant. Therefore, the inductance L_a and the flux-linkage of PM are considered constant. On the other hand, the resistance $R_a$varies practically with motor temperature. These deviations can lead to unreliable estimation of rotor speed. That is why; on-line identification of R_a and L_a is essential to enhance the performance of the PMDC motor. The mathematical model of the PMDC motor is given by rearranging "(1)"as follows:

$$L_a p i_a = v_a - R_a i_a - e \quad (5)$$

$$L_a p i_a = u - R_a i_a \quad (6)$$

where, $u = v_a - e$ (7)

Transforming "(6)" to a discrete state equation:

$$i_a(n+1) = A i_a(n) + B u(n) \quad (8)$$

where, $A = \left[1 - \frac{R_a \Delta T}{L_a}\right]$, $B = \left[\frac{\Delta T}{L_a}\right]$ (9)

$\Delta T$is the sampling period. Equation (9) is a first order discrete and can be rewritten as:

$$y = \theta_P z \quad (10)$$

where, θ_P is the parameter matrix that includes the unknown motor parameters and is given by:

$$\theta_P = [AB] \quad (11)$$

The scalar y represents the current output, i.e.

$$y = [i_a(n+1)] \quad (12)$$

The vector z contains the past input and output and is given by:

$$z = [i_a(n) u(n)]^T \quad (13)$$

Using the relation of "(10)", the unknown parameter matrix θ_P can be derived from known vectors y and z by using the least square method. This method identifies the parameter matrix$\hat{\theta}_P$ such that the square of the prediction error reaches minimum [18], i.e. Equation (14) is minimum.

$$\varepsilon_i = \left(y - \hat{\theta}_P z\right)^2 \quad (14)$$

To identify the parameter matrix $\widehat{\theta}_P$ on-line, a recursive least square 'RLS' method is used [10].The parameter matrix $\widehat{\theta}_P$ is identified recursively using the following equations:

$$\widehat{\theta}_P(k) = \widehat{\theta}_P(k-1) + \left(y - \widehat{\theta}_P(k-1)z\right)z^T P_c(k) \quad (15)$$

$$P_c(k) = \frac{1}{\lambda}\{P_c(k-1) - P_c(k-1)z(\lambda + z^T P(k-1)z)^{-1} z^T P_c(k-1)\} \quad (16)$$

where, λ is defined as the forgetting factor, the role of which is to delete past data, and P_c is the covariance matrix. Thus, the identified motor parameters are derived from the elements of the parameter vector $\widehat{\theta}_P$ as:

$$\hat{L}_a = \frac{\Delta T}{\hat{B}} \quad (17)$$

$$\hat{R}_a = \frac{(1-\hat{A})}{\hat{B}} \quad (18)$$

Therefore, the proposed identification method is simple and requires less hardware to be implemented on-line, because of the reduced calculations. In addition, the unknown matrix can be rapidly calculated and easily updated.

V. ADAPTIVE CONTROL

The Model Reference Adaptive System MRAS technique [19] is used to control the motor speed as shown in Fig. 2. The system consists of two loops: a conventional controller and an outer loop for the updating of the feed forward controller parameter, *k*. The controller parameter is updated directly based on the error between a desired response, ω_m, and the true response of the system, ω[20]. The desired response is specified using a reference model [21].

A second order model is designed to achieve a desired response of maximum overshoot less than 5% and settling time less than 1 s [22].

Hence the model transfer function G_m is given by:

$$G_m = \frac{\omega_m(S)}{\omega^*(S)} = \frac{\omega_n^2}{S^2+2\eta\omega_n S+\omega_n^2} = \frac{0.11}{S^2+1.99S+0.11} \quad (19)$$

The closed loop system has one adjustable parameter, θ, and the MIT rule is used to obtain a method for adjusting the parameter, θ, of the feed forward controller [23];

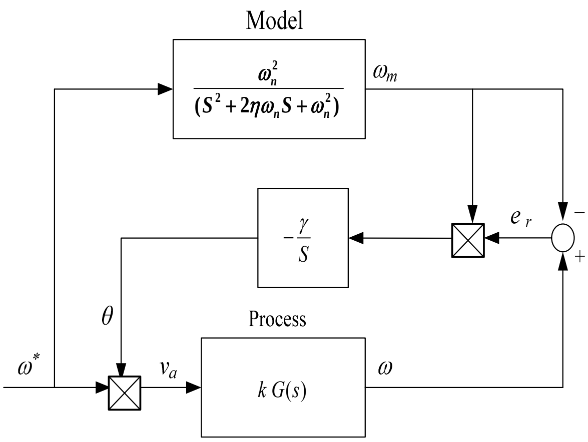

Fig. 2. Block diagram of the MRAS based on the MIT rule

$$v_a = \theta\omega^* \quad (20)$$

The error is [24]:

$$e_r = \omega - \omega_m = kG\,(d/dt)\,\theta\omega^* - G_m\,(d/dt)\,\omega^* \quad (21)$$

The MIT rule gives the following adaptation law [22]:

$$\frac{d\theta}{dt} = -\gamma\omega_m e_r \quad (22)$$

VI. SIMULINK MODEL OF THE DRIVE

Sensorless control with on-line parameter identification was realized using the system shown in Fig. 3. The PMDC motor is fed from a single-phase full bridge controlled rectifier. The block diagram consists of three main systems; speed control, sensorless drives control, and adaptive parameter identification system.

From the current and voltage signals, motor parameters are identified. Then, it is appropriate for sensorless control to use the identified parameters after they have passed through a low-pass filter because they tend to include fluctuations. The decay time constant of the low-pass filter was set to 0.02 s for the inductance parameter and 0.01 s for the resistance parameter.

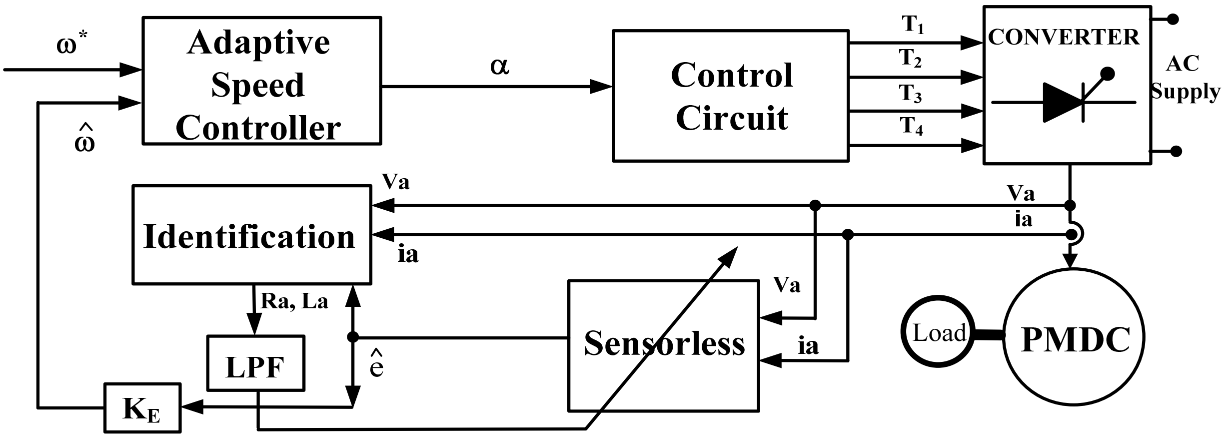

Fig. 3. Block diagram of sensorless control PMDC drive scheme with on-line parameter identification system.

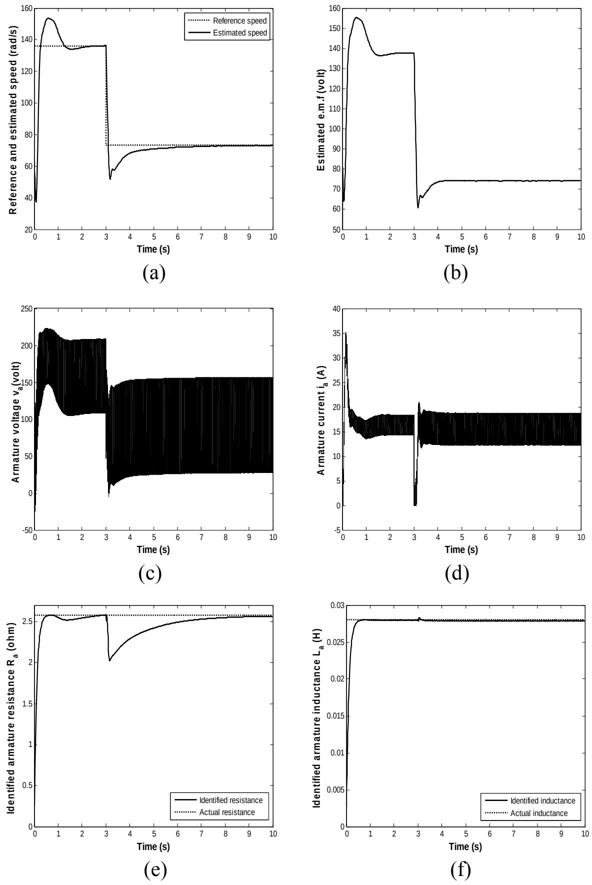

Fig.4.Speed estimation and parameter identification results, at rated load.

Using these identified parameters, the proposed observer estimates e.m.f, from which the velocity is calculated. The error between the command speed and the estimated speed is applied to an adaptive speed controller in order to output the reference delay angle α of the rectifier.

Simulation tests have been carried out in order to evaluate the adequacy of the sensorless control scheme and confirm the validity of the parameter identification system. A step change from a speed of 1300 rpm to a motor speed of 700 rpm was applied to the speed command signal at time 3 s. Fig. 4 shows the behavior of the proposed sensorless drive system due to a step change of the speed command signals.

It is clear from the above figures that appropriate motor parameters were identified, and the estimated speed coincided exactly with the rotor speed, irrespective of the load change conditions. Thus, the sensorless PMDC drive system will have adequate performance in order to obtain the necessary speed information for replacing a shaft sensor. Moreover, theaccuracy of the estimated position which depends on the motor parameters will be improved due to the presence of the identification system that can measure the motor parameters on line. Therefore, the presented sensorless drive system with the proposed on-line identification scheme gives fast and accurate transient performance over a wide range of speed and torque operation.

A. Resistance variation according to temperature change

Since the armature resistance R_a is temperature-dependent, it has to be identified on line in order to detect its variation with temperature. Fig. 5 shows on-line identification results

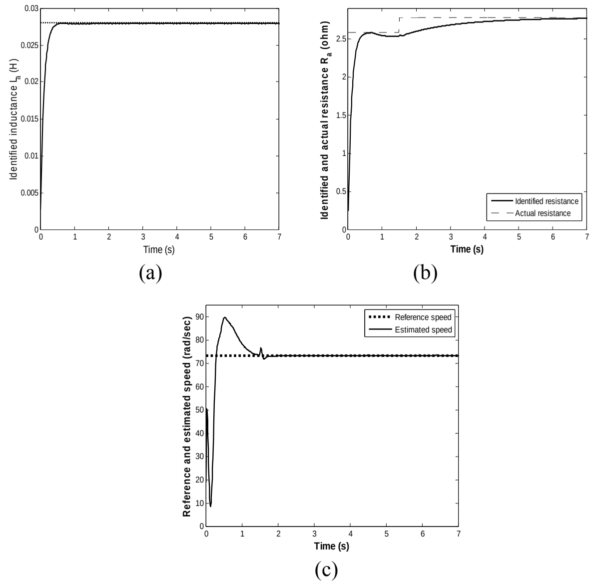

Fig.5. Parameter identification results under heat changes,at rated torque.

under heat during the operation of the PMDCM. The reference speed is set to 700 rpm, and the load torque is set to its rated value (15.7 Nm). The actual resistance increases by about 10% due to thermal effect.

From the above figures, it is clear that the identified resistance $\hat{R}_a$ follows the variation of the actual stator resistance$R_a$caused by thermal changes and also, the identified inductance $\hat{L}_a$ coincides with the actual $L_a$in less than 5s. Therefore, both; armature resistance and inductance can be identified on line accurately regardless of load variation condition or thermal change. This ensures the accuracy and the validity of the proposed on line identification method which gives fast identification performance over the whole range of load and speed operation. In such case, motor parameters can be identified on-line; thus, prior parameter measurements for R_a and L_a are not necessary.

VII. CONCLUSION

In this paper, a sensorless control scheme using a state observer and a proposed identification method are presented tomaintain speed estimation accuracy. The objective of parameter identification is to identify motor parameters used in speed estimation to maintain accuracy of the sensorless control system, since any motor parameter change can generate a position estimation error.The proposed identification method has several advantages, such as; motor parameters can be identified on-line; thus, prior parameter measurements are not necessary, the method can use any signal that satisfies the condition of persistent excitation [25] and special band pass filter are not necessary, and it is simple and easy to be implemented practically with less hardware.

Thesimulation results are included to prove the effectiveness of the overall control system under different operating conditions. These results have shown that the proposed on-line identification method can provide fairly good identification performance over a wide range of load conditions and thermal changes. It can also be incorporated into any sensorless speed control scheme. Therefore, with the use of the identification parameters, speed estimation under load changes can be realized accurately.

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IX. APPENDIX

TABLE I.
PMDCM RATING

R_a	2.581Ω
L_a	0.0028 H
Φ_f	1.0665 V/rad/s
Rated speed	1750 r.p.m
Rated torque T_{rating}	15.7 Nm
Moment of inertia J	0.02215Kg-m^2
Viscous f	0.002953Nm/rad/s
Rated Power	50 HP
Nominal voltage	240 V
frequency	50 Hz
K_E	0.935