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Online speed control of a brushless AC servomotor based on artificial neural networks

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Abstract

In this paper, an alternative approach to speed estimation of brushless AC servomotors is presented. Speed control is realized in the following steps. First, the servomotor was mathematically modelled; the driver system was designed and speed control of the servomotor was accomplished with feedback. Next, a network structure representing the electrical and mechanical properties of the servomotor was built via Artificial Neural Network (ANN) and trained with the results of the first step. The weights obtained from the neural nwork training were inserted into the control algorithm in accordance with the ANN. Finally, speed estimation was achieved based on the ANN. The complex servomotor hardware was highly simplified, the cost was significantly reduced, mechanical durability increased, maintenance need dropped considerably, low inertia was gained and the produced noise was noticeably lowered.

Key Words: *ANN, brushless servomotor, sensorless speed control, vector control, real-time control*

1. Introduction

Servomotors have received great attention in recent decades. Compared to other motor types, servomotors can deliver more torque and power for the same size; they provide safe and reliable operation and require less maintenance, which makes them attractive. Specifically, with latest developments in microprocessors, power electronics and magnets, very accurate and highly efficient servomotor control systems have been developed [1, 2]. However, the need for a feedback element is a drawback for them. The feedback element not only increases the cost but also makes the control complex. Further, the control accuracy is directly proportional to its precision. Thus, a considerable amount of research effort has been proposed on the sensorless speed control

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of the permanent magnet motor (PMM) [3, 4]. In most of the research, the main proposed alternative is the estimation of the motor position or speed. In some methods, PMMs are modelled and controlled in different coordinate systems by using indirect or direct vector control [5–9]. Other methods are based on sensed motor currents, flux linkage estimation, or injection of high frequency voltages into the motor windings [10, 11]. Some researchers have proposed methods include Kalman filters, fuzzy logic and neural network observers to obtain rotor position angle [12, 13].

In this paper, an alternative approach has been proposed for a brushless AC servomotor based on vector control. The proposed approach has been analyzed in two steps. At the first step, the servomotor speed is controlled by a vector control algorithm which gets feedback from an encoder and a customized motion control card which is attached to a PC via ISA channel. The data to train the ANN, in order to estimate the speed, is also collected at this step. At the second step, the feedback element is eliminated by additional code to the control algorithm and motor speed is controlled by motor current and the speed data from the ANN estimator. The electrical and mechanical properties of the servomotor are correlated by using adequate data and the accurate ANN model, and finally, the speed estimation is achieved.

2. Vector control of brushless AC servomotors

Vector control has been widely used in control of permanent magnet synchronous motors (PMSM) where rotor position information is required. Particularly with growing research attention in motor drives without a sensor, good results have been achieved by using vector control in the sensorless techniques recent years [4]. These sensorless control techniques require using high speed digital controllers such as DSPs or microprocessors. In this study, a software based control was applied by using a custom designed motion control card which was attached to a PC via ISA channel.

As for the vector control of the servomotor, first a mathematical model of the motor was developed to capture transient and steady state phenomena. While modelling, 3-phase coordinate values are referred to d-q reference coordinate frame to have the same control simplicity as in direct current motors [14, 15]. Therefore, servomotor speed was controlled by the vector control algorithm using the position data which is obtained from the model. The axis system used for the control is shown in Figure 1.

3-phase to d-q coordinate frame transportation is achieved via the following transform:

$$i_{sD} = \frac{2}{3}\left[i_{sA} - \frac{1}{2}i_{sB} - \frac{1}{2}i_{sC}\right] \tag{1}$$

$$i_{sQ} = \frac{1}{\sqrt{3}}\left[i_{sB} - i_{sC}\right] \tag{2}$$

$$u_{sD} = \frac{2}{3}\left[u_{sA} - \frac{1}{2}u_{sB} - \frac{1}{2}u_{sC}\right] \tag{3}$$

$$u_{sQ} = \frac{1}{\sqrt{3}}\left[u_{sB} - u_{sC}\right] \tag{4}$$

$$u_{sD} = R_s i_{sD} + \frac{d}{dt}\psi_{sD} \tag{5}$$

$$u_{sQ} = R_s i_{sQ} + \frac{d}{dt}\psi_{sQ}. \tag{6}$$

Stator D-Q and rotor d-q transformations are

$$\begin{bmatrix} i_{rd} \\ i_{rq} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} i_{sD} \\ i_{sQ} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} i_{sD} \\ i_{sQ} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} i_{rd} \\ i_{rq} \end{bmatrix}. \quad (8)$$

Since the rotor has a permanent magnet, d coordinate current is assumed zero and q coordinate current, i_{qref} is assumed as the reference current.

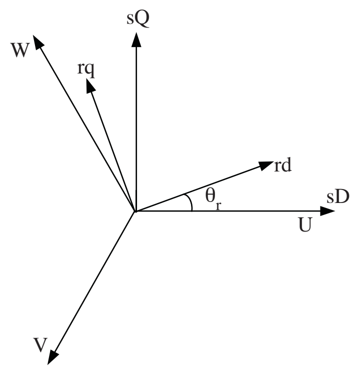


Figure 1. Brushless AC servomotor current vectors.

In the application, a 400 W, 106 V, 200 Hz, 4 pole, 3000 rpm AC brushless Servomotor with incremental encoder was used. The encoder produces 2500 pulses from A and B and 1 pulse from Z outputs per cycle. It is important to point out that there is a 90° phase shift between A and B and output signals are filtered out by a RC filter. In order to investigate the behaviour of the servomotor under load conditions, the servomotor shaft was mechanically coupled with a permanent magnet DC generator with 1 HP, 185 V, 4 A, and 4000 rpm. An adjustable load module was connected to the DC generator to have accurate and different load values. The application circuit is demonstrated in Figure 2.

The current controlled servomotor driver circuit consisted of a three-phase diode module (6RI30G160), a 2000 μF capacitor to filter the output ripple of the rectifier, and a smart power module (IPM-7MBP25RA120) as an inverter. Field effect sensors were used to measure isolated currents and voltages. Two current sensors for the motor currents and one voltage sensor for DC bus voltage were used. Four isolated voltage sources, ±15 V, were used to drive the inverter. Current sensors are fed with +5 V, voltage sensors are fed with ±15 V. Perfect isolation between controller and power circuit were performed.

The controller circuit consisted of a PC and a motion control card which was attached to the PC via ISA channel. As illustrated in Figure 3, the motion control card includes the following components: An 8-bit output port used for inverter driving signals, a fast analog-to-digital converter (ADC) used for measuring current and voltage, and HCTL 2016 chip used for measuring the speed. The driver circuit was isolated from the computer by using an optical coupler (HCPL). The period of the controller sampling signal was 30 μs, which means 2 phase current and DC bus voltage were measured in every 30 μs by the ADC (AD7864).

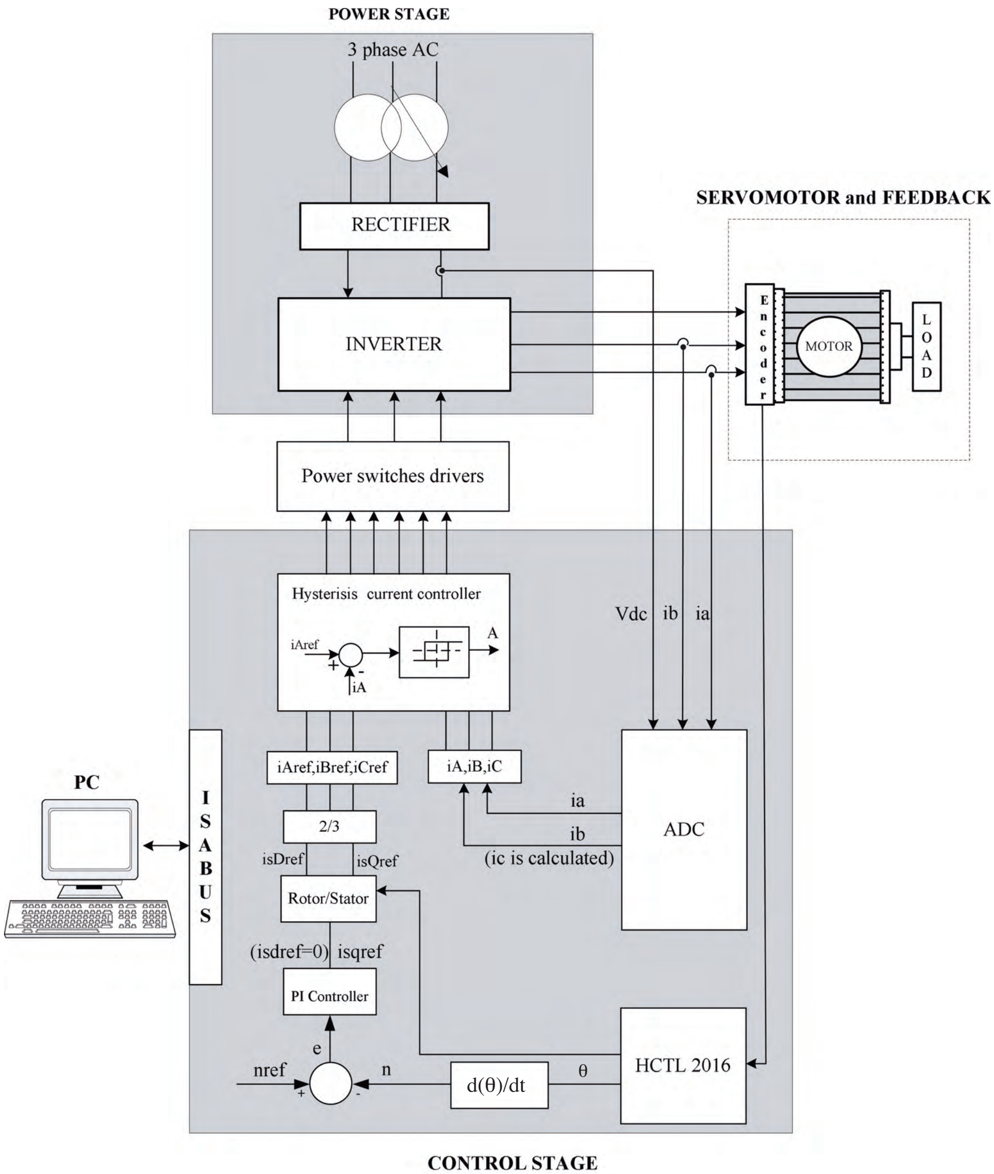


Figure 2. Servomotor driver block diagram with feedback.

In one channel of the ADC, analog data were converted to digital data in 1.65 μs. It takes 6 μs for an ADC to read the signals. Calculations in the control algorithm and firing the inverter take 15 μs. Then PC signal is delayed to be sure 30 μs have passed. It is noted that the developed driver can be used for both speed and torque control. The way to do that is to generate torque reference, i_{sqref}, depending on the speed error by PI controller while controlling the speed.

Figure 4 demonstrates the brushless AC servomotor's stator current, field and voltage behavior under full load with DC generator for the case of running with feedback element. As it can be seen from Figure 4, that control period of 30 μs is quite enough to control the stator current. In this time frame, the stator current was kept within a reference bandwidth. Current hysteresis bandwidth was chosen as ΔI=0.1 A.

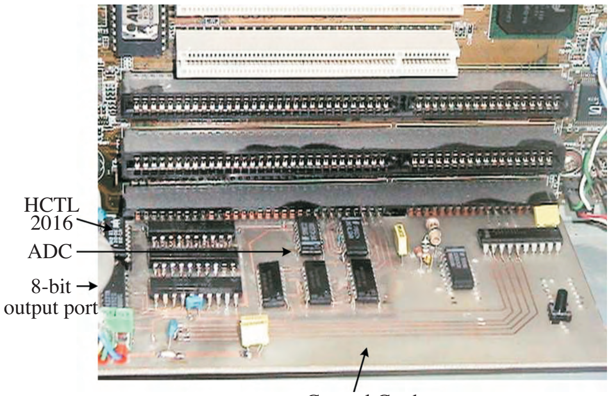


Figure 3. Motion control card.

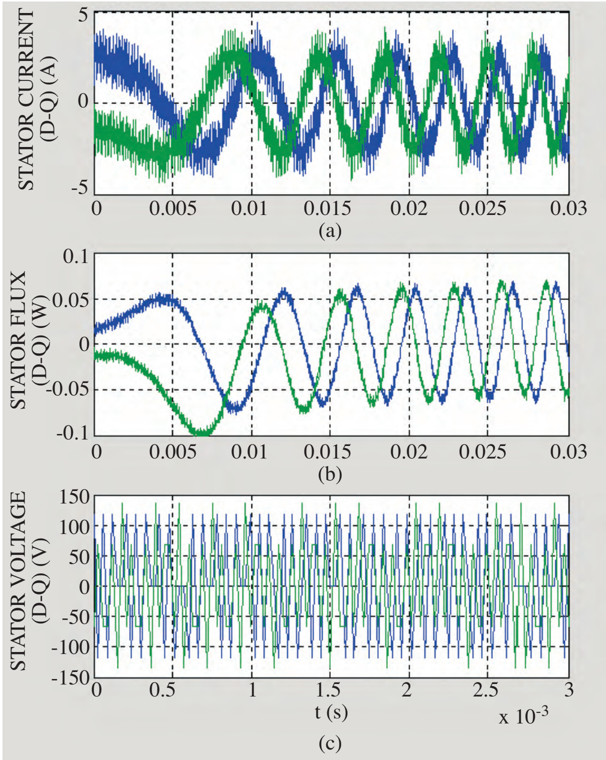


Figure 4. Under full load and 3000 rpm: (a) Stator sD and sQ axes currents, (b) Stator sD and sQ axes magnetic fields, (c) Stator sD and sQ axes voltages.

3. Speed estimation of a vector controlled brushless AC servomotor with ANN

Recent developments in industrial electrical drives indicate that the next generation of electrical drives will include some type of sensorless control. The advantages of sensorless control are reduced hardware complexity and lower cost, reduced size of the drives, elimination of the sensor cable, better noise immunity, increased reliability, and less maintenance requirements. For this reason, different sensorless control methods have been proposed in the past few years [4, 17]. Among these, ANN has been successfully used for many applications in power electronics and motion control systems. It has been stated in the literature that ANN can be applied to DTC controller design, parameter identification, and state estimation of motor control systems [16]. In this paper, an ANN was used to realize the speed control of the servomotor. Rotor position and angle were estimated by using multilayer feedforward network structure algorithm [18, 19]. The numbers of hidden stages and neurons were determined by the trial and error algorithm using a Matlab code.

3.1. Off-line speed estimation with ANN

Motor data obtained from speed incremental encoder control were used to train the ANN. This ANN training cluster consisted of different operating conditions data with voltage, speed and current samples in each of them. In order to have more accurate results, a variety of networks was tried. Since it required both fast response time and high accuracy, the best result for the training was obtained with the Matlab iterations as presented in Figure 5.

It is shown in Figure 5 that error of 10^{-8} was achieved. Since motor speed is controlled by vector control, the ANN model was established by D and Q axes current, voltage and magnetic field values and their previous values [21]. Accordingly, the 12 inputs in the network model were isD(k), isD(k-1), isQ(k), isQ(k-1), VsD(k), VsD(k-1), VsQ(k), VsQ(k-1), ψsD(k), ψsD(k-1), ψsQ(k) and ψsQ(k-1) and the only output was speed.

The network structure is shown in Figure 6. In this model, there were 12 inputs, 1 output channel and 2 hidden stages. Sigmoid function was used as the activation function in all three stages. Inputs and outputs were normalized between -1 and 1 during training. Finally, as the results of the training, the weighing factors of [W1], [W2], and [W3] were saved to be used in online operation.

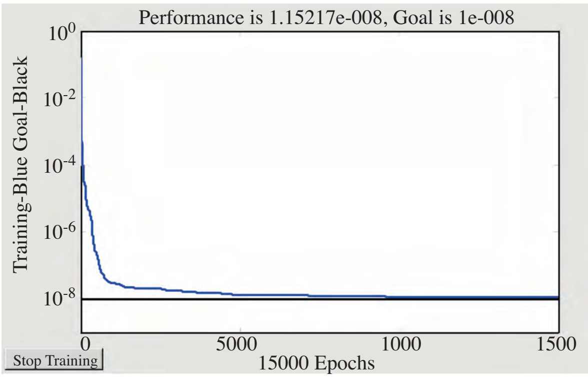


Figure 5. Result of training iteration obtained from Matlab using a 12 input and 1 output network model.

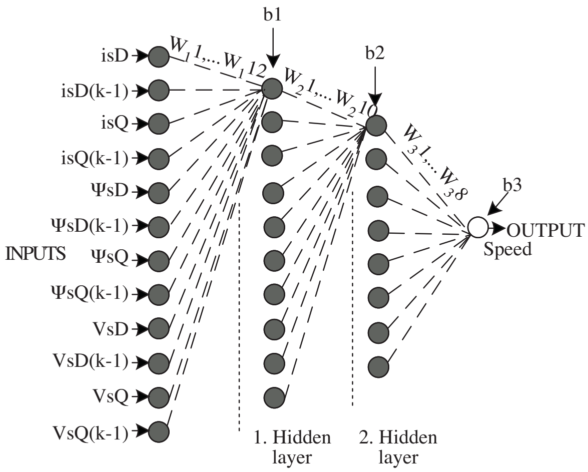


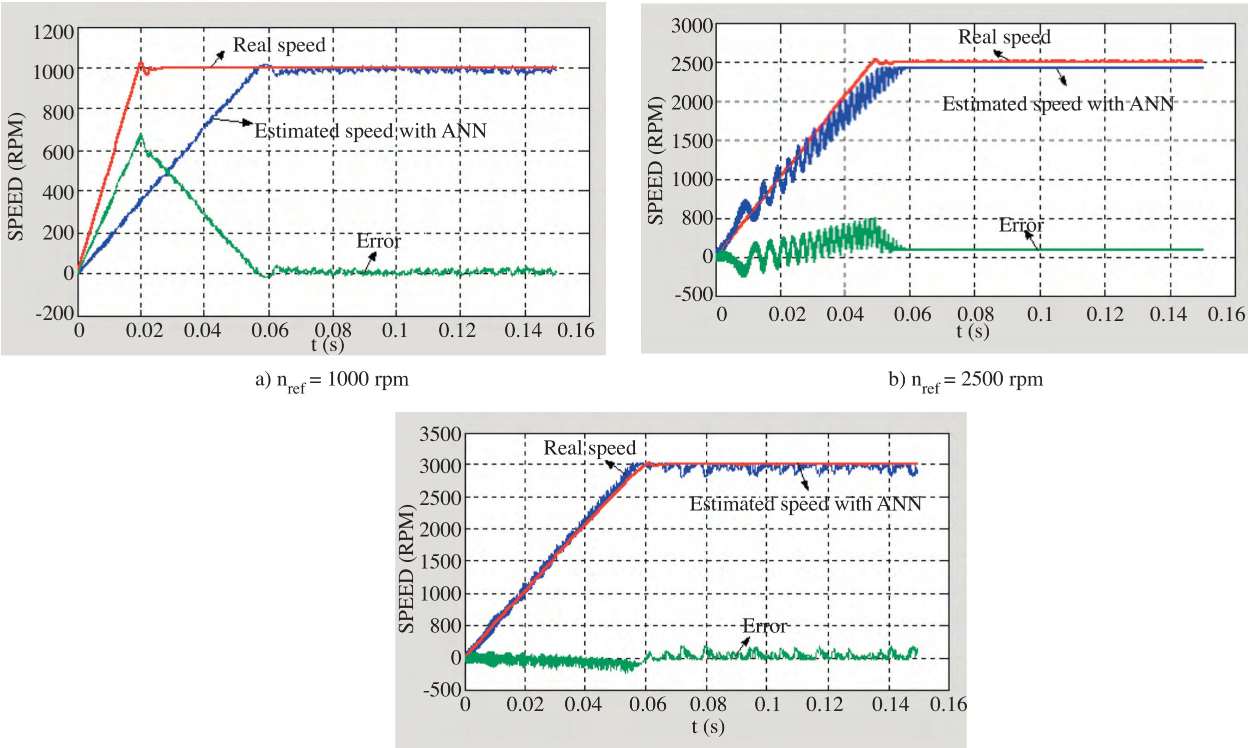
Figure 6. Diagram of the neural network structure.

Figure 7 shows the simulation results with both sensor and sensorless run at different speed levels. It is clear that the error is minimal at high speed. However, error occurs in transients at low speed, but in steady state the accuracy is improved.

3.2. Online speed estimation with ANN

In the previous section, successful estimation was established and preliminary insights of the performance of the speed estimation with the ANN were obtained by investigating off-line simulation results. As noted earlier, the results were used in online estimation.

Note that, the control circuit was modified for online speed estimation, as in Figure 8. In this circuit, the incremental encoder that gets the speed data from the motor was eliminated. Then, speed feedback was implemented with the ANN. Only extra lines were added to previous motor control code in C for sensorless control with the ANN. This additional code consisted of input and output function transformations and matrix algebra that enable the use of weighting factors. These weighting factors were represented in matrix form, and speed data was obtained with computation [21, 22]. Since current and speed are controlled in 30 μs and 1 ms, respectively, matrix algebra did not cause any delay in response time.



a) n_{ref} = 1000 rpm

b) n_{ref} = 2500 rpm

c) n_{ref} = 3000 rpm

Figure 7. Simulation results with both sensor and sensorless at different speeds; (a) n_{ref} =1000 rpm, (b) n_{ref} =2500 rpm, (c) n_{ref} =3000 rpm.

The weighting factors, which were first computed with the ANN in Matlab and second used in main C software for online motor operation, are described below. Input and output matrices were derived as follows [21, 22]:

$$\begin{array}{ll} U & [1x12] \\ Y1 = f^{Hidden1}\ ([U] \times [W1]) & [1x12]x[12x10] \\ Y2 = f^{Hidden2}([Y1] \times [W2]) & [1x10]x[10x8] \\ Y = f^{Output}\ ([Y2] \times [W3]) & [1x8]x[8x1] \\ Y = [n] & [1x1] \end{array}$$

Here, U is input and Y is the output.

The network structures for on-line study and simulation are the same. In the network model, two hidden stages, one with 10 neurons and the other with 8, were used. Momentum and training coefficients were chosen as 0.1 and 0.95, respectively. Sigmoid function was chosen as activation function. Training input and output values were normalized between -1 and 1.

Speed control results with the ANN appear Figures 9–11. Accordingly, the identification of the system with the ANN has been successfully achieved and remarkable precision has been reached at steady state operation. Without needing an extra control element, speed control was realized with only additional software lines. It eliminates the problems stem from the feedback element.

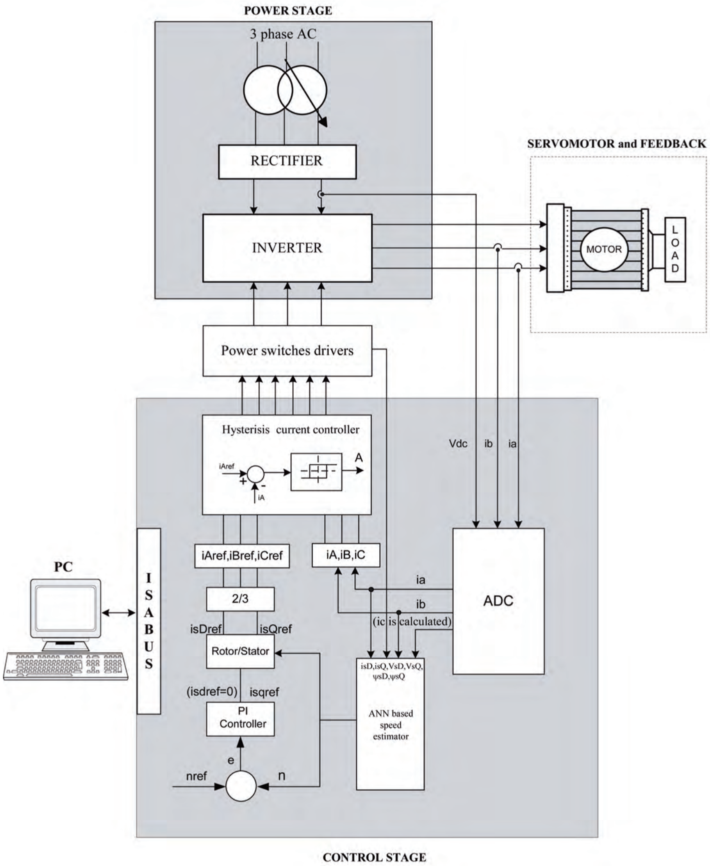


Figure 8. Servomotor driver block diagram.

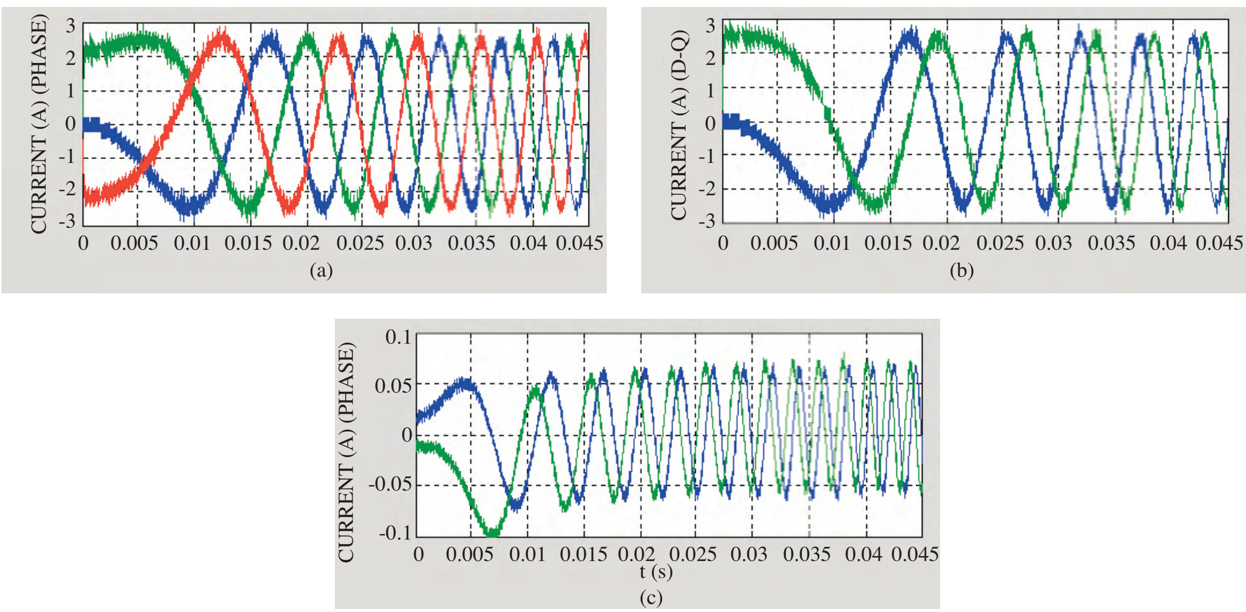


Figure 9. Online speed estimation with ANN results, with n_{ref} = 3000 rpm: (a) Stator A, B, C phase currents; (b) Stator sD and sQ axes currents; (c) Stator sD and sQ axes magnetic fields.

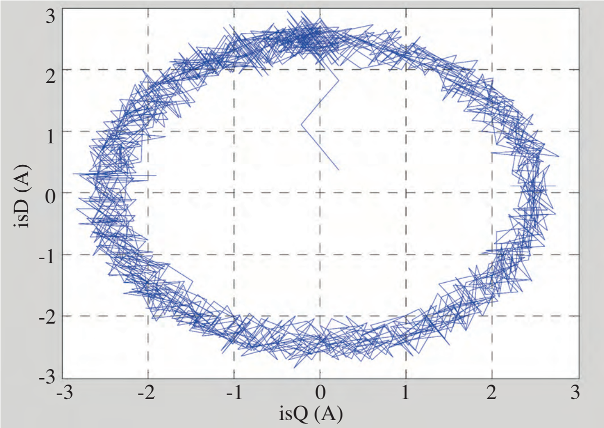


Figure 10. Stator sD and sQ currents from ANN estimator (n_{ref} = 3000 rpm).

In Figure 9, phase currents of stators A, B, and C, sD and sQ axes currents, and sD and sQ magnetic fields are shown. To get these results, the encoder was eliminated, and the motor speed was obtained from the ANN. Figure 10 shows vector components of stator current. One should realize that while sD current starts from a reference value, sQ current starts from zero. The results of speed control with and without sensor, and the comparison between them, are shown in Figure 11. As it can be seen from Figures 10 and 11, the low speed operation could generate some level of error in the sensorless control.

Sensorless motor control is yet an open issue. Actually it is well known that the main drawback of the sensorless techniques is lower speed range due to poor observability in these regimes. Observability analysis given in the literature shows that no speed observer with good performance exists for every operational regime. A better approximation could be a combination of some techniques for speed estimation and parameter estimation online [4, 17].

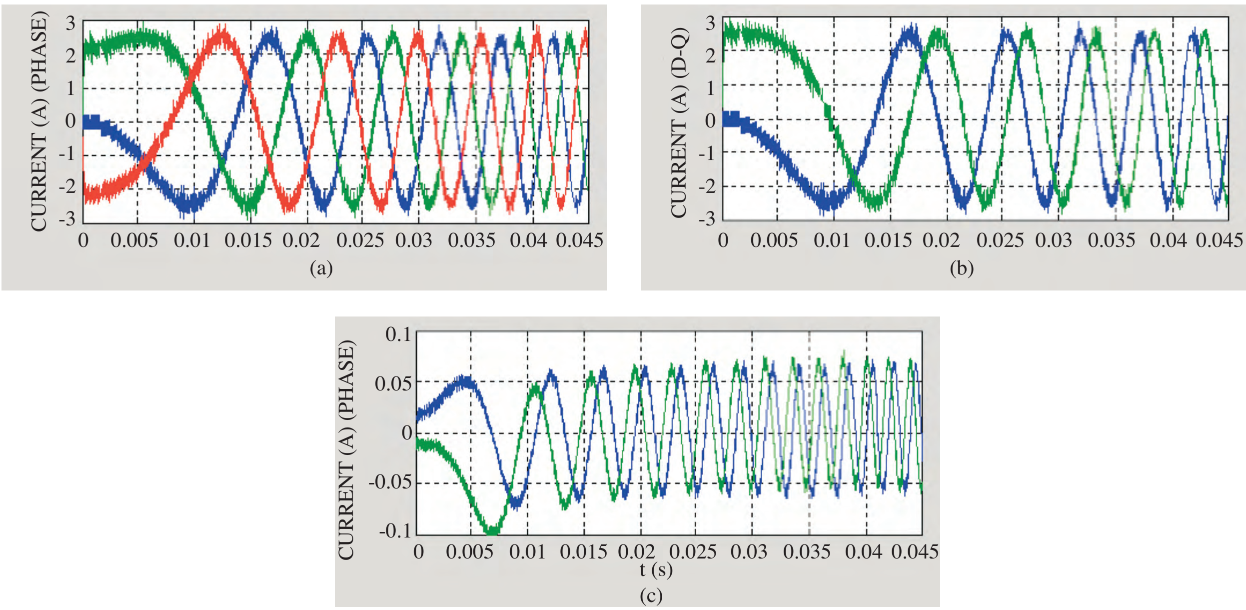


Figure 11. Sensorless ANN speed control results: (a) n_{ref} =1500 rpm, (b) n_{ref} =2000 rpm, (c) n_{ref} =2500 rpm, (d) n_{ref} =3000 rpm.

4. Conclusion

Brushless AC servomotors carry the advantage of not having brushes, being easy to maintain, having low operating noise, high efficiency and high energy density. However, the need for feedback control element for reliable and efficient operation is their disadvantage. A feedback system not only increases the cost but also makes the control system complicated. Besides, resulting mechanical problems from the feedback elements make a control system more complex.

In this study, a feed-forward ANN model was used in speed estimation to eliminate the drawbacks generated by sensors. Highly efficient and accurate results were accomplished at high speed range with this approach. The error levels in transients of low speed range can be eliminated with more study of ANN modeling. It could also be a combination of different methods with ANN, to acquire a good sensorless control performance for low speed levels. It should be remarked that the software-based control studied here avoids undesired mechanical setbacks. Moreover, this control method can easily be modified without any hardware change. Finally, with this custom-designed motion control and overall servomotor system, cost was remarkably reduced. This research could be a reference for practical servomotor control systems and used in a variety of industrial applications by modifying the proposed method

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