Neuro-Fuzzy Controller of a Sensorless PM Motor Drive For Washing Machines

Kasim M. Al-Aubidy and Mohummad M. Ali
Computer Eng. Dept, P.O. Box1,
Philadelphia University, Jordan, 19392

Abstract: The trend towards the adoption of direct drive washing machines utilizing PM motors is increasing due to the mechanical simplicity, high performance and efficiency of the system. This work deals with design and performance of a sensorless PM motor drive for washing machines. An implicit rotor position detection unit which consists of groups of search coils are inserted into the motor stator. A simple neuro-fuzzy controller has been used. The results given in this paper demonstrate the capability of such a drive system in washing machine applications where simplicity, reliability and stability are more important issues.

Keywords: PM motors, Direct drive washing machines, Nero-fuzzy control, Neural networks, Rotor position detection.

1. Introduction

Motors are driving demands accounting for about half of the electricity consumed. Many of these motors are found throughout modern household appliances, but they are driven by antiquated electromechanical control systems. Recently, the situation is changing and manufacturers are working to replace these highly inefficient drives with electronic, variable-speed control systems capable of saving up to 60% of the energy being consumed by the older generation of appliances[1].

Two appliances undergoing an energy-efficiency design upgrade are washing machines and dishwashers. To meet the need, appliance design engineers are working hard to reduce the machine's energy consumption, water use, weight, and cycle time, while delivering added benefits such as better cleaning, more productive spin cycles, and improved fabric care. To gain further energy savings, engineers are now introducing laundry algorithms that minimize the hot water that the washing cycle consumes[2]. While clutch and gearbox assemblies in washing machines have been replaced with belt-driven induction motors with tachometer feedback, digital control algorithms to enable direct drive from permanent magnet (PM) synchronous motors[3].

Among AC drives, the permanent magnet (PM) motors have became popular, due to its high torque to current ration, large power to weight ratio, high efficiency, and robustness [4]. Therefore, PM motor drives are widely used as actuators in many applications, due to its simple and reliable mechanism [2,5,6]. PM motors provide advantages over induction motors for washer applications. A direct-drive PM motor uses a larger number of motor poles to generate higher torque at lower speeds for the same power input. The ratio of the drum speed to the motor electrical frequency remains almost the same, but instead of stepping down the motor speed using, for example a pulley, increasing the motor-pole count achieves the same effect [3].

In the sensorless PM drive system, a rotor position sensor is essential for controlling the power devices of the inverter. The main problem with present rotor position detection methods is cost and reliability of the sensor. This often takes the form of an optical encoder or a Hall-Effect sensor, which is prone to contamination or accidental damage [6,7].

In sensorless systems, the rotor position can be estimated using the terminal voltage and the current through the motor phases [6]. One popular sensorless approach measures the rotor-flux position based on the stator winding's EMF. This approach is suitable when driving the PM motor in six-step mode with rectangular winding currents [3]. Such a drive system is easy to implement but produces high torque ripple which causes high acoustic-noise.

This paper presents implicit rotor position detection together with a simple neuro-fuzzy controller to adjust the voltage and frequency inputs of a PWM inverter. Such combination allows for sinusoidal waveforms to drive the PM motor at different speed and torque operating ranges.

2. Washing machine trends

Washers have historically relied on induction motors and gearboxes to power the drum and agitator. Such setups did not provide the kind of performance energy-efficient washes need at both ends of the speed range. In the past, washing machine designs employed either a two-speed single-phase induction motor with electromechanical controls or a universal brushed motor with triac-switch-phase control [3,8].

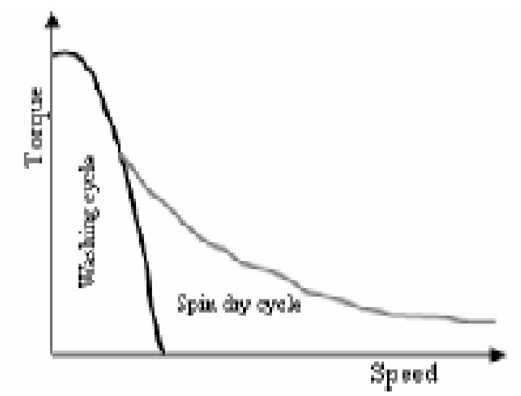

Fig. 1. Typical torque-speed characteristic of direct drive washing machines.

One trend in washing machine design is to replace the machine's traditional drive system with an electronically controlled brushless alternative [1]. For washing machines, PM motors become more attractive than induction and universal motors. In this case, eliminating control components, such as gearboxes and pulleys required in a mechanical control scheme and sensors needed for rotor position feedback. The result is a smaller and lighter motor and a drive system with greater capability, higher reliability, and improved energy efficiency. Another trend in washing machine design is the migration from vertical-axis to horizontal-axis washers to save water and energy. Vertical-axis machines require clothing to be completely immersed in water while horizontal-axis washers only need enough water to fill the base of the drum. Horizontal-axis washers require fast torque response from the controller to manage load conditions that are constantly changing. Higher spinning speeds require better balancing of the drum to prevent washing machine vibration [2].

As illustrated in Fig.1, the washing machine control task requires high torque at low speeds and low torque at high speeds. High amount of torque is required to perform the washing cycle. Higher spinning speeds lead to greater centrifugal force resulting in better water extraction, shorter spinning cycles, and shorter drying times. The actual time diagram of the wash operation is shown in Fig.2, and here the motor operates in slow speed region. The motor starts accelerating to a low speed level, then there is a certain time interval of steady spin and this is followed by the deceleration back to zero speed. Upon completion of this positive operation sequence, the negative one is followed employing the same speed profile but with targeting the negative speed level [2].

These operations alternate during wash cycle and the chosen wash program determines the overall time period of wash cycle. As illustrated in Fig.2, the washing machine operation in spin-dry cycle starts by accelerating to pre-defined high speed level for a short time. Then decelerating speed down either to stop or to proceed to a low speed level. This cycle might be repeated several times depending on a chosen wash program.

A new trend in washing machines design, found at the core of variable-speed motion control systems, is the move to sinusoidal PWM drive schemes to minimize audible noise[1].

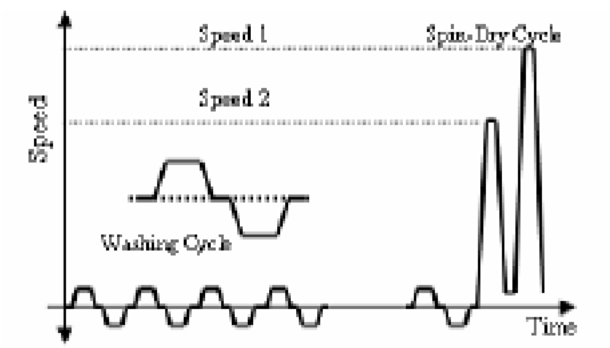

Fig. 2. Cycles of direct drive washing machines.

3. PM motor control requirements

The PM synchronous motor drive has been the object of many studies [9-12]. These drive systems are becoming particularly popular in many industrial applications, because they have many of the desirable performance characteristics of both the DC and AC motors. Some of these applications require speed control schemes and in some applications the position control is of greater importance. In some cases, the steady state operation is important, and in other cases the dynamic performance is more significant. Normally, PM motor drive systems have two modes of operation. One is the open-loop mode, in which an independent oscillator controls the motor speed. The other mode is the closed-loop mode, in which the inverter power switches are controlled directly from the rotor position sensor. An open-loop configuration is the simplest mode since there is no need for a rotor position sensor. However, a large load torque will cause pull-out and the motor will stop, therefore closed-loop mode is required [11].

Two types of inverter-fed PM motor control are used; the sinusoidal inverter control scheme and the six-step inverter control. There is a trend toward sinusoidal sensor-free control schemes rather than six-step control schemes, due to their associated torque ripple creates harmonics that lead to noise emissions[5]. When a PM synchronous motor is driven by a sinusoidal PWM inverter, the possible method of speed control is the frequency variation of the voltage applied to the motor. In this case, the motor speed (ω) is directly proportional to the inverter output frequency (*f*);

$$\omega \ \alpha \ f \qquad (1)$$

For variable-speed applications, the frequency (*f*) is variable, and a constant rms value of the phase voltage (*v*) will make the amplitude of the resultant flux (*φ*) variable also[3];

$$v \ \alpha \ f^* \varphi \qquad (2)$$

Now if frequency decreases with constant voltage, the resultant flux increases, therefore, in order to avoid magnetic saturation, it is essential to keep the voltage to frequency ratio (*v/f*) constant. It is clear that increasing the supply frequency to increase the speed requires increasing the inverter output voltages in order to achieve constant resultant flux. Now, in order to run the PM motor efficiently, it is important to synchronize the frequency of the applied voltage to the rotor position of the PM rotor. An efficient control scheme is required to run the PM motor in sensorless drive. In this case, a neuro-fuzzy controller is proposed to satisfy the washing and drying cycles of the washing machine.

4. PM motor modeling

The PM motor can be represented either in the form of an equivalent circuit or a set of equations. This procedure allows analysis of the dynamics of the drive system. The PM motor has the physical appearance of a 3-phase permanent magnet. The system equation in a d-q reference can be expressed as follows [5,11];

$$\frac{di_q}{dt} = -\frac{r_s}{L_q} i_q - \frac{L_d}{L_q}\omega_r i_d + \frac{1}{L_q} V_q - \frac{\lambda_m}{L_q}\omega_r \qquad (3)$$

$$\frac{di_d}{dt} = -\frac{r_s}{L_d} i_d - \frac{L_q}{L_d}\omega_r i_q + \frac{1}{L_d} V_d \qquad (4)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left[\lambda_m i_q + \left(L_d - L_q\right) i_q i_d\right] =$$
$$J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} + B\left(\frac{2}{P}\right)\omega_r + T_L \qquad (5)$$

where r_s, L_q, L_d, P and λ_m are the stator resistance, q and d axis stator inductances, number of poles, and flux linkage of permanent magnet respectively.

By means of the field oriented control, it can be assumed as the d-axis current is controlled by zero. Therefore, the system model expressing the rotating speed and torque equation can simply be represented as follows [5];

$$\frac{d\omega_r}{dt} = \frac{3}{2}\frac{1}{J}\left(\frac{P}{2}\right)^2 \lambda_m i_q - \frac{B}{J}\omega_r - \frac{P}{2}\frac{T_1}{J} \qquad (6)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\lambda_m i_q = k_i i_q \qquad (7)$$

From equation (7) it is clear that the motor torque (T_e) can be adjusted by changing stator current (i_q) depending on the rotor position.

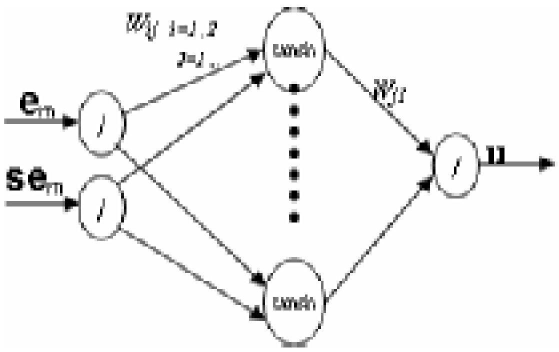

Fig.3. Neuro-fuzzy controller.

5. Neuro-Fuzzy controller

Permanent magnet motor drive is a nonlinear multivariable system and has complex dynamic performance due to the coupling effect between rotor and stator windings [7]. When such a machine is used as an actuator in real-time drive systems, it calls for complex control strategies which would be difficult to implement using traditional procedures [11]. A fast dynamic response and accurate steady state performance can be obtained for such applications by the combination of fuzzy logic and neural networks.

Depending on the methods for converting qualitative/ linguistic labels into quantitative/numerical values, the structures of the resulting controllers are significantly different. There are two possibilities for doing this;

- fuzzy set interpolation characterized by graded membership functions (structural), and
- fuzzy number translation typically featured by central values and spread widths (functional).

The functional neuro-fuzzy controller will be formed by training a back propagation neural net (BNN) on the bases of fuzzy number rules described by their central values which are extracted using clustering algorithm from the available input/output collected from other control strategies.

The multi layer persiptron (MLP) neural net needs 5620 iterations to learn the given input pattern, with learning rate of 0.1. This net has the following topology, as illustrated in Fig. 3;

- 2-node linear input layer receiving error and sum of error.
- 10-node nonlinear hidden layer with tansh activation function.
- One node linear output layer that generates the actuating signal.

6. Real-Time Implementation

The motor-drive circuit must measure the rotor position in the PM machine to synchronize the stator current with the rotor field. Given the rotor position, it is possible to drive the PM motor efficiently because the drive circuit can align the stator current to the optimum angle relative to the rotor field[2]. The PM motor is generally driven by a 3-phase PWM inverter which converts a constant voltage to 3-phase voltages corresponding to the rotor position.

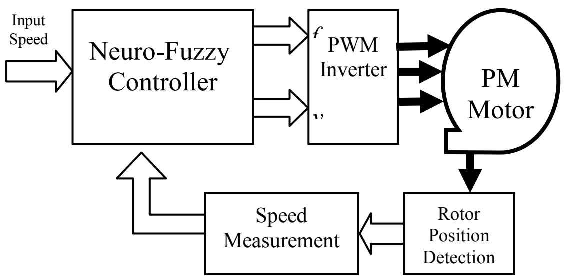

Fig. 4. Sensorless PM Motor drive system.

The hardware schematic for real-time implementation of the direct drive system is shown in Fig. 4, it consists;

- PM Motor: an eight pole PM machine.
- Implicit Sensor: a rotor position sensor producing 24 pulses each revolution.
- Speed Measurement: to provide online measurement of rotating speed (W).
- PWM Inverter: sinusoidal PWM inverter.

The hardware platform for the washing machine controller can be implemented on programmable IC together with an integrated power module. The programmable IC, may be a microcontroller or an FPGA, will implement the sensorless control algorithm that performs all the control calculations and washing machine programs.

6.1 Rotor position detection

For sensorless PM motor drive system, an implicit sensor has been used for rotor position detection and speed measurement. Three rotor position detection units (one for each phase) are used, each detection unit consists of three groups of single turn search coils inserted into the machine stator [7,11]. The resolution of the implicit sensor is 24 pulses per revolution, when an 8-pole PM motor is used, as shown in Fig.5. This resolution is sufficient for accurate speed measurement and inverter power switching control. The rotor position sensor output is used to cause an interrupt signal to the microcontroller to activate the control algorithm task. All the real-time tasks are synchronized to this interrupt signal.

At stand-still, the PM motor is started by the microcontroller, which generates a pulse train for the control logic of the PWM inverter switching. The motor is accelerated in an open-loop configuration up to 10 rpm, and then the rotor position pulses are used.

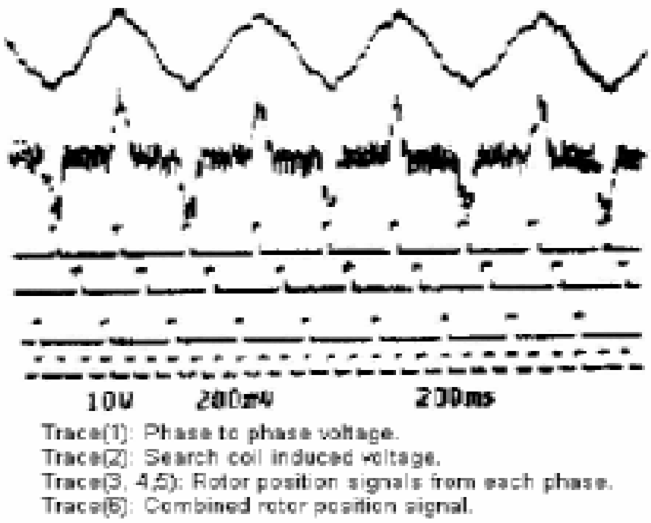

Fig. 5. Implicit rotor detection signals

6.2 Speed Measurement

The motor speed can be measured either by calculating the rotor position pulses during a fixed time interval, or by measuring the interval between two adjacent pulses coming from the rotor position sensor. In this system, the second approach is used. If the rotor position sensor produces 24 pulses each revolution, then the rotor speed is given by:

$$\omega = 2.5\, f_p/C \qquad \text{(rpm)} \qquad (8)$$

where C is the counting pulses coming from an external oscillator (f_p) during the period between each consecutive pulses coming from the rotor position sensor. In order to improve the accuracy and resolution of the speed measurement, the oscillator clock (f_p) is made proportional to the measured speed[9]. The speed measurement unit works well over a wide range of operation. It offers a fast and accurate speed measurement, which is suitable for real-time applications.

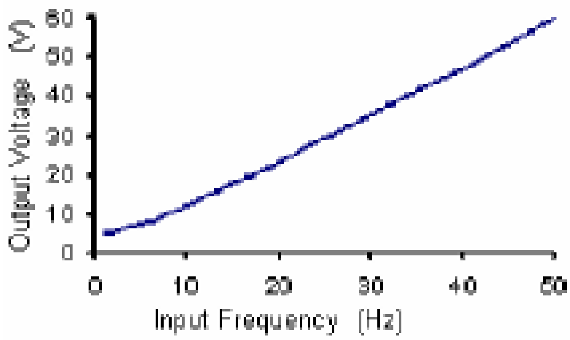

Fig. 6. Voltage/Frequency curve of the PM Motor.

6.3 PWM Inverter

The PWM inverter has two control signals; the motor voltage, and the motor frequency. These two signals are arranged to be independent control inputs into the inverter, so that each input can be adjusted without affecting the other. The input frequency command is proportional to the required speed. The input voltage command is generated from the neuro-fuzzy controller depending on the speed error and summation of the error. The inverter control logic calculates the duty cycle timing of the power switches to control the sinusoidal voltage applied to each phase of the motor. Figure 6 shows the voltage/frequency curve required for the PM motor under test.

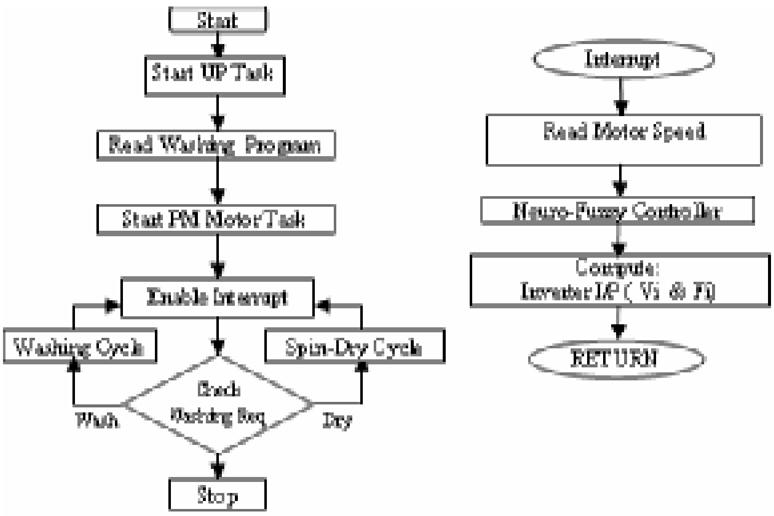

Fig.7. Real-time software design.

6.4 Software design

For real-time operation, it is essential to arrange the overall system software such that the microcontroller does not become overloaded. Figure 7 illustrates the foreground/background software. The foreground tasks are written as an interrupt service routine, and the background tasks as a standard program.

a). Background software; which includes the tasks;

- System initialization.
- Motor start-up.
- Check washing program.
- Display update.

b). Foreground software; which includes the tasks;

- Speed measurement.
- Neuro-fuzzy control.

The rotor position is sampled 24 times per revolution, and each pulse causes an interrupt to the microcontroller. The real-time response of the speed measurement and neuro-fuzzy control tasks becomes critical at high speed. For washing machine applications, and with 8-pole PM motor, the maximum speed may be less than 1000 rpm at which the sampling interval is only 2.5 msec. If the execution time of the hard tasks is critical, then it can be solved either by using high performance microcontroller or replacing speed measurement algorithm task by hardware.

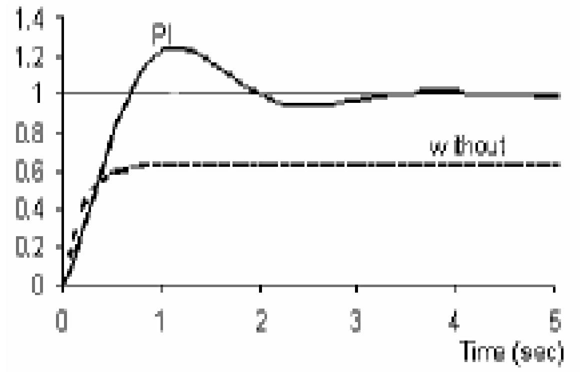

Fig.8. Transient response of the PM motor.

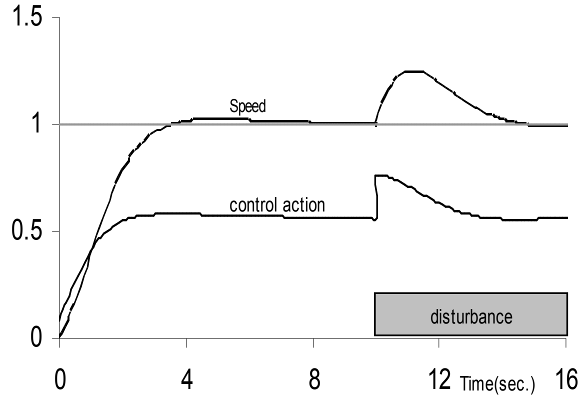

Fig.9. Transient response with added disturbance.

7. Results and discussion

A mathematical model of the PM motor has been used to test the performance and capability of the proposed system. The step response of the PM motor model with a unity feedback is given in Fig.8. By applying the conventional PI controller, a good speed controlled response can be achieved.

Taking the available input/output data to be learned by the MLP neural net to take the merits of this topology such adaptively generalization. This structure is learner based on a fuzzy number clustered input/output data controlled from the running PI controller, see table 1.

The neuro-fuzzy controller has been tested for a step input. The speed response and the actuating signals are shown in Fig.9. It is often necessary to show how the speed response vary when dealing with a disturbance of 20% from the input. As illustrated in Fig.9, the speed rises rapidly and then change slowly to follow its required value. It is clear from the response that the controlling actions can handle any disturbance and return to normal performance.

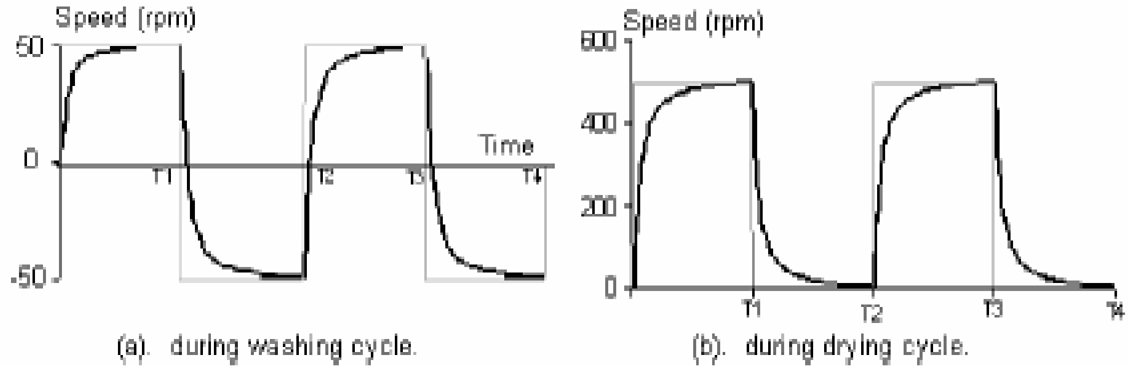

Fig.10. Transient response during washing and drying cycles.

Further tests were performed, as given in Fig.10 to show the controller performance during both washing and spinning cycles. It is clear that such algorithm has a good tracking to input speed commands, and match the functionality of the washing machine.
The obtained results demonstrate that such a controller is able to drive the motor accurately for a wide range of operation.

Table 1. Fuzzy number clusters.

Error	Summation of Error	Control Action
1.0	1.0	0.10
0.9	3.8	0.23
0.8	5.5	0.315
0.7	7.0	0.383
0.6	8.0	0.44
0.5	9.0	0.50
0.4	10.0	0.54
0.3	11.0	0.55
0.2	11.5	0.60
0.1	12.0	0.60
0.05	12.0	0.60
0	12.0	0.60

Conclusions

The PM synchronous motor is the most cost-effective and best choice for washing machine operation. The proposed system presented in this paper is a sensorless PM drive system, since there is no need for any mechanical sensor. The rotor position pulses derived from the implicit sensor (search coils) are used for position and speed measurements. A simple neuro-fuzzy control algorithm has been used to drive the power switches of the PWM inverter according to the washing program. This system allows for sinusoidal waveforms which produce low torque ripple, which consequently minimize the acoustic noise. The proposed control algorithm is simple and does not require accurate knowledge of the motor parameters, and can be implemented on a programmable IC. Such a sensorless drive system is suitable for washing machine operations that require high torque at low speed and low torque at high speed.

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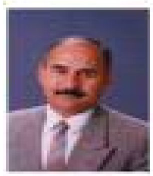
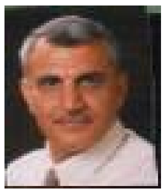


Dr. Kasim Mousa Al-Aubidy, received the BSc and MSc degrees in control & computer engineering from the university of Technology, Iraq in 1979 and 1982 respectively, and the PhD degree in real-time computing from the university of Liverpool, England in 1989. He is currently the dean of the Engineering Faculty at Philadelphia University, Jordan. His research interest includes fuzzy logic, neural networks, genetic algorithm and their applications in real-time. He is the winner of Philadelphia Award for the best researcher (2000). He is the chief editor of the International Journal of SoftComputing (IJSC) and Asian Journal of Information Technology (AJIT). He has coauthored 5 ooks and published 61apers on topics related to computer applications.



Dr. Mohammed Mahdi Ali, received the BSc, MSc and PhD degrees in computer and control engineering from the university of Technology, Iraq in 1981, 1993, and 1998 respectively. He is currently an assistant professor in the department of computer engineering at Philadelphia University, Jordan. His research interest includes fuzzy logic, neural networks, image processing, and computer interfacing. He has 8 published papers related to neurofuzzy and real-time computer control applications.