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Induction Motors Control in Mechatronics Devices

Hosein Marzi

Department of Information Systems, St. Francis Xavier University, Antigonish, NS Canada

Phone Number: *+1- 9028636241*

****Corresponding Author's E-mail:*** *hmarzi@ieee.org*

Abstract

It is a common practice to use Direct Current motors in mechatronics devices due to possibilities for their fine and rapid control. Induction electrical motors, on the other hand, are rugged and robust, however, have been a challenge and conventional drives and control mechanisms are not ideal for their fine tuning and control. As such these excellent electrical engines may not be very popular in mechatronics devices such as robotics actuators. This paper suggests use of flux vector drives and intelligent control scheme based on fuzzy controllers to improve shortcomings of alternative current electrical motors to encourage their applications in mechatronics devices.

Keywords: *Fuzzy logic, Induction Electrical Motors, AC Electrical Motros, DC Electrical Motros, Field Oriented, Flux Vector Control, Motion Control.*

I. Introduction

In mechatronics devices use of DC motors are popular since primary focus is on accuracy, controllability over speed and torque. The drawback reflects on high price of DC motors due to their design complexity [2], [5], [8]. On the other hand AC electrical motors in general are known for their low cost, robustness and rugged. In applications with moderate and gradual speed control AC motors with solid-state switching drives may be a preferred replacement. There are a number of advantages on use AC electrical motors over DC such as being less expensive, need less maintenance, smaller size and reliability. Their most significant disadvantage is less precisions in speed control. For this reason the application areas of such electrical motors are in equipment where requirement for speed control and transient performance are not of primary importance and critical, such as pumps, compressors, and fans [6], [9]. Variable frequency AC power supply is used in controlling angular speed of asynchronous AC motors. There are similarities between speed controllable AC and DC electrical motors; however, speed controllers for AC motors may require expensive electronics. In most cases AC motors are slower in reaction than DC motors. Application areas of mechatronic devices, robotic actuators, machine tools spindles and axes drives require precise speed and motion controllability to the point that until recently AC motors were not able to satisfy the complexity generally and the operation falls within the domain of DC motors. Field oriented or flux vector control of AC induction motors has been able to provide more accuracy and precise control of sensitive parameters such as position, speed, torque or acceleration. Therefore, possibility for using AC electrical motors in replacement of DC motors and the trend of such a use had continued. Based on design field oriented induction motors independent control of torque and flux is made possible through stator current adjustment with reference to rotor flux. This design is analogous to the torque control in DC motors, where commutators hold a fixed, orthogonal spatial angle between field flux and armature magneto motive force. This concept of field oriented began in Siemens Labs by Blaschke [1]. In fact, field oriented approach, decouples flux and torque components of motor current in induction motors which

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results in speed-torque controllability to the extent that field oriented induction motors match performance of DC motors. Control techniques based on Artificial Intelligence techniques such as Fuzzy Logic and Neural Networks has been applied to variety of control problems. Some original Fuzzy Control designs are modeled based on Mamdani [16] others followed using and Takagi [27]. In this study, in order to improve performance of field oriented induction motors a hybrid model of field oriented and fuzzy control has been developed and applied to an AC induction motor. In this study a more stable response and shorter transient performance was achieved.

II. AC INDUCTION MOTORS

The motor chosen for the simulation is an AC motor. The motor is modeled, Figure 1, using field oriented control scheme [3].

A. Modeling of Field Oiented

The field-oriented scheme makes control of AC machine analogous to that of DC machine. This is achieved by considering the d-q model of the AC machine in the reference frame rotating at synchronous speed ω_e. In this model i_{ds} and i_{qs} are current components of the stator current on d-q axis, where i_{ds} component is aligned with the rotor field. The rotor flux and torque can be controlled independently by i_{ds} and i_{qs}, shown in Figure 4. The electric torque T_e is proportional to the quadrature-axis current i_{qs}, component of the stator current I_s, and the rotor flux ψ_r can be controlled by the direct-axis current i_{ds}, of Is, where: $I_s = i_{ds} + J\, i_{qs}$.

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_e \varphi_{ds} \tag{1}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_e \varphi_{qs} \tag{2}$$

$$0 = R_s i_{qr} + \frac{d}{dt}\varphi_{qr} + (\omega_e - \omega_r)\varphi_{dr} \tag{3}$$

$$0 = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} + (\omega_e - \omega_r)\varphi_{qr} \tag{4}$$

$$T_e = 1.5p\frac{L_m}{L_r}(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}) \tag{5}$$

$$\begin{cases} \varphi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \varphi_{ds} = L_s i_{ds} + L_m i_{dr} \end{cases} \tag{6}$$

$$\begin{cases} \varphi_{qr} = L_r i_{qr} + L_m i_{qs} \\ \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \end{cases} \tag{7}$$

$$\varphi_{qr} = 0 \Rightarrow \frac{d}{dt}\varphi_{qr} = 0 \Rightarrow \varphi_{dr} = \varphi_r \tag{8}$$

$$\omega_{sl} = (\omega_e - \omega_r) = \left(\frac{L_m R_r}{\varphi_r L_r}\right) i_{qs} = \left[\frac{L_m}{\varphi}\right] \tag{9}$$

$$T_e = 1.5p\frac{L_m}{L_r}(\varphi_r i_{qs}) \tag{10}$$

$$\varphi_r + \tau_r \frac{d}{dt}\varphi_r - L_m i_{ds} = 0 \tag{11}$$

Where $\tau_r = L_r / R_r$ is the rotor time constant.

The transfer function of this AC motor yields angular velocity (ω) as the motor shaft output. In the simulation, ω was easily converted into the force on the cart. The motor responded well, reaching its maximum force exerted on the cart in less than 2.5 seconds.

III. TESTBED MECHANISM

Following completion of implementation of a new system, quality of its design is examined by vigorous testing. One of the test beds to challenge control designs, electrical motors, or drives is inverted pendulum. The mechanism has non-linear model that can be simplified by some assumptions and turned into a linear model. The focus of the present work is to control the balance of an inverted pendulum using a control model of an AC electrical motor and drive based on flux vector model for supplying required torque adequately and fast. Moreover, the conventional control mechanism would be replaced by fuzzy control. In the mathematical model of an AC motor an equivalent time constant is an important parameter for rapid torque production to unpredicted disturbances. Inputs to the model are current or voltage and the output is torque that is used in balancing the mechanism used as a test bed. In this investigation the mathematical model of the electrical motor is not integrated in the control model of the inverted pendulum as such the control performance may be examined with different types of motors and drives.

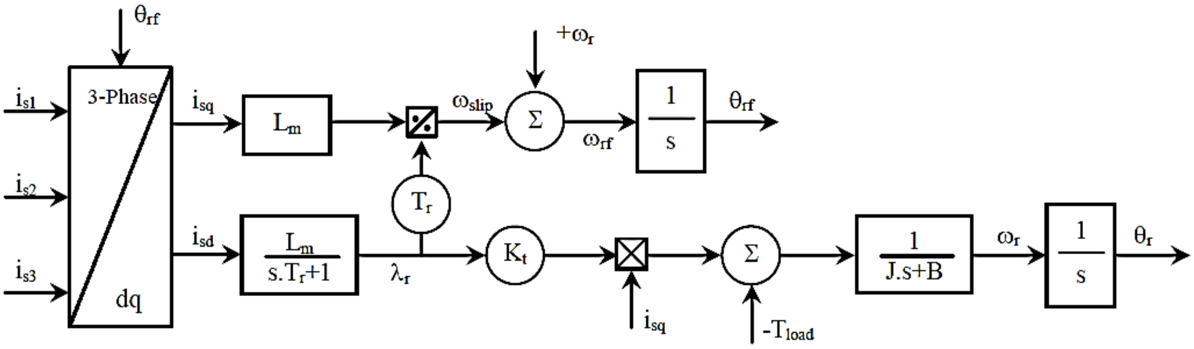

Figure 1. Magnetic Flux Control Scheme in Induction Motors

In the modeling of fuzzy controllers for the inverted pendulum, the input to the pendulum block is considered to be a torque. This torque is produced by an electrical motor which is not included in the model. That is, the torque is output of the motor. A disadvantage in this modeling is that the electrical motor dynamics is not built-in in the control system independently. On the other hand, not including the electrical motor in the control scheme of the pendulum mechanism provides the freedom to alter the electrical motor and examine the performance of the pendulum with different types of the drive. Here, a simplified model of an AC electrical motor is incorporated into the system. The electrical motor receives its inputs as current or voltage and produces a torque as output to control the balance of the mechanism.

This study aims at investigating whether a fuzzy control system based on Takagi-Sugeno model improves control performance of AC motors in producing rapid response, selecting sensitive parameters of electrical motors for high performance dynamics and ability to balance an inverted pendulum, and integration of conventional control scheme and intelligent control model.

IV. USE OF FUZZY CONTROLLERS

The conventional approach in controlling the inverted pendulum system is to use a PID (Proportional, Integral, and Derivative) controller. In order to model the system the developer would have to know every technical detail about the system and be able to model it mathematically. Use of Fuzzy Controllers are different than conventional control based on proportional, integral and derivative components in applying educated guesses to control the system [13], [26]. Fuzzy controllers have been used in various home appliances [10], more sophisticated systems such as Japan Sendai Subway [12]. Degree of Membership is used in Fuzzy Logic to generalize inputs and outputs of a system [25], [15]. In this investigation the cart holding the pendulum is moved by a field oriented AC [3], [19], [20], [21].

V. DESIGNING FUZZY LOGIC CONTROLLERS

In designing controllers based on fuzzy logic there are possibilities for selecting number of inputs and outputs [17], [18], [22]. In a simple control mechanism there is one input and one output. Fuzzy Logic Controllers can have more than one input. Two-input FLC's are easy to implement and receive great performance responses from simulations. A model of fuzzy controller that had great performance balancing the pendulum but the cart's positioning was unstable, making it an impractical rule set for real life implementation discussed in [13]. Two-input FLC's are the most commonly researched inverted pendulum systems. One of the most commonly researched types fuzzy controllers is two-input inverted pendulum systems. The 2-input system receives angle θ and angular velocity ω as its inputs. The system uses 5 membership functions for each input, and another 5 for the outputs which is the Force. The system consists of 25 (that is 5 to power 2; 5^2) rules. Table 1 shows the rule base for the inverted pendulum system. According to Table 1 a value of NL represents a negative large angle or angular velocity, and PL represents a positive large angle/angular velocity. As Table 1 indicates; if there is a situation where the angle is Zero (ZE) and the angular velocity is PS then the rule NS will be fired. Where, NL, NS, ZE, PS, PL are linguistic values of negative large, negative small, zero, positive small, and positive large.

A simulation that runs for 2 seconds is shown in Figure 2. The pendulum has an initial angle of 0.2 radians (dashed line). When the simulation is run, the angle of pendulum balances quickly, in about 1 second, but the position of the cart is not controlled (continuous line) so the cart's position will eventually drift off into the end of the track, even though the pendulum's arm is balanced.

The benefit of adding two more inputs to the system to control the X-position of the cart and the velocity of the cart will greatly benefit the stability of the system. There is a cost for better stability; this is a greater computation time, and greater complexity in the model. The cost of adding more inputs increases exponentially with the number of inputs added. The above two-input system used five membership function for each input used; this resulted in a 25 (i.e. 5^2) rule base. By adding two more inputs to the system, the systems rule base would grow to 625 (i.e. 5^4) rules. Development time for a rule base this size can be very time consuming, both in development and in computational time. Bush proposed using an equation to calculate the rules, rather than taking the time to develop the rules individually [4]. The system was a 5^4 system with 17 output membership functions (OMF). The equation used was:

$$\mathrm{OMF} = \mathrm{I} + (\mathrm{J} - 1) + (-\mathrm{K} + 5) + (\mathrm{L}+5) \tag{12}$$

This equation results in values ranging between 1 and 17. This corresponds to the OMF that is to be used in the calculation of the output. The performance of the system using this approach is not consistent with that of the original simulation, given by the author of the above Equation 12 [4]. The force given to the cart holding the pendulum was found not to be enough to balance the pendulum and the system failed within a small amount of time. It can be concluded that this system would be a good starting point for one to base a large rule set on, but the system would need some tweaking of the rules and membership functions to get to balance the system effectively.

TABLE 1. RULE-BASE MATRIX FOR THE INVERTED PENDULUM.

θ/ω	NL	NS	ZE	PS	PL
NL	PL	PL	PL	PS	ZE
NS	PL	PL	PS	ZE	NS
ZE	PL	PS	ZE	NS	NL
PS	PS	ZE	NS	NL	NL
PL	ZE	NS	NL	NL	NL

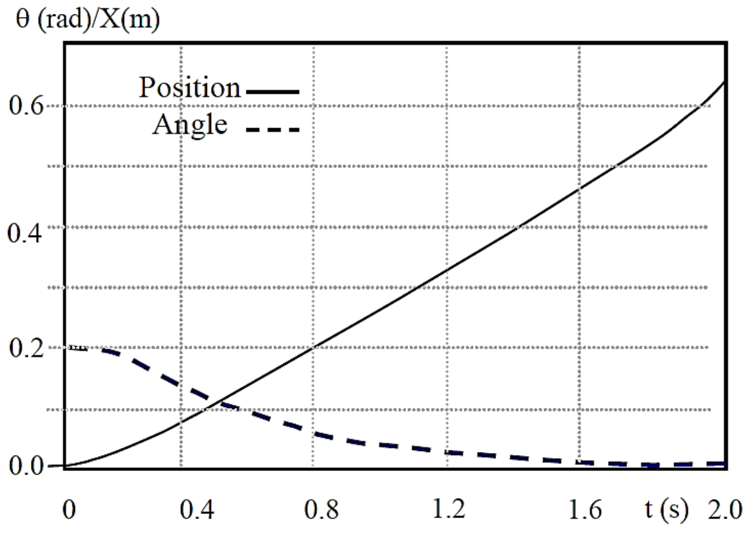

Figure 2. Variation of angle ☐ (rad) and position X(m) of pendul

The final FLC controller that was modeled for simulation was a Takagi-Sugeno type fuzzy controller. All the previous FLC's modeled were of Mamdani type. A Takagi-Sugeno type fuzzy controller [24], [14], [11], [28] varies from the traditional Mamdani type controller by using linear or constant OMF's instead of triangular, trapezoidal, Gaussian or any other method the developer decided to use. The system uses 4-inputs with only 2 input membership functions for each. This resulted in a 2^4, 16 rule system. The linear output membership functions (OMF) are calculate using the equation

$$OMF = c_0 + (c_1 * x_1) + (c_2 * x_2) + (c_3 * x_3) + (c_4 * x_4) \tag{13}$$

Where c_n is the parameters of the OMF, and x_n is the values of θ, ω, X and linear velocity V respectively. The system modeled here uses fuzzy logic toolbox of Matlab [24]. Figure 3 is the result of the simulation. The pendulum is started with an initial disturbance of 0.2 radians. As shown, the fuzzy controller overcompensates for this initial disturbance and sends the pendulum's angle (dashed line) in an opposite direction in an attempt to balance it, this is the overshoot. It takes approximately 5 seconds for the pendulums arm to balance.

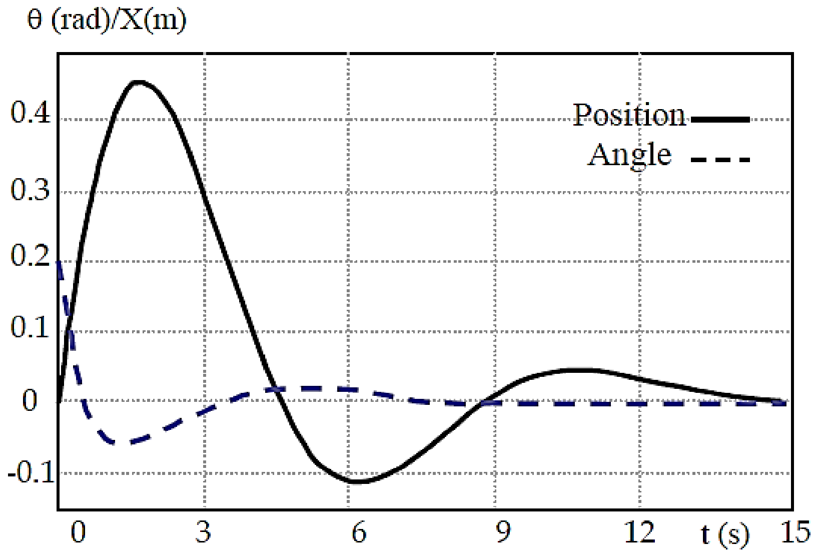

Figure 3. In adjusting the balance of pendulum angle θ (rad), and position X (m) changes with time t (s).

VI. DISCUSSION AND RESULTS

The simulation consists of four main components, the fuzzy controller, AC motor, the cart and the inverted pendulum, Figure 5. The cart passes the fuzzy controller four parameters θ, ω, X, V. Based on these four parameters the fuzzy controller outputs a voltage to the motor. The motor in turn calculates the force that will be exerted on the cart. The system then calculates the new values for parameters θ, ω, X, V and the cycle will be repeated. The fuzzy controller used in the simulation, with the AC motor included, is a 24 FLC as described above. The system runs identical to the 24 system only the settling time for the simulation, with the motor included, is larger. Figure 6 shows the results of the simulation using the same fuzzy controller as [24] with the AC motor included in the simulation. The AC motor has a delay, where it takes the motor a given time to reach a maximum force. This in turn causes the simulation take longer to reach steady state. Parameters used in the simulation of the motor are listed in Table 2. Figure 6 shows that it takes approximately 12 seconds for the pendulum's angle to become steady, and even longer for the cart's position to stabilize. The difference in the response time of this system can be found in the motor. The motor has a time constant which delays the motor's response time to an inputted voltage. A typical AC motor has a time constant larger than that of a DC motor. The shorter the time constant of the motor, the quicker the system will respond. Therefore, it can be expected that it takes longer for AC motor to balance the pendulum. The simulation shows that the system responds well even with a motor attached to the system. The cost of implementing a motor into the simulation is response time for the pendulum to stabilize. Simulations done without the addition of the AC motor cannot be considered for real life implementation because the motor is needed to investigate the response time that the system will observe in real life. In a series of tests carried on without the use of fuzzy controller, it was revealed that the pendulum can hardly overcome any disturbances. If the disturbance is very small, it takes twice longer for the pendulum to balance again in an upright position.

TABLE 2. PARAMETERS OF THE MODELED MOTOR.

T_r	=	0.06 S	Rotor time constant
L_m	=	75 mH	Magnetizing inductance
K_t	=	1.00	Motor torque constant
Rating	=	1.0HP	Motor rating
J	=	$0.06 kgm^2$	Moment of Inertial of the motor and the load
b	=	$0.002 kgm^2/s$	Coefficient of friction

Performances of vector control AC induction motors are comparable to that of DC motors; however, AC motors are rugged and low cost. Therefore, whenever possible, usage of AC motors will greatly reduce the capital cost of equipment and devices.

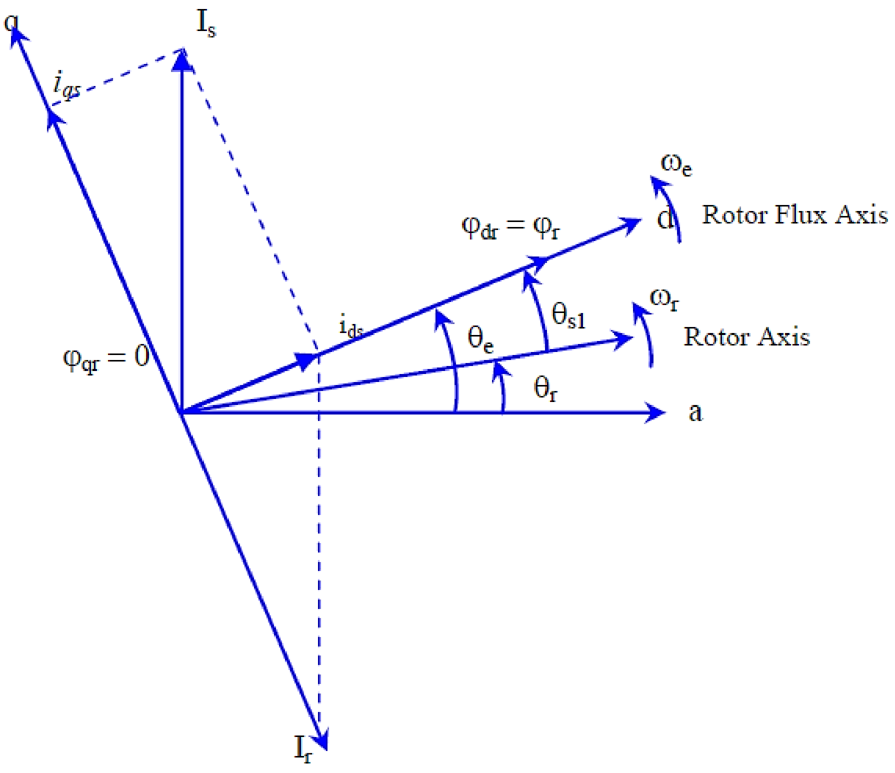

Figure 4. i_{qs} and i_{ds} components of I_s on a d-q axis.

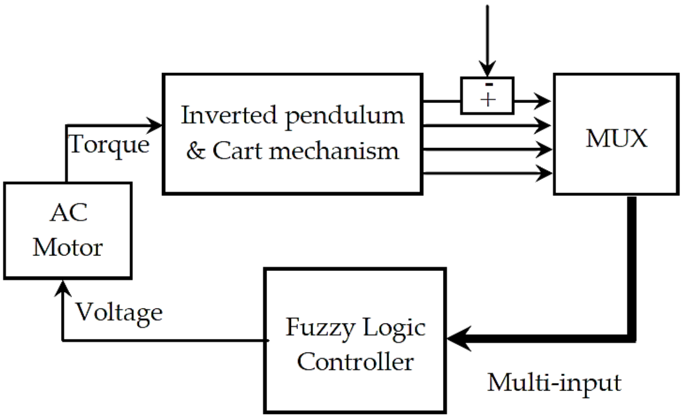

Figure 5. Schematic diagram of fuzzy controller for the inverted pendulum.

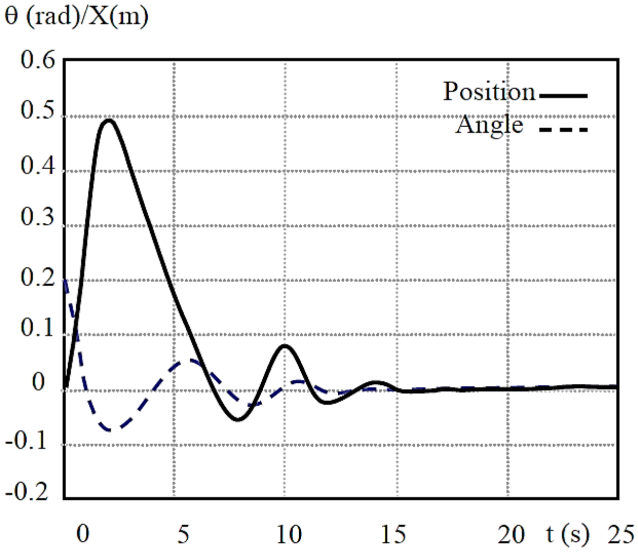

Figure 6. Variation of angle ☐ (rad) and position X(m) of the p

CONCLUSION

This work presented a control scheme based on fuzzy logic for multi-input output systems. The case addressed precision result of a complex design and a simplification compromised precision of the result. Using fuzzy logic controller there will be no absolute solution it is a trade-off between precision performance and simplicity. Here, the design of 52 and 24 were less precise, the settling time for the cart pendulum was short, therefore solution was simplified and rapid and the performance may be less satisfactory for certain cases. On the other hand the 54 was a complicated system designed for performance, it was slow and if tuned correctly would perform very precisely. In order to achieve this performance using AC motor requires a high performance electrical motor is required. The simulation results implied that an AC motor with shorter time constant will result in shorter response time. Fine tuning of fuzzy logic controller is required. Simulation with a DC motor presented a better reaction to high disturbances compared to the simulation with an AC motor. In the latter case system, reacted well toward small to moderate disturbances and recovered from them. Using fuzzy logic controller was instrumental in improvement to controllability of the system under investigation and improved the system response time. Therefore, in order to design a system to recover from large disturbances in a short time a high dynamics electrical motor with short time constant must be employed.

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Excerpt with permission from the author's articles as referenced.

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Autor

Prof. Dr. Hosein Marzi received his MSc, and Ph.D. degrees in Electrical Systems Engineering from Cardiff University, U.K, and BSc from Shiraz University, Iran. He is a Fellow of IET and IMechE, a Senior Member of IEEE, a Chartered Engineer in UK, and a Professional Engineer of Canada. He is currently a Full Professor with the Department of Information Systems, St. Francis Xavier University, NS, Canada. He was a visiting professor at the University of Toronto, Canada, a Research Fellow of EPSRC, U.K., a Research Fellow of NSERC, Canada, and a Visiting Research Associate of PPARC, U.K. under the GridLab Project. His research has been supported by SSHRC and NSERC of Canada. Areas of his research interests include real-time embedded and distributed systems, optimization techniques, intelligent systems, condition monitoring, manufacturing and mechatronics. He is still a faculty member of Francis Xavier University, NS, Canada.

email: hmarzi@stfx.ca
Phone Number: (+1-902) 863-6241