

DIRECT TORQUE CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR BASED ON FUZZY LOGIC

Dan Sun *, Jian Guo Zhu **, and Yi Kang He *

* College of Electrical Engineering, Zhejiang University
Hangzhou, Zhejiang, 310027, P.R. China
sundan_cn@hotmail.com

** Faculty of Engineering, University of Technology, Sydney
PO Box 123, Broadway, NSW 2007, Australia
joe@eng.uts.edu.au

Abstract

In the conventional direct torque control (DTC) of a permanent magnet synchronous motor (PMSM), hysteresis controllers are employed to select the proper voltage vector resulting in large torque ripples, and the inverse voltage vector, used in this system instead of the zero voltage vectors used in an induction motor, can accelerate the torque response but enlarges the torque ripples at the same time. To improve the steady state performance of the PMSM DTC system a fuzzy logic scheme is introduced in this paper. In the PMSM fuzzy DTC system, the stator flux linkage error, the torque error and the stator flux angle are all properly fuzzified into several fuzzy subsets to accurately select the voltage vector, and the real stator flux angle is mapped onto a sextant region in order to minimize the number of fuzzy rules and shorten the computation time. Experimental results show that both the steady state and dynamic performances are improved by the application of the fuzzy logic scheme.

1. INTRODUCTION

Direct torque control (DTC) has recently emerged as the main alternative to the vector control in the market of AC drives. In DTC, there is no need of the complicated vector coordinate transformation and equivalence between the DC and AC motors. Since the stator flux linkage, which can be precisely observed once the stator resistance is correctly detected, is taken as the directional flux coordinate, the influence of the rotor parameters, that is inevitable in the vector control scheme, is avoided. The DTC is implemented by selecting the proper voltage vector according to the error signals of the stator flux linkage, torque and stator flux angle, which improves the dynamic performance by avoiding the indirect control of the torque through the flux component of current in the vector control.

The DTC scheme has already been successfully realized in induction motor (IM) drives, and is being applied in permanent magnet synchronous motor (PMSM) variable speed drives [1]-[4]. There are, however, some differences between

the DTC strategies for PMSM and IM, further investigation is required on the practical implementation of DTC for PMSM. The use of the zero voltage vectors is one of the major considerations.

Applying the zero voltage vectors to a conventional PMSM DTC system will result in losing control of the motor, and the inverse voltage vector must be used to get a universal DTC strategy for all types of PMSM [5]. Because of the employment of the hysteresis controllers to regulate the stator flux and torque in conventional DTC systems, it is natural to have torque ripples. The use of the inverse voltage vector to accelerate the torque response will enlarge the torque ripples and may lead to unacceptable steady state performance. This contradiction between the steady state and dynamic performances can be resolved by subdividing the errors of torque and flux into several subsections, which is helpful in selecting the proper voltage vector. However, it is not easy to give the explicit optimal boundaries between these subsections because the DTC strategy is not based on a strict

mathematical description. For this type of problems, the fuzzy logic technique based on the language rules has proven to be effective.

The fuzzy DTC of IM was simulated in [6], but the practical implementation was not reported.

This paper proposes a novel fuzzy DTC system of PMSM for the purpose of minimizing the torque ripples. In this system, the errors of the stator flux linkage, torque, and flux angle of PMSM are all properly fuzzified into several fuzzy subsets to accurately select the voltage vector in order to smooth the torque ripples and accelerate the torque response. The stator flux angle was also mapped onto a reduced region to minimize the number of fuzzy rules, to shorten the computation time and to improve the response speed. In addition, the effects of zero voltage vectors in PMSM fuzzy DTC system are also analysed. The proposed technique has been implemented in a practical industry drive system and verified by experiments.

2. PMSM DTC THEORY

The electromagnet torque of a non-salient PMSM can be expressed as

$$T = \frac{3}{2} \frac{1}{L_s} p |\psi_s| |\psi_r| \sin \delta \quad (1)$$

This equation indicates that the torque T can be dynamically controlled by regulating the rotating speed and amplitude of stator flux linkage ψ_s to adjust the power angle δ under the condition of keeping the amplitude of rotor flux linkage ψ_r invariant. This is the basic idea of PMSM DTC.

Fig.1 illustrates the eight switching modes of an inverter depicted as eight voltage vectors, and also the six voltage vector plane regions. The stator flux linkage of the inverter fed motor in the stator two-phase reference frame can be formulated as

$$\psi_s = \int (u_s - Ri_s) dt \quad (2)$$

where u_s is the stator voltage, R the stator resistance, and i_s the stator current.

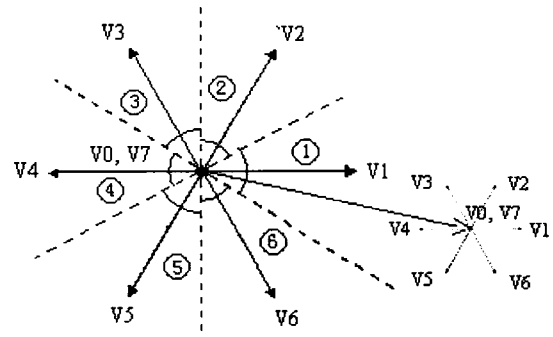


Fig.1 Voltage space vectors

Neglecting the stator resistance, the stator flux linkage can be approximately determined by the integration of the voltage vector. This implies the stator flux linkage moves in the same direction as the given voltage vector. Therefore, it is possible to control the amplitude, moving direction and speed of the stator flux linkage by selecting a proper voltage vector to regulate the power angle δ and, further, to force the torque and stator flux linkage amplitude into the prescribed band. What must be taken care is that in a PMSM the initial stator flux linkage, the initial value of the integration in (2), is nonzero. It is a vector having the same value and direction as the flux linkage due to the rotor magnet. Simulations and experiments indicate that the given initial value of the stator flux linkage strongly affects the start-up performance of the system and the precise selection of the initial voltage vectors is very important to ensure the correctness of the initial stator flux linkage.

In an IM, the stator flux linkage is uniquely determined by the stator voltage, and when the zero voltage vectors are selected the stator flux linkage vector will be standstill in the position where it was and the electromagnetic torque will decrease rapidly. In a PMSM, however, the stator flux linkage is jointly determined by both the stator voltage and the rotor magnet flux. Since the permanent magnets rotate all the time, the stator flux linkage still exists even if the zero voltage vectors are used, and as a result, the zero voltage vectors will only cause the torque decreased slightly. In the conventional PMSM DTC, because only two-value hysteresis controller is used to select the voltage vector, an inverse voltage vector is normally selected to reduce the torque rapidly.

3. PMSM FUZZY DTC

As mentioned above, the employment of hysteresis controllers in the conventional DTC results in considerable torque ripples. The use of the inverse voltage vector can accelerate the torque response, but the torque ripples are increased as well. In this case, the fuzzy logic technique can be effectively applied to solve such a contradiction between the steady state and dynamic performances in conventional PMSM DTC systems.

3.1 PMSM Fuzzy DTC Theory

Fig.2 depicts schematically a PMSM fuzzy DTC system, in which the fuzzy controller replaces the flux linkage and torque hysteresis controller and the voltage vector selecting unit in a conventional PMSM DTC system. For the fuzzy controller in Fig.2, the stator flux angle and the errors of the stator flux linkage and the electromagnetic torque are selected as the inputs and the voltage vectors as its outputs.

The function of each voltage vector is symmetric in every sextant region of the whole plane in the DTC system. For example, in region 1 of Fig.1, V2 can be selected to increase the torque and the flux linkage simultaneously, and V3 has the same effect in region 2. It is possible to figure out all the rules by analysing the state in one sextant region only. Equation (3) can be used to map the whole plane of 360° onto one sextant region ($-\pi/6 \sim \pi/6$) to reduce the number of fuzzy reasoning rules.

$$theta = \theta - \frac{\pi}{3} \left[\begin{array}{c} \theta + \frac{\pi}{6} \\ \frac{\pi}{3} \end{array} \right] \quad (3)$$

where *theta* is the actual input of the fuzzy controller after mapping, and θ is the real stator flux angle.

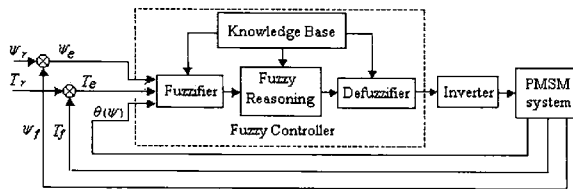


Fig.2 Schematic diagram of a PMSM Fuzzy DTC system

Although zero voltage vectors cannot be used to reduce the torque rapidly, it is possible to keep the torque and flux linkage basically invariant [6]. For this reason, two zero voltage vectors can still be applied in the PMSM Fuzzy DTC system to keep the torque constant and to further smooth the torque ripples. Consequently the outputs of the fuzzy controller should have eight applicable voltage vectors in a PMSM Fuzzy DTC system. However, two zero voltage vectors can be uniquely denoted by one variable V0 and one of these two zero voltage vectors should be determined for use according to the state of the previous voltage vector applied in order to reduce the switching frequency of the power device. As a result, the number of real outputs of the fuzzy controller is cut down to seven, which is capable to meet more requirements in comparison to the six voltage vectors normally used in a conventional PMSM DTC system.

In the PMSM DTC system, the rapid torque response is a very important performance figure and our experimental studies indicate that the demands of the torque and flux linkage cannot be all well met at the same time by selecting any voltage vector. However, it is in general easier to meet the demand of the flux linkage than that of the torque, and therefore, the torque requirement is the first to be met whenever there is a contradiction.

Generally, a fuzzy controller consists of three parts: fuzzification, fuzzy reasoning, and defuzzification. The fuzzification is performed by a membership function. The membership function of the flux linkage error, the torque error and the stator flux angle are divided into 3, 5 and 2 subsets, respectively. The subsets of the fuzzy controller output is assigned to be seven discrete voltage vectors singleton subsets, which makes the defuzzification essential. The membership functions of the flux angle, the errors of the flux linkage and the torque, and the output voltage vector are depicted in Fig.3, from which it can be seen that the number of subsets for the torque error is more than that for the flux linkage error in order to emphasize the need of the torque. In the membership of the torque and flux linkage errors, the proportion of the fuzzy zero-value region is very small since the zero voltage vectors can only be used to keep the torque and flux linkage approximately invariant for a very

short period of time. Such shape of membership function is helpful to make the torque act rapidly and accurately.

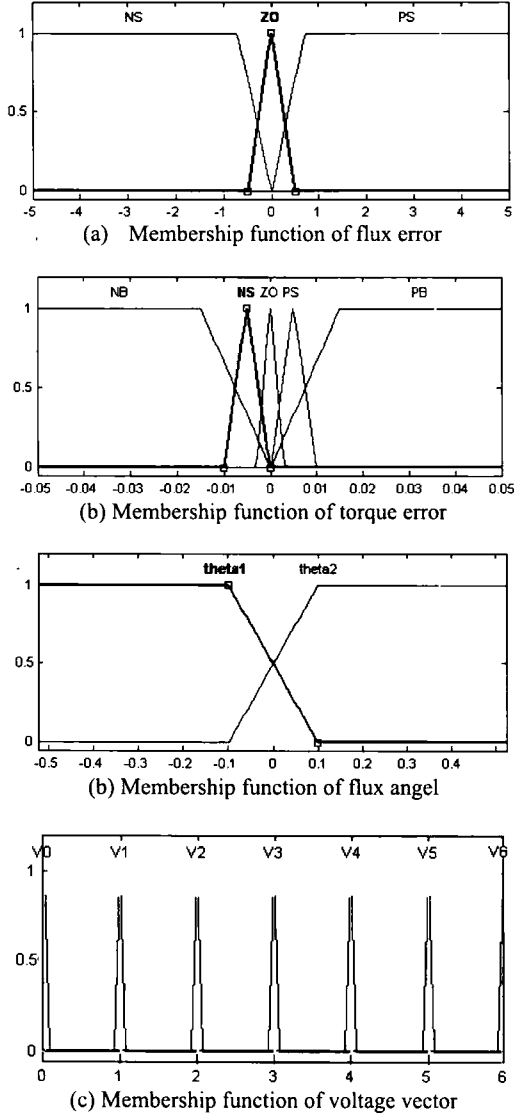


Fig.3 Membership functions in the PMSM Fuzzy DTC system

Table 1 PMSM Fuzzy DTC rules

		Theta1			Theta2			
		PS	ZO	NS	EF	PS	ZO	NS
EF	ET				EF	PS	ZO	NS
	PB	V2	V2	V3	PB	V2	V3	V3
	PS	V1	V2	V3	PS	V2	V3	V4
	ZO	V0	V0	V0	ZO	V0	V0	V0
	NS	V6	V0	V5	NS	V6	V0	V5
	NB	V6	V5	V4	NB	V6	V5	V5

Considering the effects of each voltage vector on the amplitude, rotating speed and direction of the stator flux in the PMSM DTC and combining with the practical experience of debugging at the same time, the PMSM fuzzy DTC rules, for both positive and negative direction, in region 1 of the voltage vector plane are tabulated in Table 1, where θ_1 , θ_2 , EF , ET and V_i ($i=0\sim6$) denote the fuzzy language variables of the flux angle, the flux linkage error, the torque error, and the voltage vector, respectively. In Table 1, the zero voltage vectors are used to keep the torque and flux linkage constant because they are more effective than any other voltage vectors. Because of the symmetry of the voltage vector selection in DTC, all of the rules on the whole plane could be deduced from this table of one sextant region, which reduces the number of the fuzzy rules significantly.

The fuzzy control rules in the system are expressed in IF-THEN format, and in this fuzzy system the Mamdani's method is employed for the optimal fuzzy reasoning. Since the output of the fuzzy controller is just seven singleton fuzzy subsets, defuzzification is not required. After obtaining the output voltage vector for the fuzzy controller, it should be transformed back to an actual vector to drive the inverter directly. Owing to the limited space for this paper, these methods will not be discussed in detail.

3.2 PMSM Fuzzy DTC System

Fig.4 illustrates the structure of a PMSM fuzzy DTC system with a double loop control of the flux linkage and speed. In this system, two stator phase currents i_a , i_b and the DC voltage U_{dc} are detected by voltage and current transducers and then transformed into the stator frame two phase components i_{α} , i_{β} and U_{α} , U_{β} . The stator flux linkage and torque are estimated by the two observers. The stator flux linkage components ψ_{α} , and ψ_{β} , the flux linkage amplitude $|\psi_s|$, the torque T and the flux angle θ ($-\pi/2\sim\pi/2$) can be determined as following:

$$\begin{cases} \psi_{\alpha} = \int (u_{\alpha} - Ri_{\alpha}) dt \\ \psi_{\beta} = \int (u_{\beta} - Ri_{\beta}) dt \end{cases} \quad (4)$$

$$|\psi_s| = \sqrt{\psi_{\alpha}^2 + \psi_{\beta}^2} \quad (5)$$

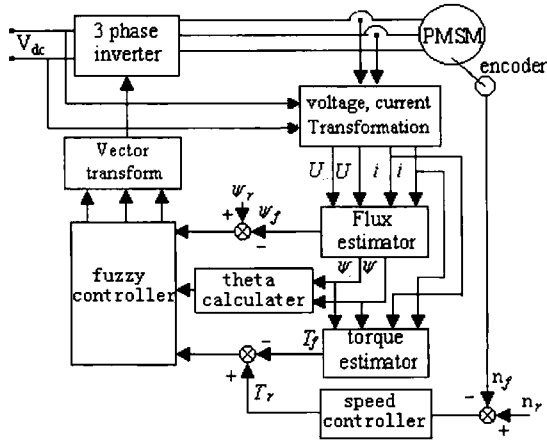


Fig. 4 The system diagram of PMSM Fuzzy DTC

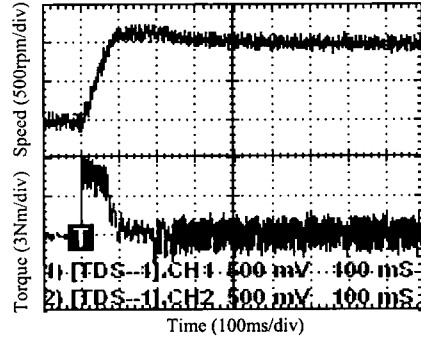
$$T = \frac{3}{2} p (\psi_{\alpha} i_{\beta} - \psi_{\beta} i_{\alpha}) \quad (6)$$

$$\theta = \arctan(\psi_{\beta} / \psi_{\alpha}) \quad (7)$$

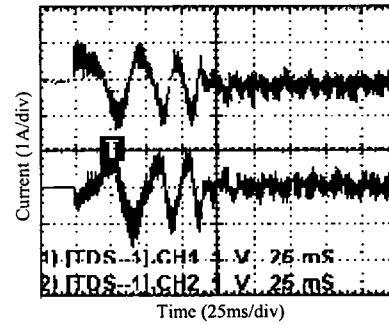
In this system, the flux hysteresis controller, torque hysteresis controller and voltage vector select unit originally needed in the conventional DTC system are replaced by a fuzzy controller. The actual speed and the initial rotor magnet position are all detected by an encoder. The output of the PI speed controller is used as the torque reference.

4. EXPERIMENTAL RESULTS

The PMSM fuzzy DTC system illustrated in Fig.4 implemented and tested in our laboratory. Figs.5-7 depict the experimental results. Fig.5 shows the start-up responses of the speed, torque and stator current at a step change in the speed reference from 0 to 1000 rpm, in which the given initial stator flux linkage was approximately the same as the measured initial flux linkage due to the rotor magnets, and the reference stator flux linkage was given as the rated flux linkage. The circular trajectory and the $(\alpha-\beta)$ axis components of the steady state stator flux linkage are shown in Fig.6(a) and (b), respectively. Fig.7 is the torque dynamic response waveform under the condition that the torque reference (the output of speed PI controller) changes abruptly from 5Nm to -5 Nm. To give prominence to the performance of the PMSM fuzzy DTC, the corresponding experimental results for a conventional PMSM DTC under the same experimental condition are also shown in Figs.8 and 9.

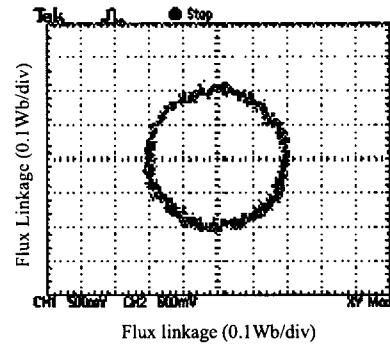


(a) Speed (top) and torque (bottom) responses

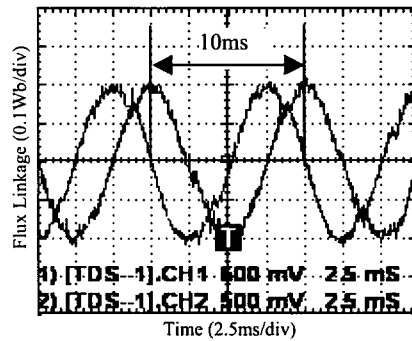


(b) Start-up current components in $(\alpha-\beta)$ axes

Fig.5 PMSM Fuzzy DTC start-up responses



(a) Stator flux trajectory



(b) Waveforms of stator flux components in $(\alpha-\beta)$ axes

Fig.6 PMSM Fuzzy DTC stator flux

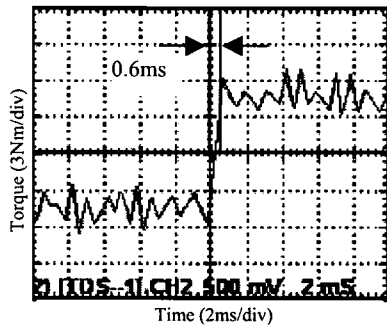


Fig.7 PMSM Fuzzy DTC dynamic torque response

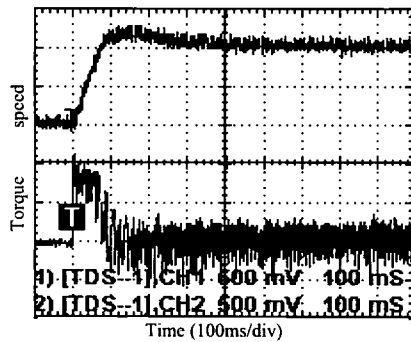


Fig. 8 Conventional PMSM DTC start-up process
Speed response (above, 500rpm/div)
Torque response (bottom, 3Nm/div)

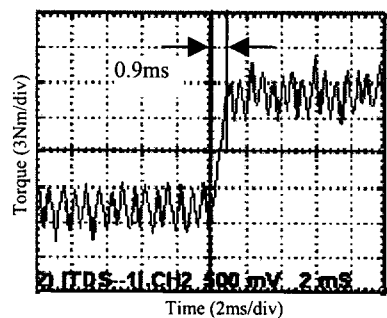


Fig. 9 PMSM Fuzzy DTC dynamic torque response

These pictures indicate that in both the PMSM fuzzy DTC and the conventional PMSM DTC the speed and torque can respond quickly, but the torque response and torque ripples are improved remarkably in the PMSM fuzzy DTC system as shown in Figs.7 and 9.

5. CONCLUSION

A novel fuzzy DTC control strategy for PMSM is proposed. In order to achieve good steady state and dynamic performance simultaneously, a fuzzy logic controller is designed, and it has been shown that the zero voltage vectors can be used in this fuzzy system although they cannot be used in the conventional PMSM DTC system. The theory is confirmed by the experimental results.

6. REFERENCES

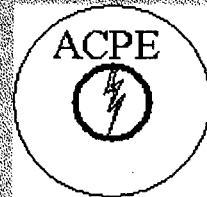
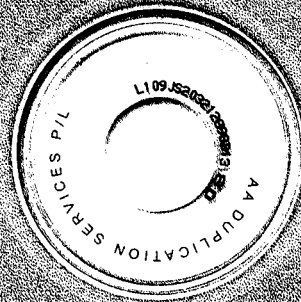
- [1] M. Depenbrock, "Direct self-control (DSC) of inverter-fed induction machine Power Electronics", IEEE Trans. on Industry Applications, 1988, 3(4), pp420-429
- [2] I. Takahashi, and Y. Ohmorim, "High-performance direct torque control of an induction motor", IEEE Trans. on Industry Applications, 1989, 25(2), pp257-264
- [3] Minghua Fu and Longya Xu, "A novel sensorless control technique for permanent magnet synchronous motor (PMSM) using digital signal processor (DSP)", NAECON 1997, pp403-408
- [4] L. Zhong, and M.F. Rahman, et al, "Analysis of direct torque control in permanent magnet synchronous motor drives", IEEE Trans. on Power Electronics, 1997, 12(3), pp528-536
- [5] Chun Tian and Yuwen Hu, "Study of the Scheme and Theory of the Direct Torque Control in Permanent Magnet Synchronous Motor Drives", Transactions of China Electrotechnical Society, 2002, Vol.17, No.17, pp7-11
- [6] Xia Yang and W. Oghanna, "Study on fuzzy control of induction machine with direct torque control approach", Proc. of ISIE'97, Vol.2, pp625-630

AUPEC 2002

Melbourne, Australia

29th September to 2nd October 2002

ISBN 0-7326-2206-9



MONASH
UNIVERSITY

Origin
energy

Australasian Universities Power Engineering Conference (AUPEC)
AUPEC2002

Producing Quality Electricity for Mankind



Melbourne, Australia
29th September to 2nd October 2002

Message from the Conference Chairman

It gives me great pleasure to welcome you all to the Australasian Universities Power Engineering Conference (AUPEC 2002). AUPEC traditionally rotates among the venues in the Australasian region and we are delighted to host the 2002 conference at Monash University, Melbourne Australia.

AUPEC is the only annual conference organised by the Australasian Committee for Power Engineering (ACPE). The primary aim of this conference is to provide a national forum for academia and industry to share innovation, development and experiences in a friendly environment. The other key aim of AUPEC is to provide postgraduate students with the opportunity to present their research findings in front of experts from both academia and industry for scholarly feedback. It also provides university academics and Industry the opportunity to interact with the technical community, to share experiences and gain the benefit from the latest developments in technology presented at the conference.

We were very pleased with the response received from our call for papers. The conference secretariat received more than 180 abstracts from prospective authors from various countries including Australia, New Zealand, Canada, Malaysia, Singapore, Japan, India, China, Finland, Egypt, Czech Republic and Iran. Members of the organizing committee selected 158 abstracts suitable for presentation at the AUPEC conference. Papers were reviewed by 60 independent reviewers from around the world. Finally, after a two-stage independent peer review process, 138 papers successfully passed the process and were accepted for presentation and discussion at the 27 technical sessions of the conference. All papers published in the conference proceedings for AUPEC 2002 have been fully refereed, having satisfied the requirements of this peer review process. My sincere thanks to all the reviewers for their time and effort toward the review process.

We are also very pleased to put forward four outstanding keynote speakers in the mornings of day one and day two of the conference.

Finally, I would like to thank all the members of the AUPEC 2002 organizing committee for their dedication and effort, without which the conference would not have been possible.

On behalf of the conference committee let me welcome you to AUPEC 2002, which is all set to be a rewarding experience in all respects.

Dr. A. Zahedi
Chairman - AUPEC 2002
29 September 2002

SYNCHRONOUS GENERATOR PARAMETER ESTIMATION BY GENETIC ALGORITHMS

R. Kiani Nezhad, R. Hooshmand, M. Parsa Moghaddam, G.A. Montazer

IMPACT OF HVDC COMMUTATION FAILURE ON TURBINE-GENERATOR SHAFT TORSIONAL TORQUES

S.O. Faried, S. Upadhyay, A.M. El-Serafi

PERFORMANCE ANALYSIS FOR INTERCOOLED, RECUPERATED AND REHEATED VARIABLE-SPEED MICRO TURBINE

J. Kaikko, J. Backman

DIRECT TORQUE CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR BASED ON FUZZY LOGIC

Dan Sun, Jian Guo Zhu, Yi Kang He

A NOVEL PI STATOR RESISTANCE ESTIMATOR FOR DIRECT TORQUE CONTROLLED PERMANENT MAGNET SYNCHRONOUS MACHINE DRIVE

L. Tang, M.F. Rahman and M. E. Haque

COMPENSATION OF THE EFFECTS OF THE FORWARD VOLTAGE DROP OF POWER SWITCHES ON DIRECT TORQUE CONTROLLED PM SYNCHRONOUS MACHINE DRIVE

L. Tang and M. F. Rahman

NONLINEAR MODELING OF A FOUR-PHASE SWITCHED RELUCTANCE MOTOR USING ANALYTICAL REPRESENTATIONS OF ITS MEASURED FLUX LINKAGE AND STATIC TORQUE

P. Chanchaoensook, M.F. Rahman and J. Lui

MODELING AND STEADY-STATE PERFORMANCE ANALYSIS OF A BRUSHLESS DOUBLY FED TWIN STATOR INDUCTION GENERATOR

Duro Basic, Jian Guo Zhu, and Gerard Boardman

NOVEL DYNAMIC MODEL FOR A THREE-PHASE INDUCTION MOTOR WITH IRON LOSS AND VARIABLE ROTOR PARAMETER CONSIDERATIONS

D. McKinnon, D. Seyoum and C. Grantham

INVESTIGATION OF THE EFFECTS OF SUPPLY VOLTAGE AND TEMPERATURE ON PARAMETERS IN A 3-PHASE INDUCTION MOTOR INCLUDING IRON LOSS

D. McKinnon, D. Seyoum and C. Grantham