Analysis and Design of a Cost Effective Converter for Switched Reluctance Motor Drives Using Component Sharing

Z. Zhang, N.C.Cheung, K.W.E. Cheng, X.D. Xue, J.K Lin, and Y.J Bao

Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong
E-mail: 09901316r@polyu.edu.hk

Abstract– In this paper, a new and cost effective converter, consisting of "half-bridge" IGBT modules and SCRs, for switched reluctance motor drives is proposed. The new method allows the sharing of the IGBT bridge to the switched reluctance motors winding, thus it significantly reduce by half of the component cost. The proposed converter topology is a variation of the conventional asymmetric bridge converter for switched reluctance motor drives. However, utilization of switch modules is enhanced considerably. The requirements of switched reluctance motor drives on converters and the operation of the proposed converter are analyzed and discussed. Furthermore, the simulation and experimental results confirm the feasibility of the proposed converter.

Keywords–Switched reluctance motor drives, Converter topology.

I. INTRODUCTION

The switched reluctance motors (SRMs) have a simple and robust structure with low inertia and direct drive capability, thus SRM drives are applicable to many industrial fields. However, the converter configuration of SRM drive is not standard. Numerous converters for SRM drives were proposed, developed and used in industrial applications [1]-[9]. Among those converters, the asymmetric bridge converter is the most popular and best-performed one, in which each phase branch consists of two discrete switching components and two freewheeling diodes, as shown in Fig 1. It is efficient for fault-tolerant and independent current control can be accomplished. However, the high switching component counts and the poor utilization is the main disadvantages of this topology. In this paper, a new and cost effective converter topology, which can be regarded as a variation of the asymmetric bridge topology, is developed. It inherits the advantages of the asymmetric bridge topology. Furthermore, it has higher utilization of switch devices. Thus, the proposed converter circuit can be designed with more compact configuration, smaller size and lower cost.

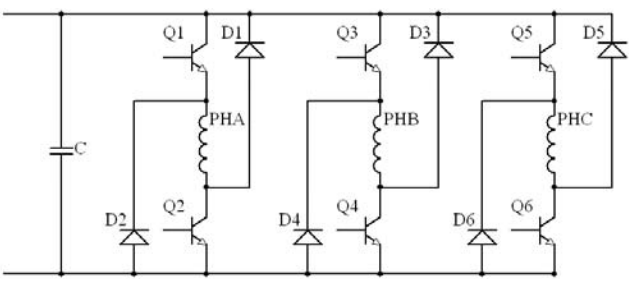


Fig. 1: Asymmetric bridge converter for three-phase SRM drives

This paper is organized as follows. In the section II, the principle of SRM drives and the requirements on converters will be described. The operation of the proposed converter topology will be analyzed in detail, in the section III. In the section IV the simulation results will be shown to verify the developed converter. Finally, the section V will give the conclusions.

II. OPERATION OF SRM DRIVES AND REQUIREMENTS TO CONVERTER

The structure of an 8/6 switched reluctance motor is shown in Fig 2. There are no windings or magnets on the rotor, thus SRM is a doubly salient and singly excited motor. The operation of an SRM drive is according to the minimum reluctance principle, which means that the rotor tries to align its poles with the position with minimum reluctance for the magnetic circuit. A position sensor is required to synchronize the stator conduction sequence by determining the rotor position. Also, the torque of an SRM drive is related to the rotor position and the inductance or flux linkage. The typical flux linkage and inductance characteristics in a four-phase SRM drive are shown in Fig 3.

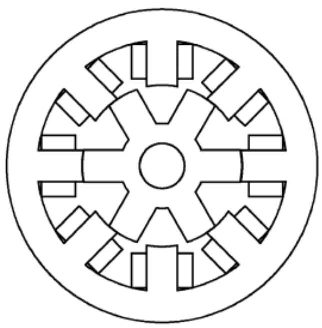
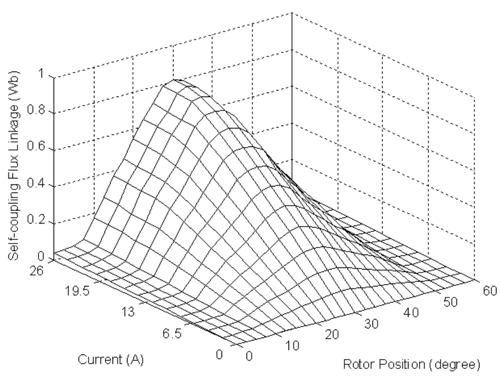
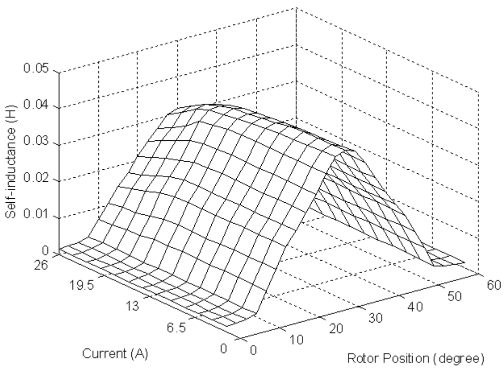


Fig. 2: Structure of 8/6 SRM



(a) Flux linkage characteristics



(b) Inductance characteristics

Fig. 3: Typical magnetic characteristics in four-phase SRM drives

Another important feature of an SRM drive is that the mutual coupling between phases can be neglected. It makes the independent current control possible. Meanwhile, the lack of mutual coupling brings about a problem of dealing with the stored magnetic field energy. An additional path has to be provided for the magnetic field energy during phase commutation. Otherwise, it will result in excessive voltage across the windings and hence on the power switches leading to their failure [10].

Neglecting the mutual coupling between phase windings and regarding all components as ideal ones, the operation of an SRM drive can be described as [11]

$$\frac{d\psi}{d\theta} = \frac{1}{\omega_r}(V_{ph} - r_{ph} i) \tag{1}$$

$$\psi(\theta, i) = L(\theta, i) i \tag{2}$$

$$V_{ph} = \begin{cases} V_{dc} & \text{(charging)} \\ 0 & \text{(freewheeling)} \\ -V_{dc} & \text{(dsicharging)} \end{cases} \tag{3}$$

$$T_{ph} = \frac{\partial W_{co}}{\partial \theta} \tag{4}$$

where ψ denotes the phase flux linkage, θ denotes the rotor position angle, ωr denotes the motor speed, Vph denotes the voltage applied to the phase winding, rph denotes the phase resistance, i denotes the phase current, L denotes the phase inductance, Vdc denotes the DC link voltage, Tph denotes the torque produced by one phase winding, and Wco denotes the co-energy.

The principle of the above operation of SRM drives gives some requirements on converters of SRM drives. First, the converter could work well in a wide speed range. That means that PWM current control can be used at low speed, and magnetizing voltage can be sufficient to build the flux in phase winding at high speed. Secondly, a high enough demagnetizing voltage is required to shorten the current tail, thus decreasing negative torque. Third, the efficiency is also considered as an important parameter. A main reason of low efficiency for converter is the disability to apply zero voltage on the phase winding during current conduction. Such an operational constraint increases the circulation of energy between the machine and dc link, resulting in higher losses and reduced system efficiency. Finally, the cost of converter has to be considered, besides the performance aspects presented above.

III. PROPOSED CONVERTER

1. Proposed converter topology

Half-bridge IGBT modules are the popular choice to build asymmetric bridge converters and many other converters in industrial applications, instead of discrete IGBT modules. Because the diodes for freewheeling are necessary even there are build-in diodes in the discrete IGBT modules. It makes the circuit less trustworthy and more complicated. Fig 4 illustrates the phase branch with half-bridge modules for typical SRM converters. It can be seen that each phase branch needs two half-bridge switch modules. Consequently, a four-phase SRM drive requires eight half-bridge switch modules. Therefore, the use of half-bridge switch modules in asymmetric bridge converter brings low utilization and high count of switch devices.

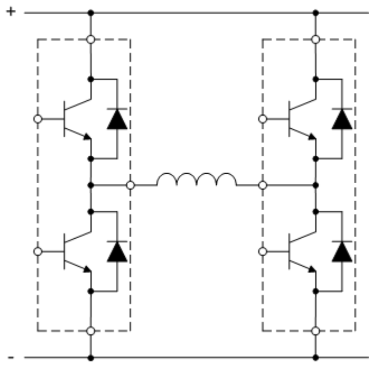


Fig. 4: Phase branch using half-bridge switch modules

To figure out the problem, a cost effective converter for SRM drives is developed in this paper. Fig 5 illustrates the proposed converter circuit for four-phase SRM drives. It can be observed that the proposed converter needs four half-bridge IGBT modules and four SCRs, in comparative to eight half-bridge IGBT modules in asymmetric bridge converters. On the other hand, each phase is controlled by different switching devices. It is helpful to reduce the temperature rise and extend the lifetime of IGBT components.

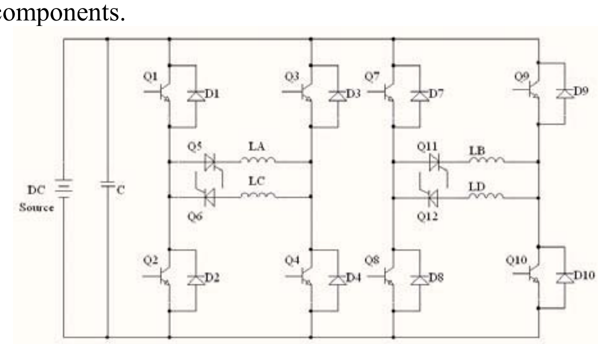
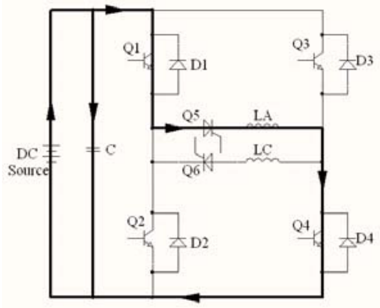


Fig. 5: Proposed Topology for four-phase SRM drives

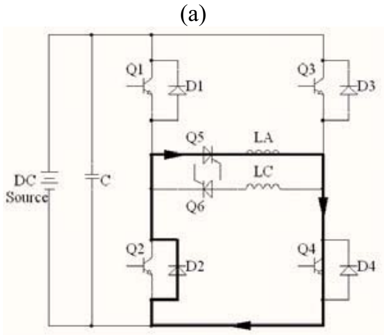
According to the principle of operation of SRM drives, the energy conversion process may occur simultaneously in two adjacent phases, in order to acquire high starting torque and low torque ripple. This mode of operation may cause a current overlap [1]. In the developed converter, therefore, alternate phases are grouped together, such as Phase A and Phase C, or Phase B and Phase D, shown in Fig 5. This allows independent current control of each phase with overlapping currents not exceeding one phase cycle duration.

2. Operation of proposed converter

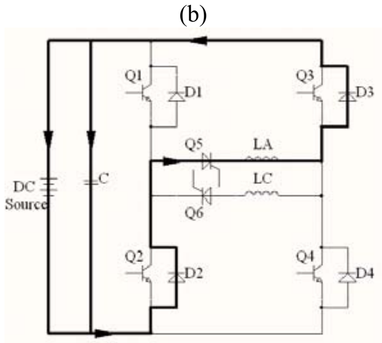
As for the developed converter, the operation of each phase includes three modes, which are named as charging, freewheeling and discharging, respectively. For the sake of simplicity of the illustration, the operation of two phases in a group is analyzed in the following discussion. Fig 6 and Fig 7 depict the operations of phase A and Phase C in a group, respectively. The typical gate signals and corresponding current profile are shown in Fig 8.



(a)

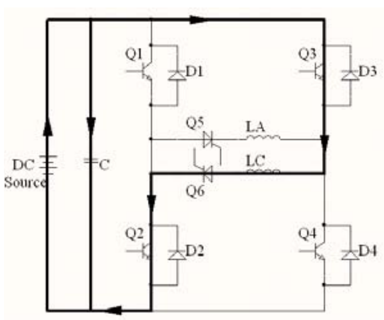


(b)

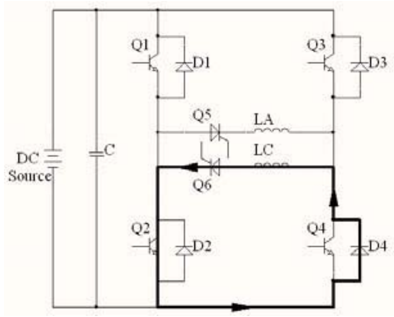


(c)

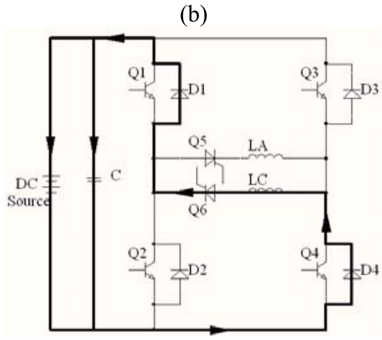
Fig. 6: Operation modes of Phase A



(a)



(b)



(c)

Fig. 7: Modes of Operation of Phase C

Mode 1: Charging

Referring to Fig 6a, if the switching devices Q1, Q4, and Q5 are turned on, the DC link voltage is then applied to Phase A and the current rises rapidly in the phase winding. In the same way, seeing Fig 7a, if the switching devices Q2, Q3, and Q6 are switched on, Phase C is charged through the switches Q2, Q3 and Q6.

Mode 2: Freewheeling

It can be seen from Fig 6b, if the switch Q1 is turned off and the switches Q4 and Q5 are still on, then current circulates though the switches Q4, Q5 and forward-biased diode D2. In this mode, there is no energy transfer between phase winding and DC source. Similarly, referring to Fig 7b, Phase C freewheels through switches Q2 and Q6 and the diode D4 when the switch Q3 is turned off and the switches Q2 and Q6 are still on.

Mode 3: Discharging

As is shown in Fig 6c, the switches Q1 and Q4 are turned off and the switch Q5 is still turned on in this mode. Consequently, Phase A discharges to the DC link capacitor, through D2, D3 and Q5. In the same way, from Fig 7c, Phase C discharges to the DC link capacitor through the switch Q6 and the diodes D1 and D4 if the switches Q2 and Q3 are switched off and the switch Q6 is still on.

3. Control methods

From the above analysis and discussion, it can be seen that three conventional control methods for typical asymmetrical bridge converters of SRM drives can be realized in the proposed converter. They are the single-pulse voltage control, the hysteresis current control and the PWM voltage control. The single-pulse voltage control includes the charging and discharging modes. The hysteresis current control consists of the charging, freewheeling and discharging modes. The PWM voltage control is composed of the charging, freewheeling and discharging modes.

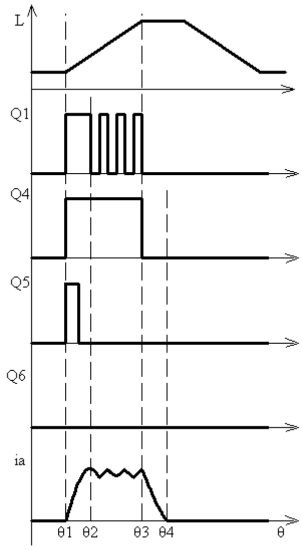
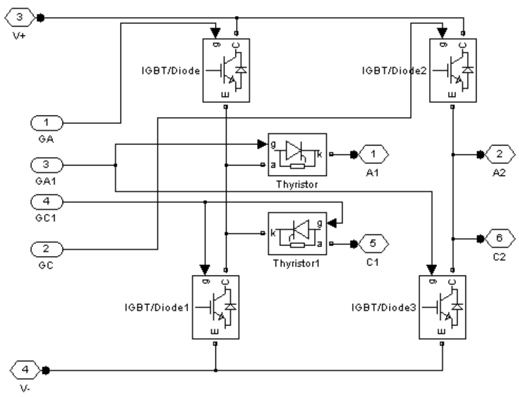


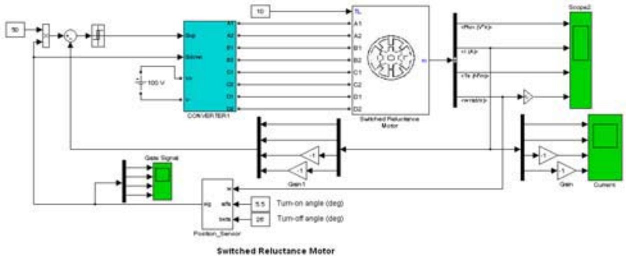
Fig. 8: Typical gate signals and current waveform

IV. VERIFICATION

In order to verify the proposed converter for SRM drives, the simulation based on MATLAB/SIMULINK was carried out. Fig 9 shows the developed simulation block diagram in MATLAB/SIMULINK. The simulation results are shown in Fig 10. In Fig 10a and Fig 10b, the gate signals of Phase A and C are illustrated, and the corresponding current profiles of Phase A and C are depicted in Fig 10c and Fig 10d, respectively. As for Phase A, for example, the phase current rises rapidly when the switches Q1, Q4 and Q5 are turned on firstly. Then, the switch Q1 is turned on or off during the hysteresis current control. The SCR Q5 shares the gate signal with the switch Q4 and both switches are always turned on during the hysteresis current control to provide the path for freewheeling. Finally, the switches Q1 and Q4 are switched off when the conduction angle reaches the specified value. The energy stored in Phase A discharges to the DC link capacitor through the switch Q5 and the diodes D2 and D3, and the phase current declines to zero fast. The measured phase current waveform can be seen in Fig. 11. It can be observed that the simulation, measured and theoretical current waveforms demonstrates that the proposed converter for SRM drives can be used to implement the hysteresis current control. In the same way, the single-pulse voltage control and the PWM voltage control are also accomplished in the proposed converter.

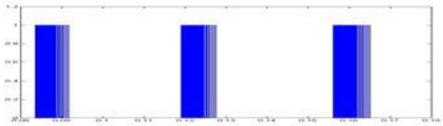


(a) Converter circuit

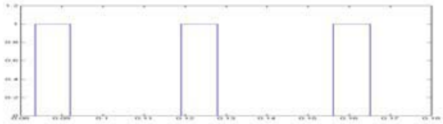


(b) SRM drives

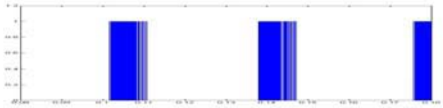
Fig. 9: Block diagram in Matlab/Simulink



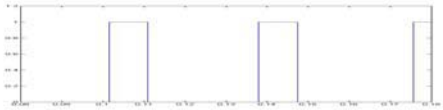
(a) Gate signal of switch Q1 for Phase A



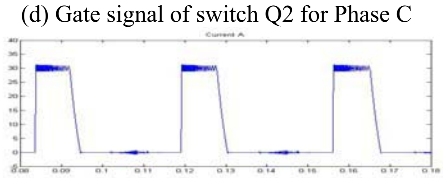
(b) Gate signal of switch Q4 for Phase A



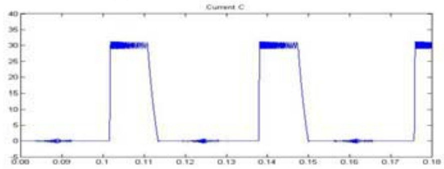
(c) Gate signal of switch Q3 for Phase C



(d) Gate signal of switch Q2 for Phase C



(e) Current of Phase A



(f) Current of Phase C

Fig. 10: Simulation waveforms

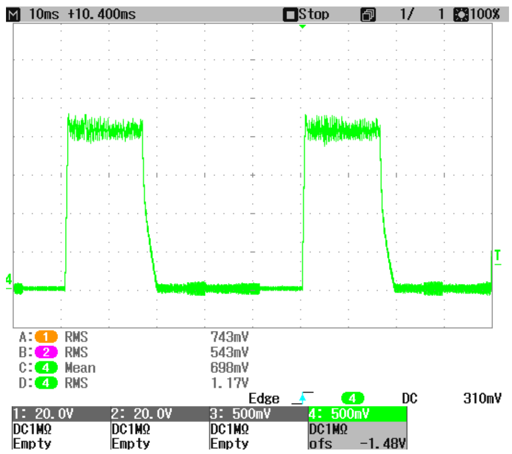


Fig. 11: Measured current profiles

From the analysis and simulation, therefore, the salient merits of the proposed converter can be summarized as: (1)

It has the higher utilization of half-bridge IGBT modules compared to traditional asymmetric bridge converters with half-bridge modules; (2) The charging, freewheeling and discharging modes can be accomplished; (3) The single-pulse voltage, hysteresis current and PWM voltage controls can be implemented; (4) The converter is capable of the positive, negative and zero voltage output capability; and (5) One current transducer is required for a group, which means that only m current transducers are needed for a 2m-phase SRM drive. The drawbacks of the proposed converter are that (1) It requires an even number of machine phases, which restricts its applicability in practice; (2) The driving circuit for converter becomes more complicated, because of the addition of SCRs; and (3) A SCR is always in the current conduction path, thus increasing the losses in the converter.

V. Conclusion

In this paper, a new and cost effective converter topology for switched reluctance motor drives has been proposed. Compared to the conventional asymmetric bridge converter, the proposed one using half-bridge switch modules is more compact and has higher utilization of power switches and lower cost, without degrading in performance. The developed converter has three conventional operating modes that are charging, freewheeling and discharging modes. Hence, the single-pulse voltage control, the hysteresis current control and the PWM voltage control are implemented in the developed converter. The simulation in Matlab/Simulink has demonstrated the proposed converter. As a result, this study provides the valuable converter for SRM drives in industrial applications. The proposed new method arrangement allows the reduction in circuit components by nearly half and mainly the main performance of the motor drive. The method can be applied for all the even number of phases of the switched reluctance motor drive.

Acknowledgment

The authors grateful acknowledge the financial support of Innovation and Technology Fund of Hong Kong SAR under the project ITP/025/09AP.

References

[1] Slobodan Vukosavic, Victor R.Stefanovic, "SRM inverter topologies: A comparative evaluation," IEEE Transactions on industry applications, Vol.27, No.6, pp.1034-1047, 1991.

[2] R. Krishnan and P. Materu, "Design of a Single-Switch-Per-Phase Converter for Switched Reluctance Motor Drives", IEEE Transactions on Industrial Electronics, vol. 37, no.6, pp469-476, 1990.

[3] R.M. Davis and R.J. Blake, "Inverter Drive for Switched Reluctance Motor Circuits and Component Ratings", IEE Proc., pp. 126-136, 1981.

[4] W. A. Harris, "Switched Reluctance Motor Control Circuit with Energy Recovery Capability", U.S. Patent No. 5,075,610, Dec. 24, 1991.

[5] C. Pollock and B.W. Williams, "Power Converter Circuits for Switched Reluctance with the Minimum Number of Switches", IEE Proc., vol. 137, Pt. B, no. 6, pp. 373-384, 1990.

[6] M. Ehsani, J.T. Bass, T.J.E. Miller, and R. L. Steigerwald, "Development of a Unipolar Converter for Variable Reluctance Motor Drives", IEEE Transactions on Industry Applications, vol. 23, no. 3, pp. 545-553, 1987.

[7] P.K. Sood, "Power Converter for a Switched Reluctance Motor", U.S. Patent No. 5,115,181, May 9, 1992.

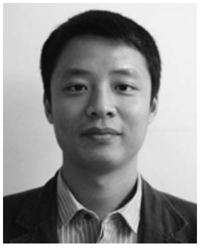
[8] P. Pillay, R. Samudio, M. Ahmed, and R. Patel, "A Chopper Controlled SRM Drives for Reduced Acoustic Noise and Improved Ride through Capability Using Super Capacitors", IEEE Transactions on Industry Applications, vol. 31, no. 5, pp. 1029-1037, 1995.

[9] C. Pollock and B.W. Williams, "A Unipolar Converter for a Switched Reluctance Motor", IEEE Transactions on Industry Applications, vol. 26, no. 2, pp. 222-228, 1990.

[10] R. Krishnan, Switched reluctance motor drives: modeling, simulation, analysis, design and applications, CRC Press, 2001.

[11] X. D. Xue, K. W. E. Cheng, and S. L. Ho, "Simulation of Switched Reluctance Motor Drives Using Two-Dimensional Bicubic Spline", IEEE Transactions on Energy Conversion, Vol. 17, No. 4, December 2002, pp471-477.

Biography



Zhu Zhang obtained his MSc degree from South China University of Technology, Guangzhou, China, in 2004. He is currently working toward the Ph.D. degree at the Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong. His research interests include motor design and power electronics.

Norbert C. Cheung received the B.Sc. degree from the University of London, London, U.K., in 1981, the M.Sc. degree from the University of Hong Kong, Kowloon, Hong Kong, in 1987, and the Ph.D. degree from the University of New South Wales, Kensington, NSW, Australia, in 1996.
He is currently working in the Department of Electrical Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong. His research interests are motion control, actuators design, and power electronic drives.

K.W.E.Cheng obtained his BSc and PhD degrees both from the University of Bath in 1987 and 1990 respectively. Before he joined the Hong Kong Polytechnic University in 1997, he was with Lucas Aerospace, United Kingdom as a Principal Engineer.
He received the IEE Sebastian Z De Ferranti Premium Award (1995), outstanding consultancy award (2000), Faculty Merit award for best teaching (2003) from the University and Silver award of the 16th National Exhibition of Inventions. He has published over 200 papers and 7 books. He is now the professor and director of Power Electronics Research Centre.

X. D. Xue received the B.Eng. degree from Hefei University of Technology, Hefei, China, in 1984, the M.Eng. degree from Tianjin University, Tianjin, China, in 1987, and the Ph.D. degree from the Hong Kong Polytechnic University, Kowloon, Hong Kong, in 2004, all in electrical engineering.
He was a Lecturer and an Associate Professor with the Department of Electrical Engineering, Tianjin University, from 1987 to 2001, where he was engaged in teaching and research. He is currently a Research Fellow with the Department of Electrical Engineering, Hong Kong Polytechnic University. He is the author of over

70 published papers. His research interests include electrical machines, electrical drives, and power electronics. His current research is focused on electric machines and drives applied to electric vehicles and wind-power generations.

J. K. Lin is currently working toward the Ph.D.degree.
He has been a Research Assistant with the Department of Electrical Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong. His research interests include power electronics.

Y. J. Bao obtained his Bachelor's degrees in automatic department from Northeastern University, Qinhuangdao, China, in 2000. He received his Master's degree in automatic department from Shanghai University, Shanghai, China, in 2003. Currently, he is an Research Associate in the department of Electrical Engineering at the Hong Kong Polytechnic University, Hong Kong, China. His research interests include motor & generator control and drive.