Unipolar SPWM HF Link Soft Switching DC/AC Converter

Chee Lim NGE and Zainal SALAM

Abstract—**This paper proposes a modified natural commutated control HF link inverter topology that consists of a center-tapped transformer and three bidirectional switching arms on the transformer secondary side. The topology is able to simultaneously utilize unipolar SPWM control scheme and natural commutation technique. The conversion efficiency is inherently high due to the existence of freewheeling periods per switching cycle and the utilization of zero current switching (ZCS) and zero voltage switching (ZVS) operation. Moreover, with minimum number of power switches at cycloconverter stage, the conduction loss can be further reduced. The operating principles of the proposed topology and control scheme are discussed and verified by simulation results.**

Index Terms— **Bidirectional, HF transformer, Inverter, Power electronics, Pulse width modulation.**

I. Introduction

NOWADAYS, power converters tend to operate at higher frequency, in order to reduce the size of reactive components and increase the power density. Fig. 1 shows the conventional high switching frequency push-pull PWM inverter, which has a small low pass filter. Although the topology is simple, it requires a large isolation transformer because the waveform applied on the winding of the transformer consists of low frequency harmonics.

In order to reduce the size and weight of the transformer, high-frequency (HF) link power conversion systems have been examined [1-3]. This type of converter normally has two conversion stages. There are two main circuits for the HF link inverter; namely the dc-dc type and the cycloconverter type. HF link inverters with cycloconverter at the output stage of the system have a merit of bidirectional power flow. However, HF link cycloconverter type inverters that employ SPWM technique to reduce the output voltage harmonic components, suffer from inherent problem of voltage surge across transformer secondary side main switches. It is due to forced interruption of continuous current flow in leakage inductances of HF transformer by cycloconverter stage self

This project was supported by the Intensification of Research in Priority Areas (IRPA) grant from the Ministry of Science, Technology and the Environment, Malaysia (MOSTE).

The authors are with the Department of Energy Conversion, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia.

0-7803-8724-4/04/$20.00 ©2004 IEEE.

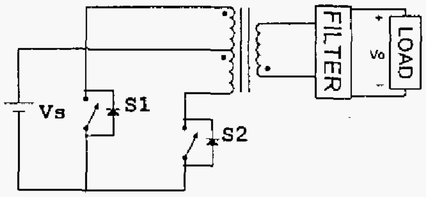

Fig. 1. Conventional push-pull inverter.

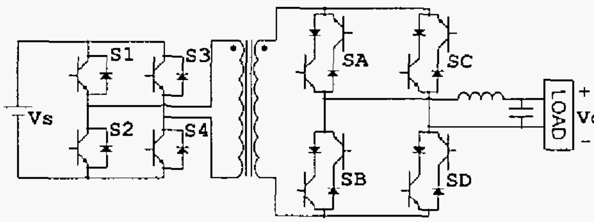

Fig. 2. Natural commutated phase angle control HF link inverter.

turn-off devices. To solve this problem, several voltage clamp circuits have been developed [4-5].

Fig. 2 shows the widely known phase angle control HF link dc/ac converter that utilizes natural commutation technique to avoid forced interruption of current flow in leakage inductances and results in a reduced voltage spike [6]. This non-resonant approach has the advantage of low circuit complexity and no increased device voltage or current ratings. The topology consists of four pairs of bidirectional switching arms at the cycloconverter stage. This converter system must employ bipolar SPWM switching scheme to avoid occurrence of voltage surge.

The authors proposed an alternative natural commutated control HF link inverter topology that consists of a center-tapped transformer and three bidirectional switching arms on transformer secondary side. This topology is able to simultaneously utilize unipolar SPWM switching scheme and natural commutation technique.

II. Operating Principles

A. Circuit Configuration

The proposed circuit configuration is shown in Fig. 3. It is a two-stage cycloconverter type HF link dc/ac converter with single-phase output stage. This circuit topology enables bidirectional power flow. Therefore, it is suitable for renewable energy source systems. The primary side of the HF transformer terminals is connected to the voltage source

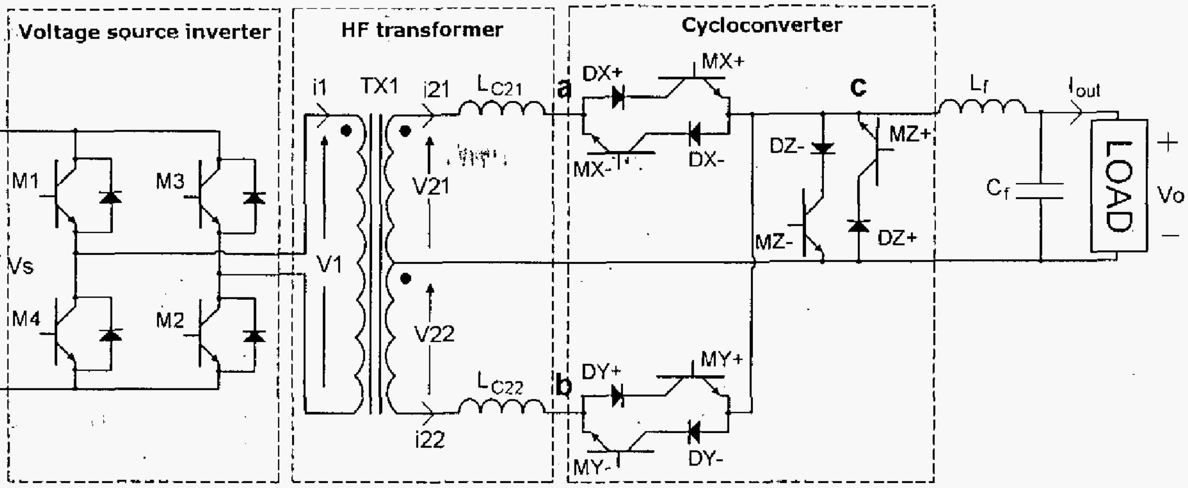

Fig. 3. Proposed natural commutated unipolar SPWM control HF link Dc/Ac converter

inverter. The bridge inverter generates square wave constant frequency output. The waveform consists of only high frequency harmonics so that a small sized high frequency transformer is allowed. The inverter operates with ZVS condition because of the existence of natural commutation phenomena at cycloconverter stage.

The cycloconverter stage has three bidirectional switching arms. The first switching arm *X* consists of transistors *MX+*, *MX–* and diodes DX+, DX-. The second switching arm *Y* consists of transistors *MY+*, *MY–* and diodes *DY+*, *DY–*. These two switch sets are the powering switching arms that transfer instantaneous power from the dc voltage source to the load. The third switching arm *Z*, which consists of transistors *MZ+*, *MZ–* and diodes *DZ+*, *DZ–* provides freewheeling path for the output current when the output voltage is clamped to zero. For the control of secondary cycloconverter stage, edge aligned unipolar PWM switching scheme is applied. Since the converter uses self turn-off devices to operate in natural commutation mode, overlap periods t_{c1} and t_{c2} are added to the control pulse pattern. The utilization of natural commutation technique allows total soft-switched operation at the inverter and cycloconverter stage. The soft switching mechanism and commutation phenomena are discussed in detail later.

B. Control Signal Timings

Fig. 4 shows the basic control signal timings for both inverter and cycloconverter stages. The control signals are synchronized to the same reference oscillator. At the inverter stage dead time t_d is added to every switching transition to avoid cross conduction. For the cycloconverter stage, the switching signals are obtained by comparing the modulating waveform with the saw-tooth carrier waveform. Switching arm *X* turns on when the output voltage follows HF transformer output voltage, while switching arm *Y* turns on when the output voltage reverses HF transformer output voltage. Overlap period t_{c1} is set at switching transition from freewheeling switching arm to powering switching arms while t_{c2} is set at switching transition from powering switching to freewheeling switching arm. The direction of output current flow determines the switching of "+" and "–" groups at cycloconverter stage.

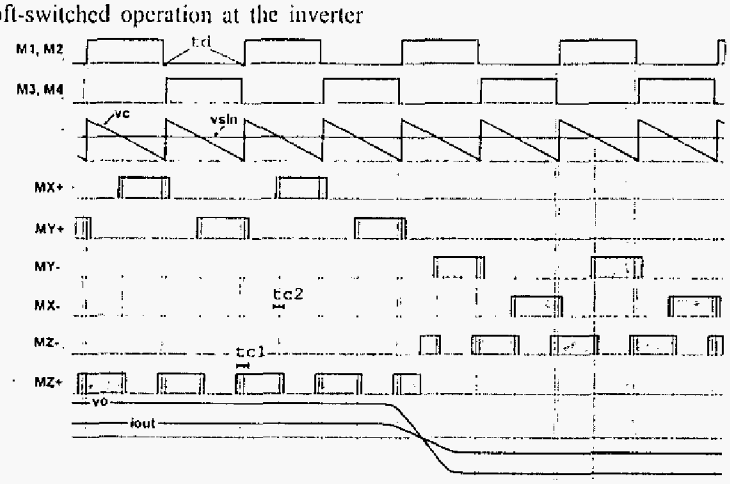

Fig. 4. Control signal timings

C. Principles of Soft Switching Operation

The ZCS operation and the natural commutation mechanism at cycloconverter stage during overlap period t_{c1} are explained in Fig. 6. Assume positive voltage across transformer primary side winding with output voltage v_o and output current I_{out} positive. Immediately prior to *MX+* turns on, the load current freewheels though *DZ+* and *MZ+*. When *MX+* turns on at zero current, *DX+* is forward biased and is also turned on. Considering commutation from switching arm *Z* to *X* between t_1 and t_2, and that the load current I_{out} is assumed constant, the following equations are written:

$$v_{21} = L_{c21}\frac{di_{21}}{dt} + v_a \tag{1}$$

$$i_{21} + i_{MZ+} = I_{out} \tag{2}$$

That is,

$$\frac{di_{21}}{dt} + \frac{di_{MZ+}}{dt} = 0 \tag{3}$$

Given that at time t_1,

$$v_{21}(t_1) = V_p = \frac{V_s}{\left(N1/N2\right)} \tag{4}$$

where *N1/N2* is transformer turns ratio. Also,

$$v_a(t_1) = 0 \tag{5}$$

Combining equations (1) and (2) yields

$$\frac{di_{21}}{dt} = -\frac{di_{MZ+}}{dt} = +\frac{V_p}{L_{C1}} \tag{6}$$

When freewheeling current i_{MZ+} reaches zero, commutation process is completed. At time t_2 transistor *MZ+* is turned off at zero current, and results in no voltage surge. From t_2 onwards, voltage at point *c* rises to $+V_p$ while instantaneous power transfers from dc source to the load.

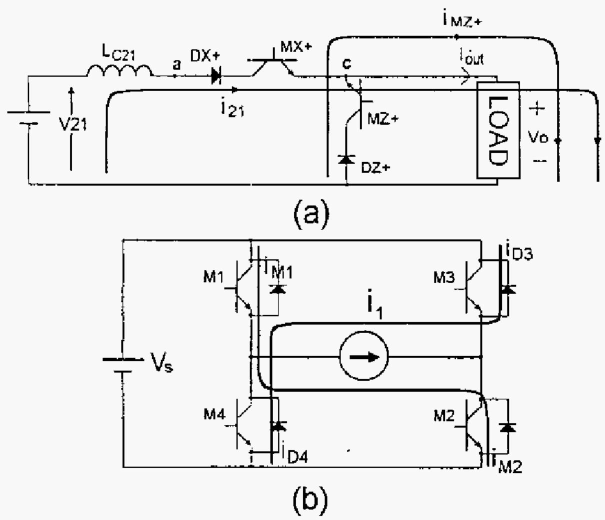

Fig. 5. Current flow path for a) natural commutation b) forced commutation

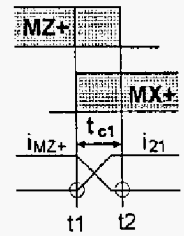

Fig. 6. Principle of ZCS operation during overlap period t_{c1}

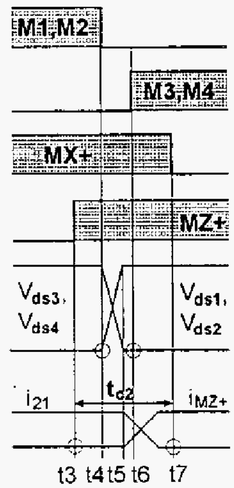

Fig. 7. Principle of ZVS and ZCS operation during overlap period t_{c2}

The ZVS operation at inverter stage, ZCS operation and the natural commutation mechanism at cycloconverter stage during overlap period t_{c2} are explained in detail in Fig. 7.

Immediately before *MZ+* turns on, instantaneous power transfers from dc source to the load through transistors *M1*, *M2*, and switching arm *X*. At time t_3, *MZ+* is turned on at zero current, since that *DZ+* is reversed biased and voltage at point *c* is clamped to $+V_p$. *M1* and *M2* turn off at zero voltage at time t_4, forcing i_1 to commutate from *M1* and *M2* to anti-parallel diodes of *M3* and *M4*. As a result, output capacitances of *M3* and *M4* are discharged; voltages V_{ds3} and V_{ds4} fall to zero while V_{ds1} and V_{ds2} rise to $+Vs$. At time t_5, v_1 is inverted to $-Vs$ so that v_{21} equals to $-V_p$. *DZ+* is forward biased and voltage at point *c* is held to zero. At time t_6, *M3* and *M4* turn on at zero voltage. Between time t_4 and t_6, is dead time t_d, which is set to avoid cross conduction and also enable ZVS operation. Load current I_{out} commutate from switching arm *X* to *Z* between t_5 and t_7 with the following equation:

$$\frac{di_{21}}{dt} = -\frac{di_{MZ+}}{dt} = -\frac{V_p}{L_{C1}} \tag{7}$$

When transformer current i_{C21} reaches zero, commutation process is completed. At time t_7 transistor *MX+* is turned off at zero current, and results in no voltage surge. From t_7 onwards, load current I_{out} freewheels through switching arm *Z* while instantaneous power is supplied from *LC* filter to the load.

Since the converter control signals are periodical symmetry, soft switching operations and natural commutation mechanisms during switching transitions between switching arms Y and Z are similar to operations as explained above. Therefore, every switching operation at the both conversion stages is performed with soft switching manner.

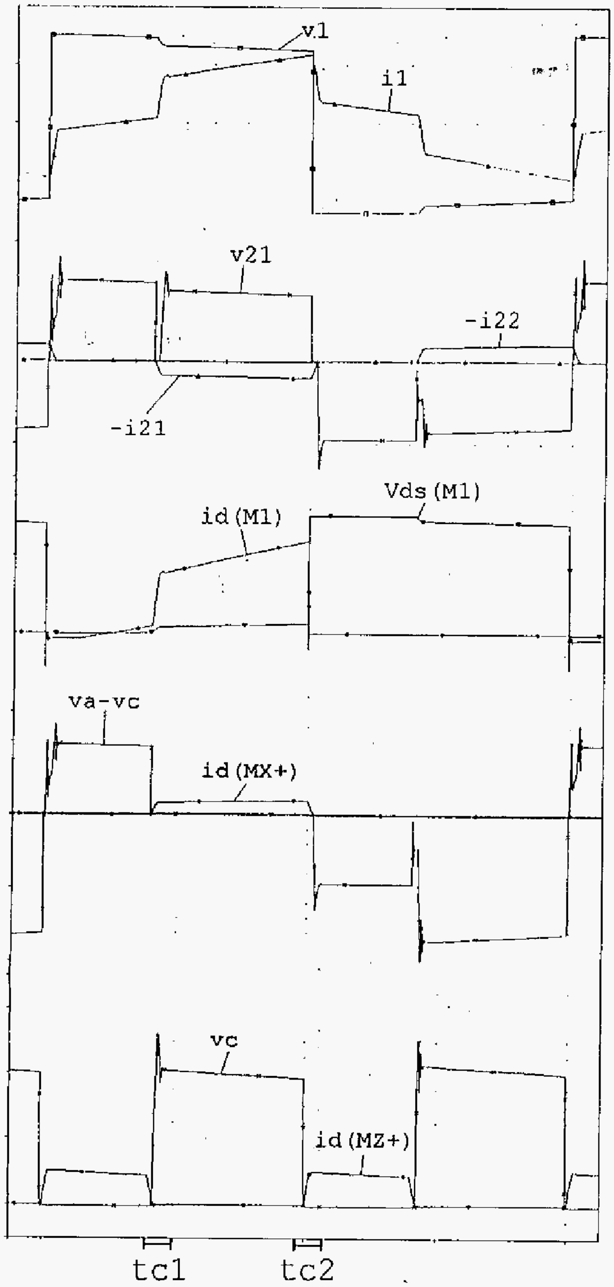

Fig. 8. Simulation operating waveforms with duty ratio $D = 50\%$

III. Simulation Results

Fig. 8 shows the operating waveforms from SPICE simulations for the proposed topology. Theoretical analyses for commutation period t_{c1} and t_{c2} are verified in the expanded waveforms shown in Fig. 9 and Fig. 10. Soft switching operations and commutation mechanisms at both stages can be clearly observed. The simulation results show ringing waveforms in cycloconverter stage during diode turn off transitions. The waveforms are mainly due to diode reverse recovery characteristics and can be suppressed by using RC snubber circuits. SPICE simulation parameters are given in Table I.

TABLE I
Parameters of SPICE Simulation

DC input voltage, V_S		150 V
Switching frequency, f_{sw}		25 kHz
Filter Inductor, L		5 mH
Filter capacitance, C		500 nF
Transformer turns ratio, $N1/N2$		3 : 8
Transformer secondary side leakage inductance		40 μH
Rated resistive load, R		50 Ω
Commutation period	t_{c1}	4 μs
	t_{c2}	4.2 μs
Delay time, t_d		0.4 μs

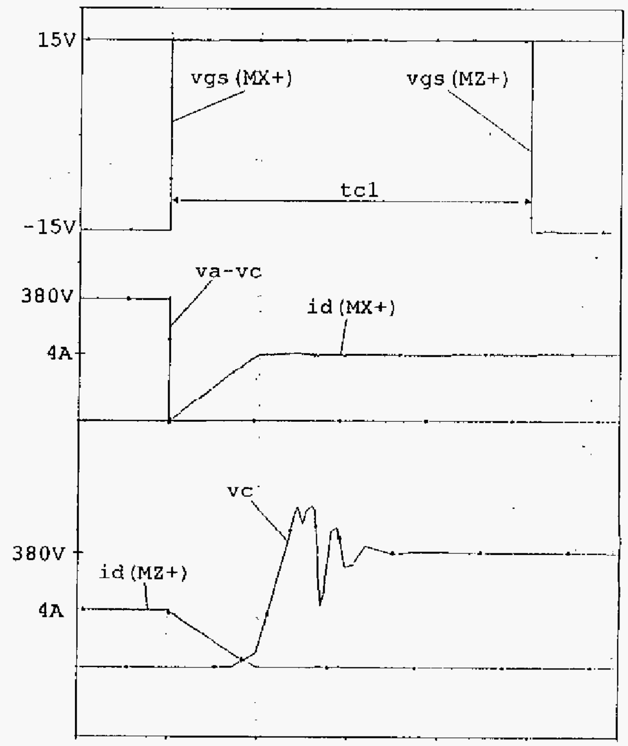

Fig. 9. Expanded waveforms of commutation period t_{c1}

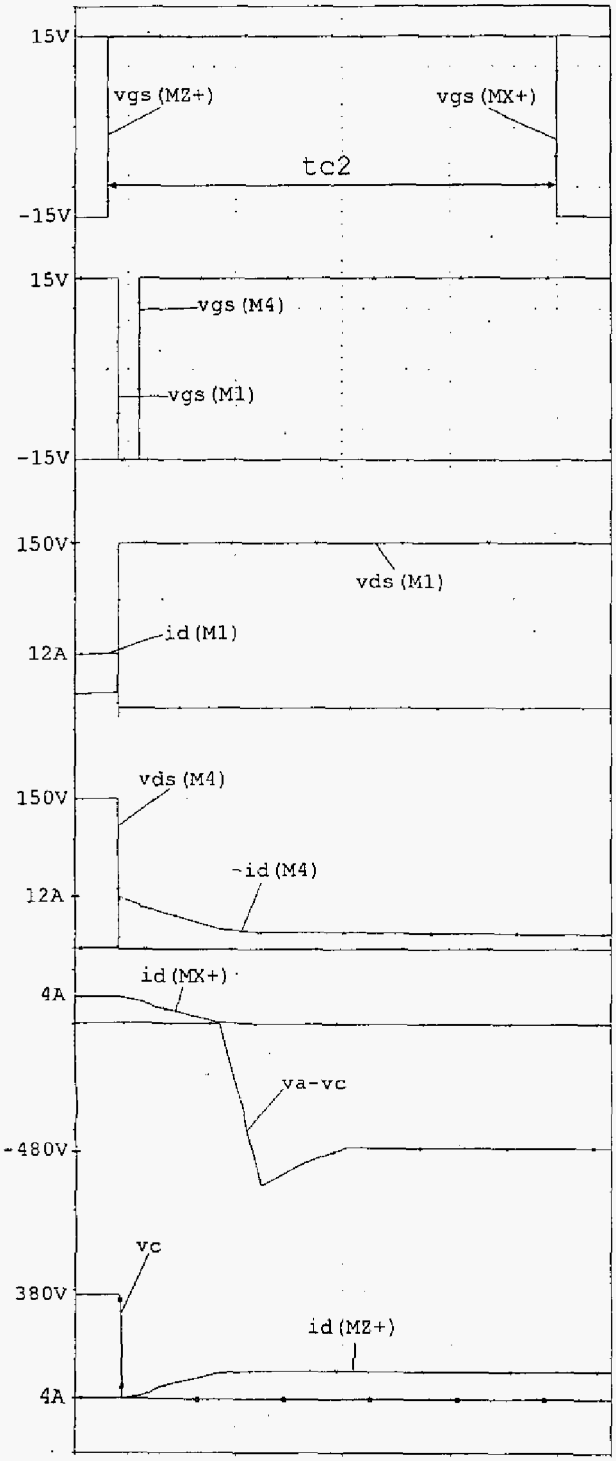

Fig. 10. Expanded waveforms of commutation period t_{c2}

IV. Conclusion

In this paper, a modified natural commutated control HF link inverter topology that consists of a center-tapped transformer and three bidirectional switching arms on the transformer secondary side has been proposed. The main features that improves the power conversion efficiency are summarized as follows:

1. The topology consists of only three bidirectional switching arms to perform natural commutation unipolar SPWM switching scheme. As a result, the conduction loss is reduced.
2. The proposed switching scheme results in the existence of two freewheeling periods per switching cycle.
3. Both inverter and cycloconverter stage operate at soft switching operation.

The proposed topology provides i) electrical isolation with HF transformer, ii) bidirectional power flow, and iii) high efficiency power conversion.

V. References

[1] K. Harada, H. Sakamoto, and M. Shoyama, "Phase-controlled DC-AC converter with high-frequency switching," *IEEE Trans. Power Electronics*, vol. 3, pp. 406-411, Oct. 1988.

[2] T. Kawabata, K. Honjo, N. Sashida, K. Sanada, and M. Koyama, "High frequency link DC/AC converter with PWM cycloconverter," in *Proc. IEEE IAS Conf., 1990*, pp. 1119–1124, Oct. 1990.

[3] P. K. Sood, T. A. Lipo, and I. G. Hansen, "A versatile power converter for high-frequency link systems," *IEEE Trans. Power Electronics*, vol. 3, no. 4, pp. 383 - 390, Oct. 1988

[4] H. Fujimoto, K. Kuroki, T. Kagotani, and H. Kidoguchi, "Photovoltaic inverter with a novel cycloconverter for interconnection to a utility line," in *Proc. IEEE IAS'95 Conf.*, vol. 3, pp. 2461–2467, Oct. 1995

[5] I. Yamato, N. Tokunaga, Y. Matsuda, Y. Suzuki, and H. Amano, "High frequency link dc-ac converter for UPS with a new voltage clamper," in *IEEE PESC*, pp. 749-756, June 1990.

[6] M. Matsui, M. Nagai, M. Mochizuki, and A. Nabae, "High-frequency link dc/ac converter with suppressed voltage clamper circuits – naturally commutated phase angle control with self turn-off devices," *IEEE Trans. I.A.*, vol. 32, no. 2, Mar./Apr. 1996.

VI. Biographies

Chee Lim Nge was born in Penang, Malaysia, on July 28, 1980. He received the B.Sc. degree from UTM in 2003, in electrical engineering. He is currently working towards the M.E.E. degree at the Department of Energy Conversion, Faculty of Electrical Engineering, UTM. His research interests include high-frequency soft-switching converters and automotive electronic ballast.

Zainal Salam was born in Seremban, Malaysia in 1963. He received his secondary education from Victoria Institution, Kuala Lumpur. He obtained his B.Sc., M.E.E. and Ph.D. from the University of California, UTM and University of Birmingham, UK, in 1985, 1989 and 1997, respectively. He has been a lecturer at UTM for 18 years and is currently the Head Department of Energy Conversion Department. He had been working in several researches and consulting works with SIRIM and GBT on battery powered converters. Currently, he is involved in several IRPA projects in the area of renewable energy, power electronics and machine control.