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Cross-Connected Source Multilevel Inverter for Active Power Filtering Using Unified Constant-Frequency Integration Control

Hairol Jaffar[1], Naziha Ahmad Azli[2]
[1,2]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia

Article Info	ABSTRACT
	This paper proposes an Active Power Filter (APF) system which utilizes a five-level nonconventional Cross-Connected Source Multilevel Inverter (CCSMI) with a modified Unified Constant-Frequency Integration (UCI) control. The CCSMI consists of six power switches which can produce five output voltage levels. With the use of the CCSMI, the parts count is reduced with equivalent or better performance compared to the use of conventional multilevel inverters. The capability of the proposed system is tested using three types of nonlinear loads with different characteristics. The APF system is simulated under steady-state condition using MATLAB/Simulink. The results obtained show improvement in the supply current Total Harmonic Distortion (THD) with room for enhancement, using the proposed APF system.

Corresponding Author:

Naziha Ahmad Azli,
Faculty of Electrical Engineering,
Universiti Teknologi Malaysia,
UTM Skudai, 80310 Johor Bahru, Johor, Malaysia.
Email: naziha@fke.utm.my

1.   INTRODUCTION

Nowadays, the burden of power electronics-based equipment which presents the characteristics of nonlinear loads is inescapable. Power electronics devices are known to produce harmonics or cause distortion in the supply current although the introduction of various control methods in the power electronics system may increase its efficiency and reliability [1]. To overcome the harmonic-related problems, active power filters (APFs) have been introduced [2] and chosen for use in the utility and industrial power systems [3]. APFs have been introduced to replace the conventional passive filters (PFs) in many applications due to the drawbacks of passive filters when operating with nonlinear loads. The basic concept of an APF involves the injection of current with the same amplitude and in the reverse order of the load current harmonics into the power system. As a result, the APFs can effectively compensate both reactive power and harmonic currents drawn by nonlinear loads.

For the past few years, the research trend in APF is towards optimization and simplification of control strategies especially in practical applications [4]. Unified Constant-Frequency Integration (UCI) control in particular, has been designed to reduce the complexity in calculation related to active power filtering [5]. This control method has been proposed based on the One-Cycle Control (OCC) method [6]. OCC is a pulsed nonlinear control technique which has been introduced to simplify the complexity of calculation and derivation of control signals while at the same time avoid the sensitivity of the component parameters. In active power filtering application, the UCI control shows the improvement in terms of performance by providing a low cost circuitry development and fast switching control loop [7]. By using the UCI control method, most of the conventional voltage sensors and the multipliers in the control loop are

extinguished, which in turn makes the control circuitry simple and robust [8]. In fact, a UCI control method requires only two main sensing elements which are current and voltage sensors. The employment of an integrator with reset is the main component. In addition, components such as comparators, clocks and flip-flops are part of the circuit that controls the output of the inverter in the APF system.

In order to improve the performance of the APF, multilevel inverters (MLIs) have been proposed to replace the conventional two or three-level inverters. The MLIs which have been available since 1981 [9] can be classified into three, namely Cascaded H-Bridge (CHMI), Diode-clamped and Flying Capacitor. Multilevel inverters have shown better performance and suitability for use in APF systems as a function of improving the power quality in electrical distribution systems [10]. A new multilevel inverter topology known as the multistring Cross-Connected Source Multilevel Inverter (CCSMI) has been proposed in [11]. The topology is also known as Capacitor Tied Switches (CTS) [12] which has been derived from a similar multilevel inverter topology named as Packed U-Cell (PUC) [13]. The topology shows improvement in terms of parts count compared to the conventional CHMI. The reliability of the CCSMI topology has been further studied to show its advantages both in terms of number of power switches and overall construction cost [14]. The extensive and comprehensive study presented in [15] shows that the CCSMI can be extended to higher levels and can even operate under asymmetrical sources.

In this paper, the results obtained from a simulation study using MATLAB/Simulink on a single-phase APF system based on the nonconventional CCSMI topology with UCI control are presented. The performance of the proposed system is analyzed based on the simulation results under steady-state condition with voltage source and current source types of nonlinear load.

2. CROSS-CONNECTED SOURCE MULTILEVEL INVERTER TOPOLOGY

Figure 1 shows the difference in terms of physical construction between a five-level conventional CHMI and the nonconventional CCSMI. Basically, the CCSMI topology requires only six power switches to produce a five-level output voltage compared to the eight power switches used in the former. For the CCSMI, two power switches S_{a2} and S_{b2} operate at line frequency whereas the other four power switches S_{a1}, S_{a3}, S_{b1} and S_{b3} operate at a higher switching frequency. As a result, the voltage stress and power losses in the CCSMI circuit is found to be reduced by nearly half of that of the CHMI [16]. Table 1 depicts the one cycle switching states of a CCSMI that produce a five-level output voltage.

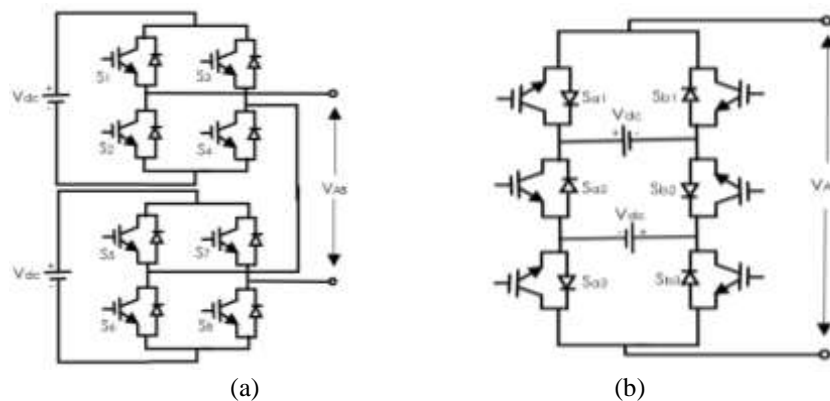| (a) | (b) |

Figure 1. Five-level MLI topology comparison (a) Conventional CHMI (b) Nonconventional CCSMI

Table 1. Five-level CCSMI switching states and output voltage

Switching State						Output
S_{a2}	S_{b2}	S_{a1}	S_{b1}	S_{a3}	S_{b3}	V_{AB}
0	1	1	0	1	0	+2Vdc
0	1	0	1	1	0	+1Vdc
0	1	1	0	0	1	+1Vdc
0	1	0	1	0	1	0V
1	0	1	0	1	0	0V
1	0	1	0	0	1	-1Vdc
1	0	0	1	1	0	-1Vdc
1	0	0	1	0	1	-2Vdc

3. RESEARCH METHOD

In this work, the simulation model of a CCSMI APF with UCI control in a single-phase electrical network has been designed using MATLAB/Simulink. The APF has been designed to produce a nearly sinusoidal supply current with the lowest possible percent Total Harmonic Distortion (THD). The methodology of the work considers two major tasks. The first task is to analyze the imperfectness of the source current waveform which is drawn by typical nonlinear loads in a single-phase power system. The nonlinear loads considered in this work is an uncontrolled rectifier which is coupled to a resistor connected in parallel to a capacitor (RC), a resistor connected in series to an inductor (RL) and an inductor connected in series to a parallel connected resistor and capacitor (RLC), respectively. The second task involves the development of the simulation model of the nonconventional five-level CCSMI APF together with UCI control which has been modified to suit the former.

3.1. Single-phase CCSMI APF system

The proposed CCSMI APF power stage is shown in Figure 2. The CCSMI is connected in parallel to the voltage source and the nonlinear load as well. The CCSMI acts as a voltage source inverter which converts the DC voltage across the capacitor to an AC voltage to the line. The function of the CCSMI is to eliminate the current harmonic and reactive current component generated by the nonlinear load so that the source current draws nearly sinusoidal waveform. V_{dc} is the total voltage across capacitors C_{f1} and C_{f2}. The input reference signal to the UCI control unit is denoted as $i_s.R_s$, which is sensed from the source current at the point of common coupling in the system (R_s is the equivalent current sensing resistance). The output of the UCI control unit produces six switching pulses to control the switching operation of the CCSMI operation.
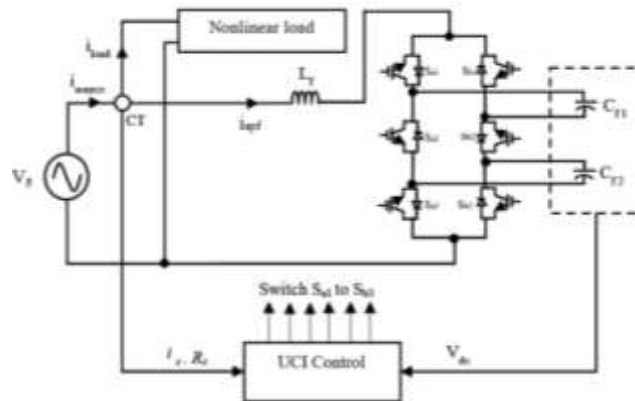

Figure 2. Single-phase CCSMI APF model

3.2. UCI Control of the CCSMI APF system

Figure 3 shows the schematic diagram of the UCI controller for the proposed single-phase CCSMI APF system. The UCI controller used is based on that initially developed for conventional single-phase inverters in APF systems [17] with a proposed modification to suit the CCSMI. The modified UCI controller contains only one integrator with a constant clock input signal, three comparators, two flip-flops with constant clock input signal to set the flip-flops operation and a set of logic circuit. Figure 3(b) illustrates the set of logic circuit that generates the five pulses signal to the CCSMI power switches.

The signal V_{dc} is sent to the integrator unit with one of the signal passing through the negative gain before being connected to the integrator unit. The output of the integrator is compared with the reference signal $R_s.i_s$ which becomes the input signal to the flip-flop. The clock gives a constant pulse signal to the flip-flop. The output of the flip-flop then produces the switching signal to the logic circuit unit. The logic circuit unit processes the signals to produce a switching control signal to the six CCSMI power switches. The $R_s.i_s$ signal also directly goes into the comparator unit to control two of the CCSMI power switches that operates at line frequency as highlighted earlier. The function of *Phase Delay* (delay of 180^0) and *Abs* is to ensure that the switching pattern produced by the flip-flops can generate a five-level PWM signal as should by the CCSMI. The constant clock signal for the flip-flop is T_s whereas T_i is the clock signal for the integrator unit. Under unipolar operation and dual duty ratio with the CCSMI topology, the value of T_i is set at $2T_s$.
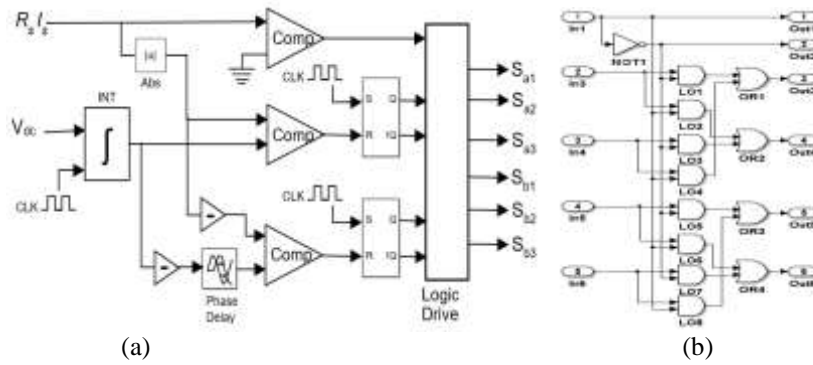
(a)   (b)

Figure 3. (a) Modified UCI controller for the CCSMI APF system (b) Set of logic drive circuit

4.   RESULTS AND ANALYSIS

Figure 4 shows the proposed single-phase CCSMI APF model with UCI control which has been simulated using MATLAB/Simulink. The mains voltage source is set to 220 Vrms at a line frequency of 50 Hz whereas the switching frequency is set to 10 kHz and the integrator frequency is 5 kHz. The power rating of the CCSMI is 5 kW. The values for L_f and R_f are 2.5 mH and 0.1 Ω respectively. The simulation of the proposed APF system is verified by considering three types of nonlinear loads which are known to produce source current harmonics in the power system, as mentioned earlier.
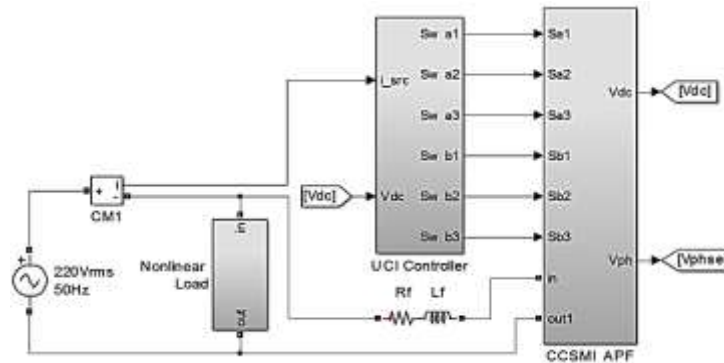

Figure 4. A Simulink circuit model of the proposed system

Figure 5 depicts the nonlinear load which considers the uncontrolled rectifier coupled with a parallel RC load. The value of R1 is 250 Ω while C1 is 1000 µF. The source current as shown in Figure 6(a) gives a THD of 146.72%. After compensation with the APF current, the supply current THD reduces to 5.70% as presented in Figure 6(b). Figure 7(a) and (b) show the THD measurement of the source current both before and after compensation with the APF current.
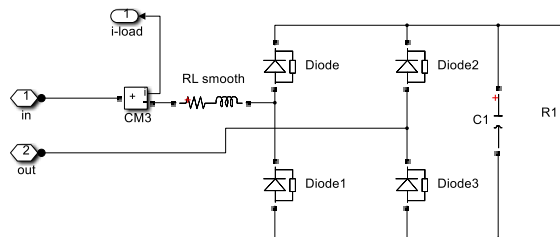

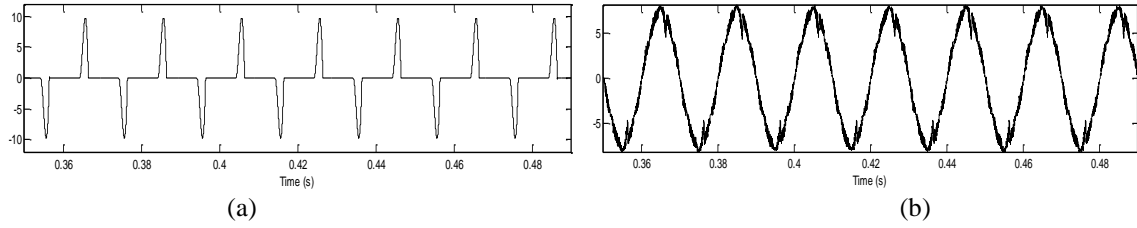Figure 5. An uncontrolled rectifier coupled with a parallel RC load

(a)   (b)

Figure 6. Steady-state response of the source current (a) before compensation (b) after compensation

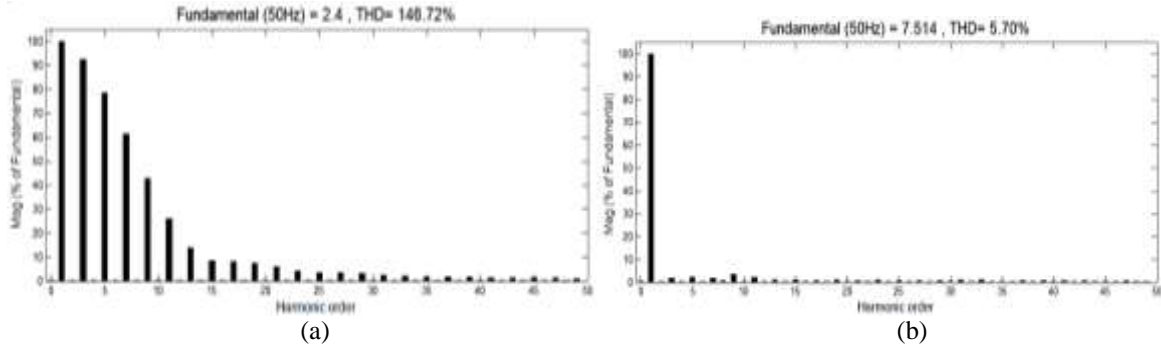
(a)   (b)

Figure 7. THD of the source current (a) before compensation (b) after compensation

Figure 8 depicts the nonlinear load which considers an uncontrolled rectifier coupled with a series RL load. In this case, the value of R1 is 25 Ω while L1 is 250 mH. The source current as shown in Figure 9(a) produces a THD of 41.40%. Figure 9(b) shows the improvement in the source current after compensation with the APF current whereby, the THD reduces to 6.58%. Figure 10(a) and (b) show the THD measurement of the source current both before and after compensation with the APF current.
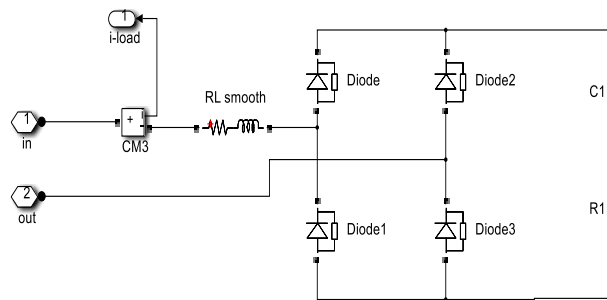

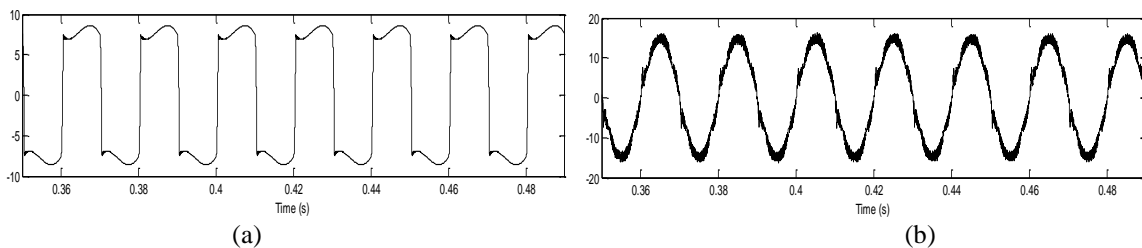Figure 8. An uncontrolled rectifier coupled with a series RL load

(a)   (b)

Figure 9. Steady-state response of the source current (a) before compensation (b) after compensation

Fundamental (50Hz) = 10.07 , THD= 41.40%   Fundamental (50Hz) = 15.44 , THD= 6.58%

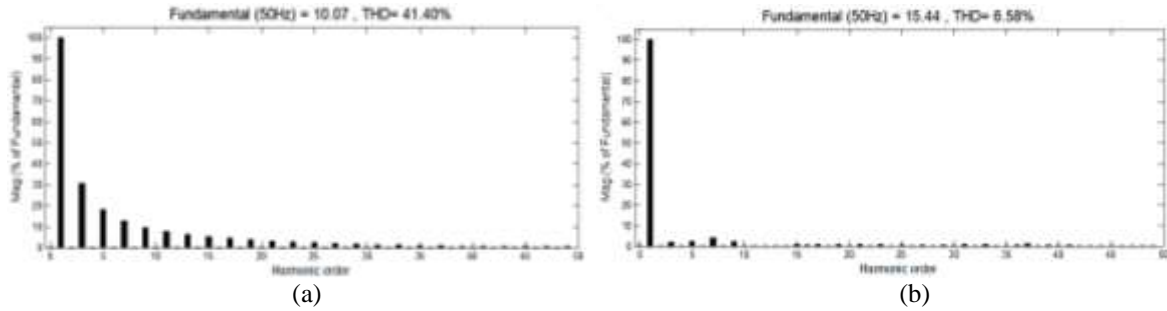(a)   (b)

Figure 10. THD of the source current (a) before compensation (b) after compensation

Figure 11 depicts the nonlinear load which considers an uncontrolled rectifier coupled to an inductor connected in series to a parallel connected resistor and capacitor (RLC) load. In this case, the value of R1 is 25 Ω, L1 is 50 mH and C1 is 500 μF. The source current as shown in Figure 12 (a) gives a THD of 36.59%. Figure 12 (b) shows improvement in the source current after compensation with the APF current with a reduced THD of 5.93%. Figure 13 (a) and (b) show the THD measurement of the source current both before and after compensation with the APF current.
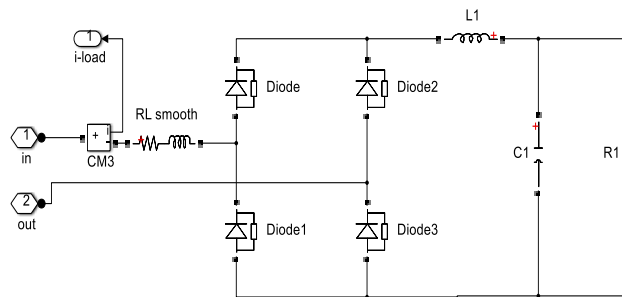
Figure 11. An uncontrolled rectifier coupled to an inductor connected in series to a parallel connected resistor and capacitor (RLC) load
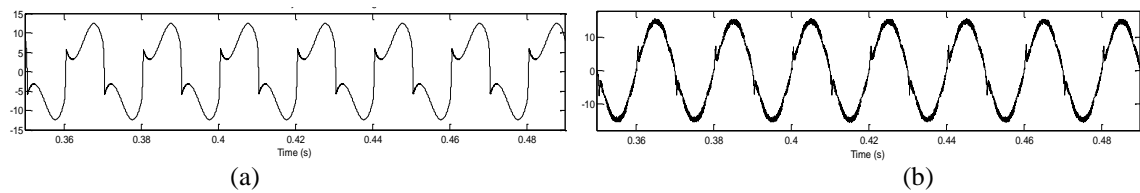

(a)   (b)

Figure 12. Steady-state response of the source current (a) before compensation (b) after compensation

Fundamental (50Hz) = 11.16 , THD= 36.59%   Fundamental (50Hz) = 15.17 , THD= 5.93%

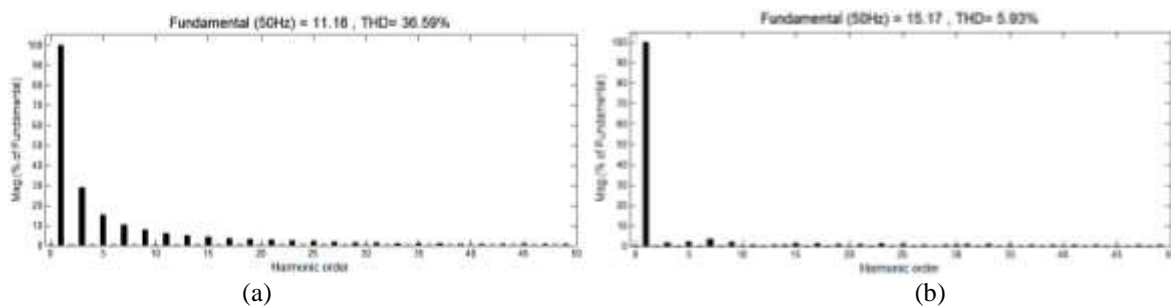(a)   (b)

Figure 13. THD of the source current (a) before compensation (b) after compensation

5. CONCLUSION

In this paper, a single-phase APF system that integrates the nonconventional CCSMI with UCI control has been proposed. The system is tested under various types of nonlinear loads and results based on steady-state condition shows significant improvement in the source current THD. The main advantage of this proposed system is its ability to compensate the distorted source current due to nonlinear loads more effectively while at the same time reducing the parts count with the use of the nonconventional CCSMI. This in turn contributes to overall reduction in the voltage stress of the CCSMI power switches. In addition, the proposed APF system has also been designed to operate under unipolar mode with only four power switches operating at high frequency while the other two operating at line frequency. Furthermore, the simple modified UCI controller that do not require any reference current generation, adds to the reliability of the proposed APF system. The simulation results presented have confirmed the capability of the proposed CCSMI with UCI control APF for a single-phase system, despite variations in the nonlinear load characteristics.

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BIOGRAPHIES OF AUTHORS

Hairol Jaffar received his Bachelor's degree in Electrical Engineering from Universiti Teknologi MARA (UiTM), Malaysia in 1998 and M. Eng. Degree from the University of South Australia (UniSA) Adelaide, Australia, in 2011. He is working as a Vocational Training Officer under Ministry of Human Resource, Malaysia and currently fulltime study for his Ph.D. degree in Universiti Teknologi Malaysia (UTM), Johor, Malaysia. His current research interest is an Active Power Filtering system with unconventional multilevel inverter topology using Unified Constant Frequency Integration Control.

Naziha Ahmad Azli received her B. Sc. Degree in Electrical Engineering from University of Miami, Florida, USA and M.E.E. and Ph.D. from Universiti Teknologi Malaysia (UTM) in 1986, 1992 and 2002 respectively. She is now an Associate Professor at UTM with which she has been affiliated since 1988. She currently teaches Power Electronics at both undergraduate and post-graduate levels at the university. Her research interests are power quality, renewable / alternate / distributed energy and intelligent systems applied to power electronics converters.