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Single-Phase PFC Converter for Plug-in Hybrid Electric Vehicle Battery Chargers

Shakil Ahamed Khan, Md. Ismail Hossain, Mousumi Aktar
Departement of Electrical and Electronic Engineering
Rajshahi University of Engineering and Technology

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ABSTRACT

In this paper, a front end ac–dc power factor correction topology is proposed for plug-in hybrid electric vehicle (PHEV) battery charging. The topology can achieve improved power quality, in terms of power factor correction, reduced total harmonic distortion at input ac mains, and precisely regulated dc output. Within this context, this paper introduces a boost converter topology for implementing digital power factor correction based on low cost digital signal controller that operates the converter in continuous conduction mode, thereby significantly reducing input current harmonics. The theoretical analysis of the proposed converter is then developed, while an experimental digital control system is used to implement the new control strategy. A detailed converter operation, analysis and control strategy are presented along with simulation and experimental results for universal ac input voltage (100–240V) to 380V dc output at up to 3.0 kW load and a power factor greater than 0.98. Experimental results show the advantages and flexibilities of the new control method for plug-in hybrid electric vehicle (PHEV) battery charging application.

Corresponding Author:

Shakil Ahamed Khan,
Departement of Electrical and Electronic Engineering,
Rajshahi University of Engineering and Technology,
66 Green Road, Dhaka-1215, Bangladesh.
Email: shakil_pilabs@yahoo.com

1. INTRODUCTION

AC–DC conversion of electric power is widely used in several applications such as adjustable-speed drives, switch-mode power supplies, uninterrupted power supplies (UPSs), and battery energy storage. Conventionally, ac–dc converters, popularly referred to as rectifiers, are implemented using diodes and thyristors to provide uncontrolled and controlled dc power with unidirectional and bidirectional power flow [1]. Plug-in hybrid electric vehicle (PHEV) is a hybrid vehicle with a storage system that can be recharged by connecting the vehicle plug to an external electric power source [2]. The most common charger power architecture includes an ac–dc converter with power factor correction (PFC) [3] followed by an isolated dc-dc converter with input and output EMI filters [4]. Current pulses with high peak amplitude are drawn from a rectified voltage source with sine wave input and capacitive filtering. The current drawn is discontinuous and of short duration irrespective of the load connected to the system. Since many applications demand a DC voltage source, a rectifier with a capacitive filter is necessary. However, this results in discontinuous and short duration current spikes. When this type of current is drawn from the mains supply, the resulting network losses, the total harmonic content, and the radiated emissions become significantly higher.

At power levels of more than 500 watts, these problems become more pronounced. Major drawbacks include poor power quality in terms of injected current harmonics, resulting in voltage distortion and poor power factor (PF) at the input ac mains and slow varying rippled dc output at the load end, low efficiency, and large size of ac and dc filters [5]. Two factors that provide a quantitative measure of the power quality in an electrical system are Power Factor (PF) and Total Harmonic Distortion (THD). The amount of useful power being consumed by an electrical system is predominantly decided by the PF of the system.

This paper focuses primarily on design and implementation of Power Factor Correction (PFC) using a low cost microcontroller for plug in hybrid electric vehicle charger. The software implementation of PFC using the 8-bit microcontroller is explained in detail. Fuzzy logic based control algorithm was implemented for better performance of the proposed converter. In conclusion, some test results and waveforms are presented to validate the digital implementation of the PFC converter. The low cost and desired performance capabilities of the digital controller, combined with a wide variety of power electronic peripherals such as an Analog-to-Digital Converter (ADC) and a Pulse Width Modulator (PWM), facilitate the digital design and development of a plug-in hybrid electric vehicle charger.

1.1 Boost Topology

Power Factor is a parameter that gives the amount of working power used by any system in terms of the total apparent power. Power Factor becomes an important measurable quantity because it often results in significant economic savings. The objective of PFC is to make the input to a power supply look like a simple resistor. This allows the power distribution system to operate more efficiently, reducing energy consumption.

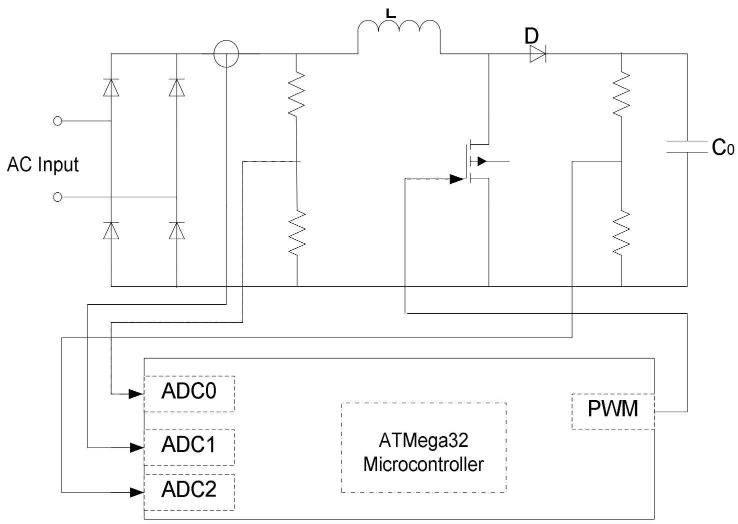

Figure 1.Proposed boost PFC converter

A boost topology PFC converter boosts the input voltage and shapes the inductor current similar to that of the rectified AC voltage. The voltage rating of the power switch is equal to the output voltage rating of the converter. The basic boost converter circuit is shown in Fig.1.The boost topology PFC converter can be operated in Continuous Conduction mode unlike other basic topologies, such as the buck converter or buck-boost converter. This mode reduces harmonic content in the input current. However, the operation in continuous conduction region depends on the inductor value and the amount of load on the system.

Active PFC must control both the input current and the output voltage. The current is shaped by the rectified line voltage so that the input to the converter appears to be resistive. The output voltage is controlled by changing the average amplitude of the current programming signal. The effective resistance of the resistive load specified to the AC line varies slowly according to the power demands of the actual load. The line current remains proportional to the line voltage,

The basic function of PFC is to make the input current drawn from the system sinusoidal and in-phase with the input voltage. Figure 1 shows the component blocks required for PFC and the PFC stage interfaced to a microcontroller. This is an AC-to-DC converter stage, which converts the AC input voltage to a DC voltage and maintains sinusoidal input current at a high input Power Factor. As indicated in the block diagram, three input signals are required to implement the control algorithm.

The input rectifier converts the alternating voltage at power frequency into unidirectional voltage. This rectified voltage is fed to the chopper circuit to produce a smooth and constant DC output voltage to the load. The chopper circuit is controlled by the PWM switching pulses generated by the microcontroller, based on three measured feedback signals:
• Rectified input voltage
• Rectified input current
• DC bus voltage

The only output from the microcontroller is firing pulses to the boost converter switch to control the nominal voltage on the DC bus in addition to presenting a resistive load to the AC line. The output DC voltage of the boost converter and the input current through the inductor are the two parameters that are essentially controlled using active PFC.The technique used here for PFC is the Average Current Mode control.

In Average Current Mode control, the output voltage is controlled by varying the average value of the current amplitude signal. The current signal is calculated digitally by computing the product of the rectified input voltage, the voltage error compensator output and the voltage feed-forward compensator output. The rectified input voltage is multiplied to enable the current signal to have the same shape as the rectified input voltage waveform. The current signal should match the rectified input voltage as closely as possible to have high Power Factor. The voltage feed-forward compensator is essential for maintaining a constant output power because it compensates for the variations in input voltage from its nominal value.

2. PFC SOFTWARE IMPLEMENTATION

The inner loop in the control block forms the current loop. The input to the current loop is the reference current signal I_{ACREF} and the actual inductor current I_{AC}. The current error compensator is designed to produce a control output such that the inductor current I_{AC} follows the reference current I_{ACREF}. The current controller GI produces a duty cycle value after appropriate scaling to drive the gate of the PFC MOSFET.

The outer loop in the control block forms the voltage loop. The input to the voltage loop is the reference DC voltage V_{DCREF} and the actual sensed output DC voltage V_{DC}. The voltage error compensator is designed to produce a control output such that the DC bus voltage V_{DC} remains constant at the reference value V_{dcref} regardless of variations in the load current I_O and the supply voltage V_{AC}. The voltage controller G_V produces a control signal, which determines the reference current I_{ACREF} for the inner current loop as shown in Figure 2.

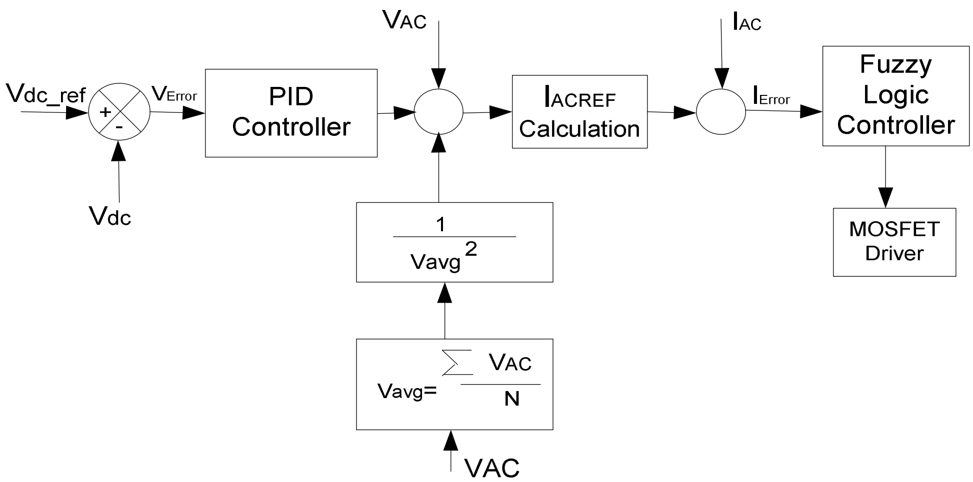

Figure 2. PFC software implementation

The output voltage is controlled by the voltage error compensator. When the input voltage increases, the product of V_{AC} and V_{PI} increases, and thereby increasing the programming signal. When this signal is divided by the square of the average voltage signal, it results in the current reference signal being reduced proportionally. The outcome is that the current is reduced proportional to the increase in voltage, thereby keeping the input power constant. This ensures that the reference control output I_{ACREF} from the voltage compensator is maximum such that the rated output power is delivered at minimum input voltage.

2.1 Fuzzy control system

Fuzzy logic controllers (FLC) have the advantages of working with imprecise inputs, not needed an accurate mathematical model, handling nonlinearity [6]. For controlling such a complicated system, FLC looks very promising for this application. The inputs to a PFC fuzzy logic controller are usually an error *E* and a change of error Δ*E* as given in Eq. (1) and Eq. (2) respectively.

$$E(n) = I_{acref} - I_{ac} \quad (1)$$

$$\Delta E(n) = E(n) - E(n-1) \quad (2)$$

Where I_{acref} *is* calculated by measuring the voltage error compensation as given in Eq.(3), voltage feed forward compensation V_{FFC} and V_{AC} signal as given in Eq.(4)

$$V_{ERROR}=V_{DCREF}-V_{DC} \quad (3)$$

$$I_{acref} = V_{FFC} \times V_{AC} \times V_{ERROR} \quad (4)$$

E and ΔE are calculated and converted to the linguistic variables during fuzzification. Linguistic variables are non-precise variables that often convey a surprising amount of information. Fig. 3 shows the relations between measured error and the linguistic term, such as positive small, positive medium and positive big. At some point the error is positive small and at some point the error is positive big the space between positive big and positive small indicates an error that is, to some degree, a bit of both. The horizontal axis in the following graph shows the measured or crisp value of error. The vertical axis describes the degree to which a linguistic variable fits with the crisp measured data.

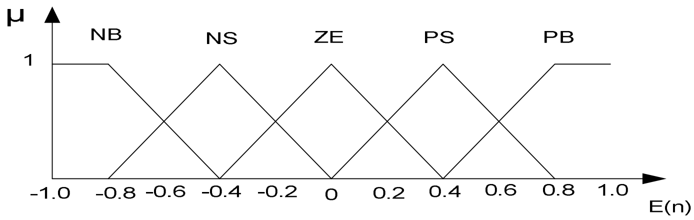

Figure 3. The relationship between linguistics variable and error

To add the linguistics variable positive big to a computer program running in an embedded microcontroller, translation the graphical representation into meaningful code is needed. The following C code fragment gives one example of how to do this. The function error- Positive Big ( ) returns a degree of membership, scaled between 0 and 1, indicating the degree to which a given error can be positive big. This type of simple calculation is the first tool required for calculations of fuzzy logic operations.

```
char Error_ Positive Big (int  CRISP)
   {
     if (CRISP < 0.4)
         return(0);
    else
        {
          if (CRISP >= 0.4)
             return(CRISP * 2.5);
         else
             {
               return(1);
             }
        }
  }
```

Rule evaluation is done by using an algorithm where loops compare the antecedent value depending on the rule being evaluated in a repeated fashion until all rules are evaluated.

The fuzzy logic controller output is typically a change in duty ratio ΔD of the power converter. The linguistic variables assigned to ΔD for the different combinations of E and ΔE as shown in Table 1 which is based on a boost converter.

Table 1. Fuzzy rule base table

ΔE \ E	NB	NS	ZE	PS	PB
NB	NB	NS	NS	ZE	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	ZE	PS	PS	PB

The final step in the fuzzy logic controller is to combine the fuzzy output into a crisp systems output. The result of the defuzzification has to be a numeric value which determines the change of duty cycle of the PWM signal used to drive the MOSFET. There are various methods to calculate the crisp output of the system. Centre of Gravity (COG) method is used in our application due to better results it gives. The COG for our application is expressed mathematically as given in Eq.(5).

$$\Delta D = \frac{\sum_{n=1}^{4} Y[i] \times F[i]}{\sum_{n=1}^{4} Y[i]} \tag{5}$$

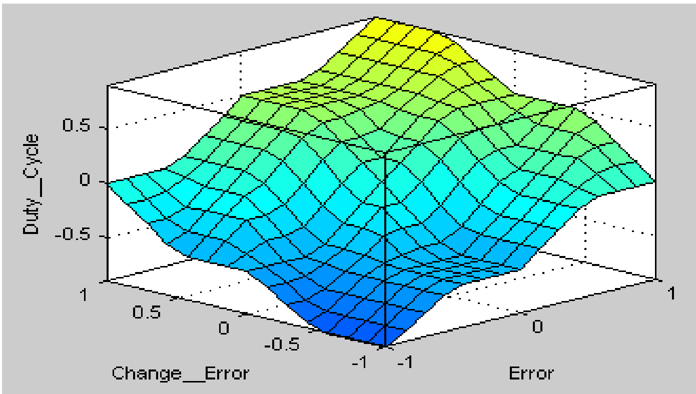

Figure 4. Fuzzy control output surface

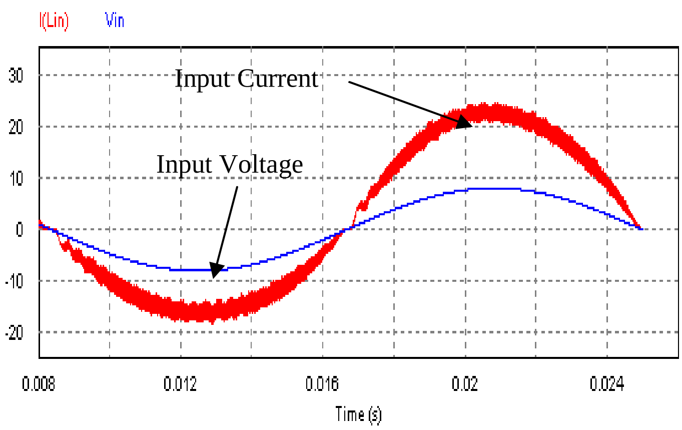

Figure 5. Simulation waveforms of proposed PFC boost converter

Where Y[i] is the i^{th} members of the output vector and F[i] are the multiplying coefficients of the output membership function as shown in Table 1, and ΔD is the change of duty cycle, and this number represents a signed number which is added or subtracted from the present duty cycle to generate the next system response for PFC as given by Eq.(6). Fuzzy control output surface using Matlab simulation is shown in Figure 4.

$$D_{new} = D_{old} + \Delta D \tag{6}$$

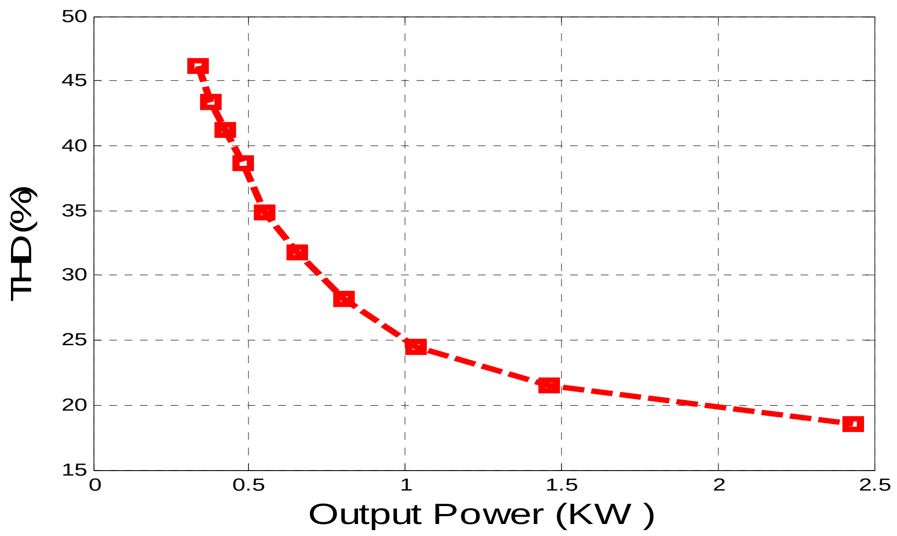

Figure 6. Total harmonics distortion versus output power

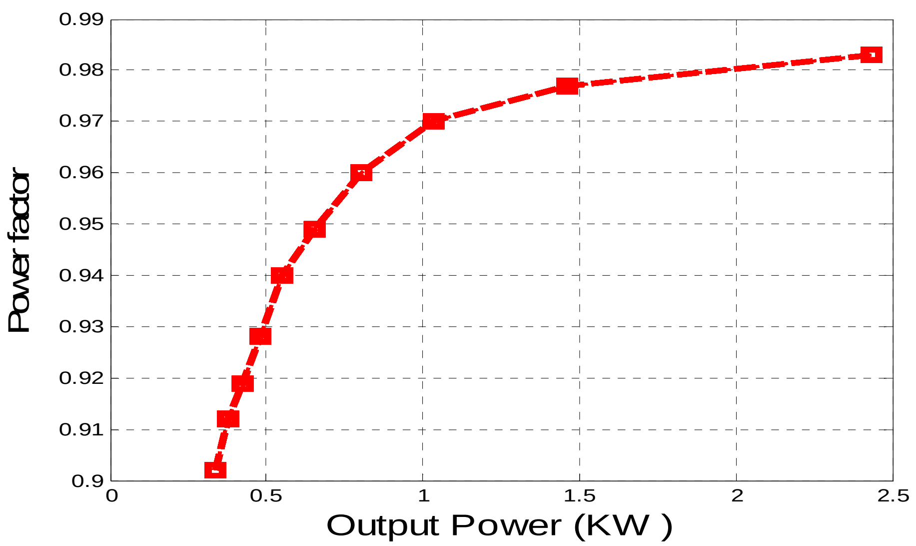

Figure 7. Power Factor versus output power

3. EXPERIMENTAL RESULTS

Simulation waveform of the proposed PFC boost converter is shown in Figure 5. Curves of the input current total harmonic distortion are provided in Figure 6 for 230V input. The power factor is greater than 0.98 from half load to full load as shown in Figure 7. Digital implementation of the proposed controller was implemented using ATmega32 microcontroller. Proteus software was used to verify steady state waveforms of each component. The input current is in phase with input voltage, it has close to unity power factor and its shape is close to a sinusoidal waveform as shown in Figure 8. Also the output voltage is regulated at around

380V as shown in Figure 9.The converter is operating at 70 kHz switching frequency, 230 V input voltage and 3.0 kW output power.

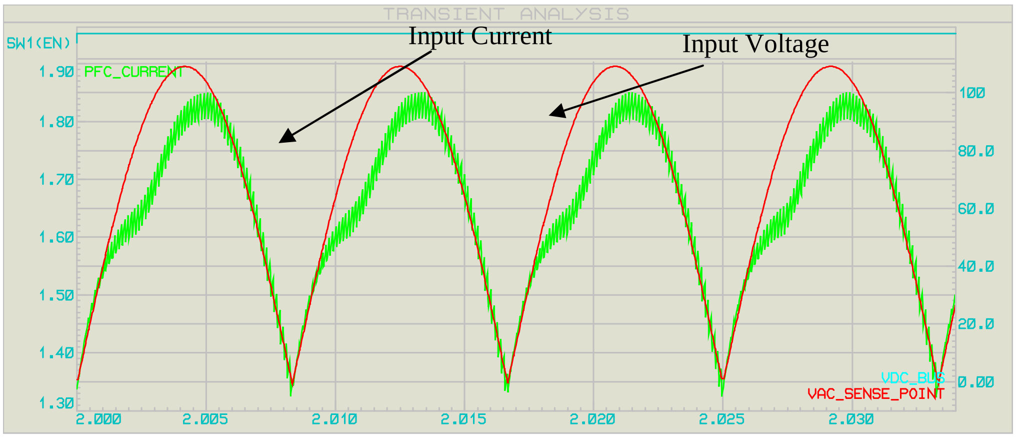

Figure 8. Rectified Input voltage and input current

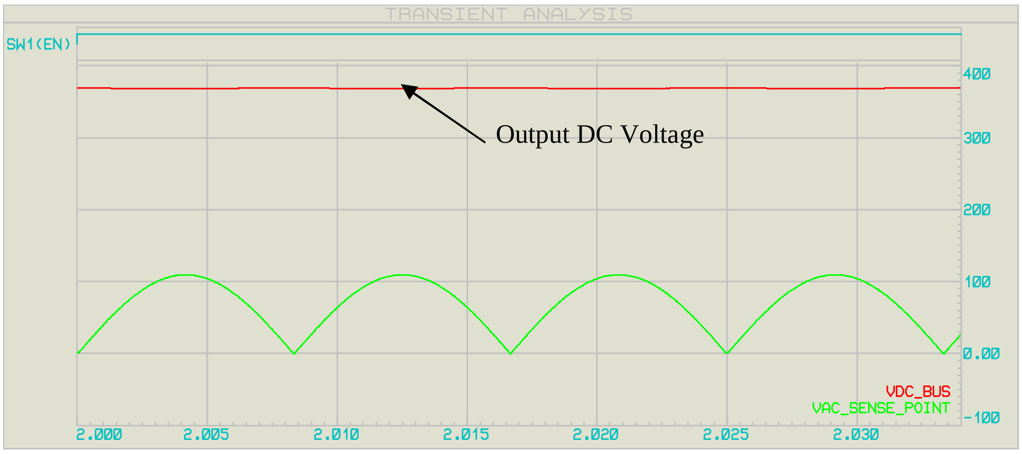

Figure 9. Output voltage and rectified input voltage

4. CONCLUSION

A PFC based AC-DC boost converter topology has been presented in this paper for the front-end AC-DC converter in PHEV battery chargers. The proposed converter topology has been analyzed and performance characteristics presented. A microcontroller based simulation was done to verify the proof-of-concept. The total harmonics distortion, regulated output dc voltage and power factor was measured and showed great results. The converter topology shows a high input power factor, high efficiency over entire load range and excellent input current harmonics. It is an excellent option for single phase PFC solution in plug in hybrid electric vehicle charger application.

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BIOGRAPHIES OF AUTHORS

Shakil Ahamed Khan did his B.Sc Engg. (Electrical & Electronic Engineering) from Rajshahi University of Engineering and technology, Bangladesh. He is presently working as lecturer at Dhaka International University. His research interests are power electronics applications in power quality, Renewable Energy and its grid integration, Smart Grid and Micro Grid, Plug-in Hybrid Electric Vehicle, Industrial motor drive and automation.

Md Ismail Hossain did his B.Sc Engg. (Electrical & Electronic Engineering) from Rajshahi University of Engineering and technology, Bangladesh. He is presently working as lecturer at International Islamic University Chittagong. His research interests are Power Electronics, Industrial motor drive and automation, Hybrid electric vehicle, Microcontroller and Embedded Systems, Electrical Machine, Renewable energy and its grid integration and Smart Grid.

Mousumi Aktar did her B.Sc Engg. (Electrical & Electronic Engineering) from Rajshahi University of Engineering and technology, Bangladesh. She is presently working as lecturer at Dhaka International University. Her research interests are Power Syetems, power electronics, Renewable Energy, Industrial motor drive and automation.