

# Bidirectional AC/DC Converter Using Simplified PWM with Feed-Forward Control

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**ABSTRACT:** A simplified pulse width modulation (PWM) strategy for the bidirectional ac/dc single phase converter is developed. The number of switchings of the simplified PWM strategy is one fourth that of the conventional uni-polar PWM and bipolar PWM. Based on the simplified PWM strategy, a feasible feed forward control scheme is developed to achieve better rectifier mode and inverter mode performance compared with the conventional dual loop control scheme. The simplified PWM strategy with the new feed forward control scheme has lower total harmonic distortion than the bipolar PWM and higher efficiency than both unipolar and bipolar PWMs. Both simulation and experiments are done to verify the validity of the PWM strategy and control scheme.

**KEYWORDS:** Bidirectional AC/DC converter, Simplified PWM, Feed forward control, Single phase boost converter.

## I. INTRODUCTION

Solid-state AC/DC conversion of electric power is widely used in adjustable-speed drives (ASDs), switch-mode power supplies (SMPSs), utility interface with non-conventional energy sources such as solar PV, fuel cell, biomass, wind energy etc., battery energy storage systems (BESSs) such as flywheels, in process technology such as electroplating, welding units, etc., battery charging for electric vehicles, power supplies for telecommunication systems etc. Conventionally, AC/DC converters, also called rectifiers, are developed using thyristors and diodes to provide controlled and uncontrolled dc power with unidirectional and bidirectional power flow [1]. Poor power quality in terms of injected current harmonics caused by voltage distortion and poor power factor at input ac mains and slow varying rippled dc output at load end, low efficiency and large size of ac and dc filters are some of the demerits of such rectifiers [2]. In light of their increased applications, a new breed of rectifiers has been developed using new solid state self-commutating devices such as MOSFETs, IGBTs, GTOs, etc., Such devices are generally known as converters, but specifically named as switch-mode rectifiers (SMRs), power-factor correctors (PFCs) [3], pulse width-modulation (PWM) rectifiers, multilevel rectifiers, etc [1].

The single-phase AC/DC PWM converters are usually employed as a utility interface in the grid-tied renewable system which helps to utilize the distributed energy resources (DERs) efficiently and retain power system stability. Some of the requirements for such AC/DC PWM converters are providing power factor correction functions [4], low distortion line currents, high-quality dc output voltage, and bidirectional power flow capability. The PWM strategies that are usually utilized are bipolar PWM (BPWM), unipolar PWM (UPWM), hybrid PWM (HPWM), and Hysteresis switching [5][6].

Paper is organised as follows: In Section II, the new converter system based on the design review is developed and the operational principles are explored along with the control strategy used. The Section III includes the simulation study done on the bidirectional AC/DC converter topology along with its results. Section IV deals with the design of the experimental hardware and the results obtained. Finally, conclusions are drawn in Section V.

## II. SINGLE PHASE BIDIRECTIONAL AC/DC CONVERTER

A bidirectional single-phase AC/DC converter is utilized as an interface between the ac utility grid system and DERs to deliver power flows bi-directionally and to maintain good AC current shaping and DC voltage regulation, as shown in Fig. 1. Good current shaping can avoid harmonic pollution in an AC grid system, and good dc voltage regulation can provide a high-quality dc load [7].

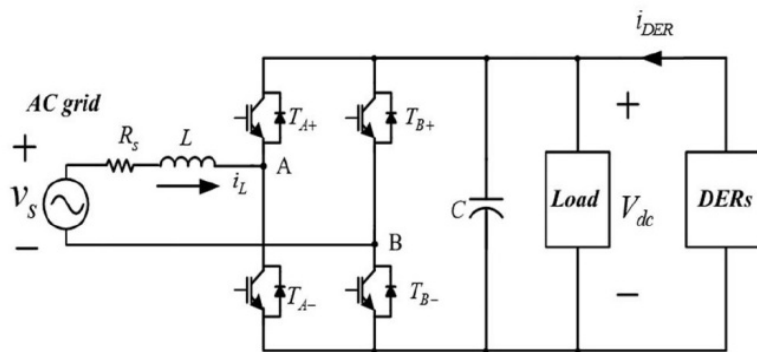


Fig. 1 Single-Phase Bidirectional AC/DC Converter for Renewable Energy System [7]

### A. Operation Principle of the Proposed AC-DC Converter

When DERs have enough energy to energize the DC bus, it can be easily transferred into the ac grid through the bidirectional ac/dc converter. Alternatively, the bidirectional ac/dc converters can simultaneously and quickly change the power flow direction from utility grid to dc grid, when the DER power does not have enough energy to provide electricity to the load in the dc bus and hence give power to the dc load and energy storage system [8][9].

To achieve bidirectional power flow in a renewable energy system, a PWM strategy such as BPWM or UPWM may be applied for the single-phase full-bridge converter to obtain better AC current shaping and DC voltage regulation. Compared to the conventional SPWM techniques, the simplified PWM strategy proposed has only one active switch status change occurrence in the switching period to achieve both charging and discharging of the ac side inductor current. Therefore, the proposed simplified PWM strategy reduces the switching losses and provides high conversion efficiency. A feed forward control scheme is developed to enhance the control ability of the control system by providing fast output voltage response as well as improved current shaping in both the rectifier and inverter mode [7].

### B. Simplified PWM

The simplified PWM requires only one active switch to change its status during the switching period to achieve both charging and discharging of the ac side inductor current. The Tables I and II lists the switching statuses of the proposed simplified PWM for rectifier mode and inverter mode operation, respectively.

TABLE I  
RECTIFIER MODE SWITCHING COMBINATION IN SIMPLIFIED PWM [7]

Source Voltage	Status	TA+	TA-	TB+	TB-	Inductor status
$v_s > 0$	A	OFF	OFF	ON	OFF	$V_L > 0$
	B	OFF	ON	OFF	OFF	
	E	OFF	OFF	OFF	OFF	$V_L < 0$
$v_s < 0$	C	ON	OFF	OFF	OFF	$V_L < 0$
	D	OFF	OFF	OFF	ON	
	E	OFF	OFF	OFF	OFF	$V_L > 0$

TABLE II  
INVERTER MODE SWITCHING COMBINATION IN SIMPLIFIED PWM [7]

Source Voltage	Status	TA+	TA-	TB+	TB-	Inductor status
$v_s > 0$	A	ON	OFF	OFF	OFF	$V_L > 0$
	B	OFF	OFF	OFF	ON	
	E	ON	OFF	OFF	ON	$V_L < 0$
$v_s < 0$	C	OFF	ON	OFF	OFF	$V_L < 0$
	D	OFF	OFF	ON	OFF	
	E	OFF	ON	ON	OFF	$V_L > 0$

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## 1. Rectifier Mode:

Assume the internal impedance of the single-phase AC grid system, shown in Fig. 1, is highly inductive and represented by L. The equivalent series resistance of L is neglected. When AC grid voltage source,  $v_s > 0$ , the circuit operates according to the switching combination of statuses A or B as listed in Table I. The voltage across the inductor is  $v_s$ , hence, the inductor current is in the charging state. While the converter is in Status E, all the switches are turned OFF and the inductor voltage is  $v_s - V_{dc}$ , which decreases the inductor current; therefore, the inductor current is in discharging state.

When the AC grid voltage,  $v_s < 0$ , the circuit operates with the switching combination given in status C or D, where the voltage across the inductor L is given by  $v_s$ . The inductor current is found decreasing in both these states, hence, the inductor current is in the discharging state. When the converter is in Status E, all the switches are turned OFF and the inductor voltage is given by  $v_s + V_{dc}$ , which increases the inductor current. Therefore, in this condition, the inductor current is in the charging state.

## 2. Inverter Mode:

When the converter is operated in the inverter mode with the switching combination as listed in Table II, the actual inductor current is in the reverse direction compared to the AC grid voltage. Consider the AC grid voltage,  $v_s > 0$ , the input current is in the reverse direction,  $I_L < 0$ . Both statuses F and G give inductor L positive voltage to charge the inductor current and status H gives L negative voltage to discharge the inductor current.

While the AC grid voltage source,  $v_s < 0$ , the input current is in the reverse direction,  $I_L > 0$ . Both Statuses I and J give inductor L negative voltage to discharge the inductor current and Status K gives L positive voltage to charge the inductor current.

Thus, regardless of whether the ac grid voltage source is operating in the positive half-cycle,  $v_s > 0$  or the negative half-cycle,  $v_s < 0$ , the converter inductor current can be increased or decreased properly to achieve ac current shaping and dc voltage regulation in the simplified PWM operated in both the rectifier and inverter mode.[7]

### Comparison of PWM Strategies

A comparison of the BPWM, UPWM, and the proposed simplified PWM strategies are conducted, in order to understand the merits of the simplified PWM strategy.

TABLE III  
STATUSES OF THE ACTIVE SWITCHES IN BPWM [6]

Status	TA+	TA-	TB+	TB-
A	OFF	ON	ON	OFF
B	ON	OFF	OFF	ON

TABLE IV  
STATUSES OF THE ACTIVE SWITCHES IN UPWM [6]

Status	TA+	TA-	TB+	TB-
A	ON	OFF	ON	OFF
B	OFF	ON	OFF	ON
C	ON	OFF	ON	OFF
D	OFF	ON	OFF	ON

BPWM only has two switching statuses (Table III), because if status of one switch is determined,  $T_{A+}$ , then the other switches,  $T_{A-}$ ,  $T_{B+}$  and  $T_{B-}$  are all determined. In the UPWM, the switching signals of ( $T_{A+}$ ,  $T_{A-}$ ) and ( $T_{B+}$ ,  $T_{B-}$ ) are controlled separately by comparing carrier waveform with original and reverse control signals. Therefore, UPWM has four switching statuses listed in Table IV [6].

The switching time is defined as the number of changes in switching status regardless of whether the switch is turned ON or turned OFF. By considering the status change of active switches for the BPWM from Table III, it can be observed that BPWM needs eight active switching times in a switching period. From Table IV, one can see that the UPWM also needs eight active switching times in the switching period. From Tables I and II, One can find that the proposed simplified PWM needs only two active switching times in the switching period. In addition, it is also observed that only one active switch is activated in a carrier cycle period. This implies that the switching losses in simplified PWM are one-fourth of that of the conventional BPWM and UPWM strategies.

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### C. Feed forward Control Scheme

Suppose, the converter is operated in the rectifier mode, to derive the state-space averaged equation for the simplified PWM strategy, the duty ratio  $D_{on}$  is defined as  $D_{on} = T_{on}/T$ , where  $t_{on}$  is the time duration when the switch is turned ON, i.e,  $S_{on} = 1$  and  $T$  is the time period of triangular waveform. The duty ratio  $D_{off}$  is defined as  $D_{off} = 1 - D_{on}$ , which is the duty ratio when the switch is OFF.

When  $v_s > 0$ , the duty ratios corresponding to Statuses A and E are  $D_{on}$  and  $D_{off}$ , respectively. The state space average equation is derived as,

$$v_s - (1 - D_{on})V_{dc} = 0 \tag{1}$$

In the steady state operation, the dc voltage is equal to the desired command,  $V_{dc} = V_{dc}^*$ ; therefore,

$$D_{on} = \left(1 - \frac{v_s}{V_{dc}^*}\right) \tag{2}$$

When  $v_s < 0$ , the duty ratios corresponding to Statuses E and C are  $D_{on}$  and  $D_{off}$ , respectively. The state space average equation is derived as,

$$v_s + D_{on}V_{dc} = 0 \tag{3}$$

Similarly, when the converter is operated in the steady state,  $V_{dc} = V_{dc}^*$ ; therefore,

$$D_{on} = -\frac{v_s}{V_{dc}^*} \tag{4}$$

The switching duty ratio in terms of the control signal  $v'_{cont}$  and the peak value  $\hat{V}_{tri}$  of the triangular waveform can be expressed as,

$$D_{on} = \frac{v'_{cont}}{\hat{V}_{tri}} \tag{5}$$

Therefore, the switching duty ratios in both conditions  $v_s > 0$  and  $v_s < 0$  is derived as,

$$v'_{cont} = \begin{cases} \left(1 - \frac{v_s}{V_{dc}^*}\right) \hat{V}_{tri}, & v_s > 0 \\ -\frac{v_s}{V_{dc}^*} \hat{V}_{tri}, & v_s < 0 \end{cases} \tag{6}$$

Consider that the converter is operated in the inverter mode with the switching combination listed in Table II, during the condition  $v_s > 0$ , one can choose statuses F and H for increasing and decreasing the inductor current, and during the condition  $v_s < 0$ , statuses I and K for decreasing and increasing the inductor current, respectively. The control signal is obtained using the same method used for the rectification mode and the control signal  $v'_{cont}$  obtained in the inverter mode is the same as that in the rectifier mode.

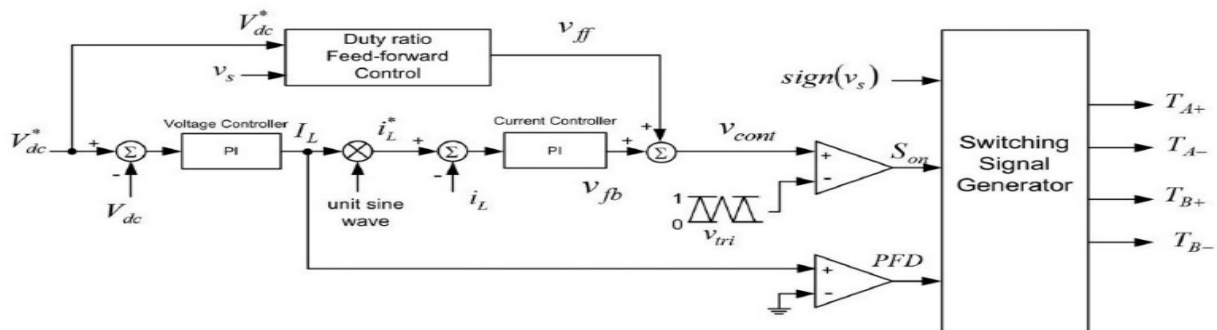


Fig. 2 Feed-forward control scheme for the proposed simplified PWM strategy [7]

The developed control scheme for the simplified PWM is presented in Fig 2. Since the control signal  $v_{cont}$  is proportional to  $D_{on}$ , the calculated signal  $v'_{cont}$  in (6) can be regarded as the duty ratio feed-forward control signal  $v_{ff}$  to be added into the dual-loop feedback control signal  $v_{fb}$  to enhance the control ability of the bidirectional AC/DC converter by providing fast output voltage response as well as improved current shaping. The switching signal generator requires the grid voltage sign ( $v_s$ ),  $S_{on}$ , and PFD combined with Tables I and II to generate the switching pulses for the switches  $T_{A+}$ ,  $T_{A-}$ ,  $T_{B+}$  and  $T_{B-}$ . [7].

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### D. Parameters Design

Inductor and capacitor play a major role in the operation of a bidirectional AC/DC converter. Inductance is used for bi-directional power flow and boost operation, while the capacitance is used to maintain the constant DC output by reducing the output DC ripples. The modulating index must be less than 1 for PWM pulse (say, M.I = 0.8), since the amplitude of modulating signal must be greater than of the amplitude of carrier signal [10][11][12].

For sinusoidal AC voltage,  $v_s = V_s \sin \omega t$

Voltage gain: The boost voltage obtained in the output can be calculated by,

$$V_{dc} = \frac{v_s}{(1-d)} M. I \tag{7}$$

Input current: AC side peak supply current is given by,

$$I_s = \frac{2 P_o}{v_s \cos \phi} \tag{8}$$

Inductance: The fundamental component of PWM switch should be given by  $V_r$ . It should be varied from the supply voltage at an angle of  $\delta$  as the line is similar to that of transmission line.

$$L = \sqrt{\frac{V_r^2 - v_s^2}{(\omega I_s)^2}} \tag{9}$$

Capacitance: The output capacitance is given by,

$$C = \frac{P_o}{2 \pi f V_{dc} \Delta V} \tag{10}$$

Resistive Load:  $R = \frac{V_o^2}{P_o}$  (11)

Output Current:  $I_o = \frac{P_o}{R}$  (12)

Carrier frequency: The carrier frequency should be minimum of the order of  $11 * f_s$ , where  $f_s$  is the supply or fundamental frequency. For 50Hz supply it should be above 550Hz.

### III. SIMULATION STUDIES

A simulink model is built using MATLAB/Simulink software to test the feasibility of the proposed scheme. Fig. 3 shows the simulink model of a bidirectional AC/DC converter modelled according to the parameter design.

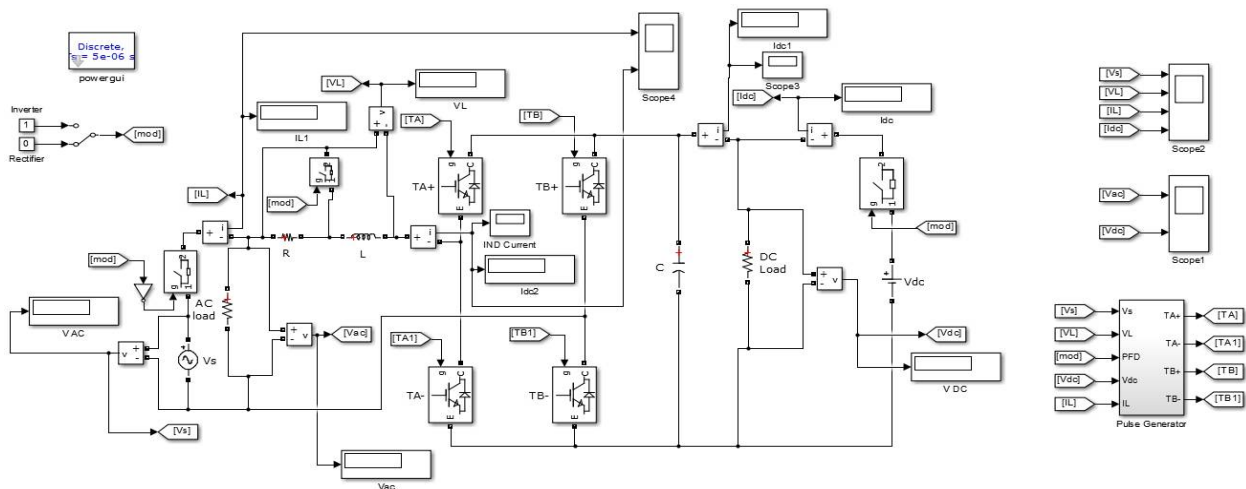


Fig. 3 Simulink Model of a Bidirectional AC/DC Converter

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For AC to DC conversion, the input is assumed as  $110\sqrt{2}$  V, 50 Hz and the corresponding output to be obtained is 300 V DC. Reverse operation should occur in the inversion mode.

TABLE V  
SIMULATION PARAMETER VALUES FOR THE BIDIRECTIONAL AC/DC CONVERTER

Parameters	Value
AC grid voltage ( $v_s$ )	$110\sqrt{2} \sin \omega t$ V, 50 Hz
AC input Current ( $I_s$ )	7.73 A
DC Voltage Command ( $V_{dc}$ )	300 V dc
Inductance (L)	1.65 mH
Series Resistance ( $R_s$ )	$0.77 \Omega$
Capacitance (C)	$1400 \mu F$
Load (R)	$150 \Omega$
Output Power ( $P_o$ )	600 W
Switching Frequency ( $f_s$ )	40 kHz

The Table V shows the simulation parameters for the bidirectional AC/DC converter system using the MATLAB/Simulink software as per the parameter design equations derived.

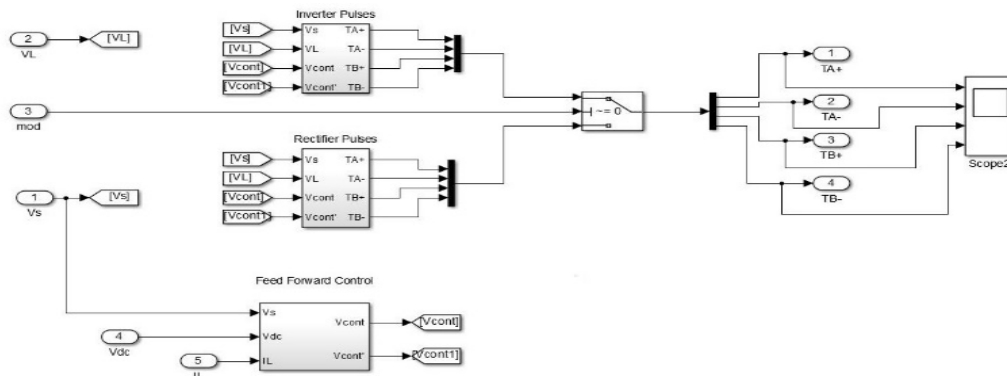


Fig. 4 Simulink Model of Pulse Generator using Simplified PWM with Feed-Forward Control

The figure 4 shows the Simulink model of switching pulse generator using simplified PWM with feed-forward control utilized for the operation of the bidirectional AC/DC converter. According to the mode of operation, different pulses are given to the switches as shown in table I & II.

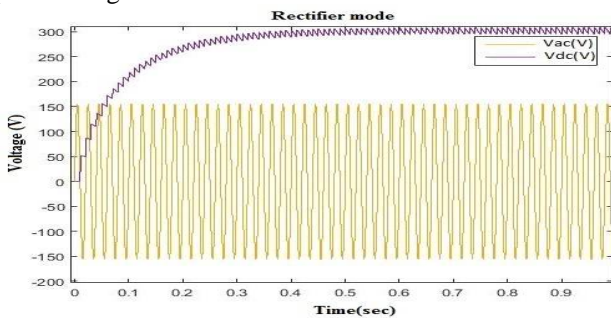


Fig. 5 Simulation Result for Rectifier Mode

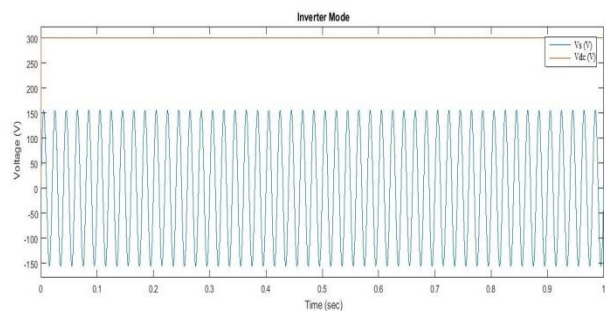


Fig. 6 Simulation Result for Inverter Mode



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The simulation results of the proposed bidirectional AC/DC converter in rectifier mode and inverter mode are shown in figures 5 and 6, respectively. In Rectifier Mode, the input sine wave of  $110\sqrt{2}$  V, 50 Hz is converted into a DC output of  $300\text{ V} \pm 10\text{ V}$ . In Inverter mode, a 300V DC is converted to 115.56 V, 50 Hz sine wave with THD 4.92%.

TABLE VI  
SIMULATION RESULTS IN RECTIFIER MODE

Rectifier Mode		
Control Scheme	THD	Power Factor
Dual Loop control	40.93%	0.89
Feed forward Control	9.56%	0.95

TABLE VII  
SIMULATION RESULTS IN INVERTER MODE

Inverter Mode		
Control Scheme	THD	Power Factor
Dual Loop control	15.4%	0.932
Feed forward Control	4.92%	0.975

The summary of results obtained when the converter is operated in the rectifier and inverter mode using simplified PWM strategy, with both the conventional dual-loop and feed forward control scheme, are shown in Tables VI and VII, respectively. The feed forward control is found to be superior to dual loop control in terms of both THD and power factor.

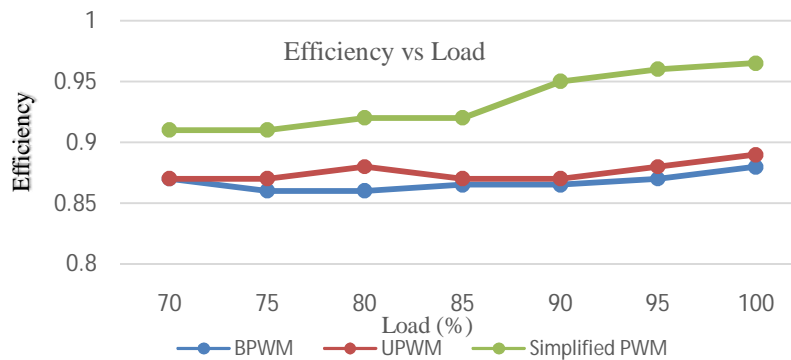


Fig 7: Measured efficiency of the ac/dc converter operated in BPWM, UPWM and Simplified PWM.

The efficiency of the ac/dc converter operated at full load 600W utilizing BPWM, UPWM, and the simplified PWM was measured and the results shown in Fig. 7 indicates that the simplified PWM strategy has higher efficiency than UPWM and BPWM because of the reduced switching losses. The efficiency at full load operation is found to be 0.965 using the Simplified PWM strategy.

## IV. EXPERIMENTAL STUDIES

In order to verify the effectiveness of the simplified PWM strategy with feed-forward control scheme, a prototype system was constructed as shown in Fig 8. The adopted active switches were Metal Oxide Semiconductor Field Effect Transistor (MOSFET IRF540N) with the body diode utilized as the anti-parallel diodes. The system controller was implemented with Arduino Mega2560 board.

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Fig. 8 Completed Laboratory Setup of the Bidirectional AC/DC Converter

Parameters	Value
AC grid voltage ( $v_s$ )	24 V, 50 Hz
AC input Current ( $I_s$ )	7.73 A
DC Voltage Command ( $V_{dc}$ )	48 V dc
Inductance (L)	1.45 mH
Capacitance (C)	1800 $\mu$ F
Load (R)	57.6 $\Omega$
Output Power ( $P_o$ )	40 W
Switching Frequency ( $f_s$ )	40 kHz

TABLE VI  
PARAMETERS VALUES FOR THE EXPERIMENTAL PROTOTYPE

However, the implemented actual ac grid voltage source was a distorted-sinusoidal-waveform voltage source with total harmonic distortion  $THD_v = 5\%$ . The prototype model shown in Fig.8 is designed for feeding a 40 W resistive load as given in Table VI. The grid supply voltage 230 V, 50 Hz AC is converted into 24V, 50Hz AC using a step down transformer, to provide a 48 V boosted DC output. The output obtained from the experiment conducted on the bidirectional AC/DC converter validates the theoretical findings.

## V. CONCLUSION

A bidirectional single-phase ac/dc converter using simplified PWM strategy with feed-forward control is designed. The number of switching status change in simplified PWM is one-fourth of that of the conventional BPWM and UPWM switching. The efficiency of the AC/DC converter operated in the simplified PWM strategy is higher than that in the UPWM and BPWM strategies. Based on the feed-forward control scheme, both ac current shaping and dc voltage regulation are achieved in both the rectifier and inverter operating modes. From the simulation analysis, it is clear that by using the feed forward control scheme for the closed loop control of the bidirectional AC/DC converter, the THD decreases and pf is increased compared to conventional dual loop control scheme in both rectifier and inverter modes. Finally, the prototype system was constructed and tested, using Arduino mega 2560 board as the controller. Both the simulation and experimental results verify the validity of the proposed PWM strategy and control scheme.

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