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Bidirectional AC/DC Converter PWM Strategy To Reduce Switching Loss with Feedforward Control in Grid-Tied Micro Grid System

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***Abstract*-— This paper proposes the simplified pulse width modulation (PWM) strategy in the bidirectional ac/dc single-phase converter with the feed-forward control scheme. In this, the number of switching of the proposed simplified PWM strategy is reduced to one-fourth to that of the unipolar & bipolar PWM. The feed-forward control scheme is used to achieve better performance of the ac/dc converter in both the rectifier & inverter mode as compared with the conventional dual-loop control scheme. The simplified PWM strategy with feed-forward control scheme has higher efficiency than that of the unipolar PWM & bipolar PWM strategies. Also, the total harmonic distortion is less in this PWM strategy. The simulation & experiments are carried out to verify the validity of the proposed PWM strategy & control scheme.**

***Keywords*: Simplified PWM strategy, Feed-forward control, Bidirectional ac/dc converter.**

I. INTRODUCTION

In recent years, demand of electricity is increasing rapidly because of various technical inventions, awareness of its usefulness, etc. Widely used sources are the conventional sources. But now-a-days, due to the increasing use of electricity & its high cost, these conventional sources are in degradation. Hence, it becomes a major challenge to develop commercially relevant substitute sources for generation of electrical energy. Tremendous research works are being carried out to develop feasible & pollution free power generation resources. Most probable renewable energy resources are solar i.e. photovoltaic, wind, biomass, hydro, fuel cells.

These renewable resources are connected to the grid through grid connected single-phase AC/DC PWM converters. Conventionally, AC/DC converters are called as rectifiers & DC/AC converters are called as inverters. These AC/DC converters are developed using thyrister& diodes in order to provide controlled & uncontrolled dc power with unidirectional & bidirectional power flow. The converter with approximately sinusoidal input currents & bidirectional power flow can be achieved by coupling a PWM rectifier & PWM inverter to the DC-link in a single-phase full-bridge rectifier. By using this, both the ac grid side & renewable energy resources sides are maintained properly.

As the power quality is defined by the current quality, the PWM technique is most popularly used in the voltage-source converters[19]. Poor power quality in terms of injected current harmonics causes due to the voltage distortions, poor power factor at input ac mains & slow varying rippled dc output at load end, low efficiency & large size of ac & dc filters are some of the demerits of the conventional rectifier[6]. To reduce the aforementioned problems of the conventional rectifiers, new kind of rectifiers using new solid-state self commutating devices such as MOSFETs, IGBTs, GTOs, etc. have been developed.

In this paper, the single-phase PWM converter is utilized in between the ac grid system & the renewable energy sources that operates efficiently to retain the power system stability. Some of the requirements of single-phase AC/DC PWM converters are to provide the power factor correction function[4], low distortion line currents[1], high-quality dc output voltage[2] & bidirectional power flow capability[8], etc. Some of the PWM strategies that have been used are bipolar PWM (BPWM), unipolar PWM (UPWM), hybrid PWM (HPWM) & Hysteresis switching[3][7]. But in the aforementioned PWM strategies, the switches are operated at higher frequencies than that of the ac line frequency with larger switching power losses.

To come up with the aforementioned problems, a new family of PWM strategy is developed in this paper. This newly developed PWM strategy requires only one active switch state to be changed during the switching period of the single-phase AC/DC converter. Also, the

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new feed-forward control method is developed in which converter can operate well in both the rectifier & inverter mode. This newly developed feed-forward control can provide fast output voltage response & improve input ac current shaping in both the UPWM & BPWM strategies also.

II. SINGLE-PHASE BIDIRECTIONAL AC/DC CONVERTER MODEL

The single-phase AC/DC converter is connected in between the DERs & ac grid system to provide the power flows bidirectionally as shown in fig. 1. The converter with approximately sinusoidal input currents& bidirectional power flows can be achieved by coupling a PWM rectifier & a PWM inverter to the DC-link in a single-phase full-bridge rectifier. By using this, both the ac grid side & DERS sides are maintained properly. On ac side, for maintaining sinusoidal ac current shaping PWM rectifier is used & by using PWM inverter on DC side the voltage regulation is accomplished.

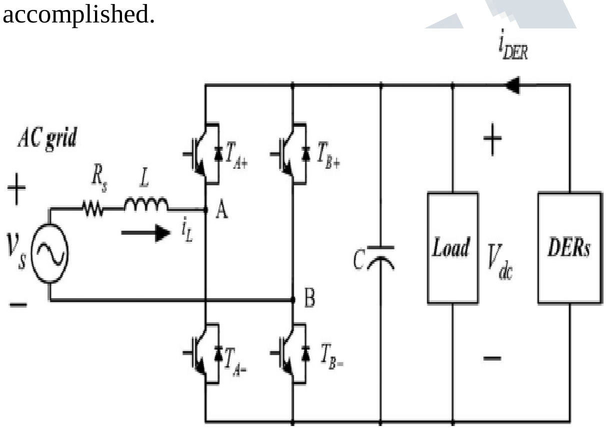

Fig. 1 Application of a bidirectional single-phase ac/dc converter in the renewable energy system

2.1 Operation Principle of The Proposed AC/Dc Converter:

In renewable energy system, the bidirectional AC/DC converter plays an important role to achieve the power system stability & also for efficient use of the distributed energy resources (DERs). The energy generated from distributed energy resources is used to provide electricity to the DC loads. But due to the deficiency of energy resources if there is no sufficient power to the DERs then in such cases the bidirectional ac/dc converter plays an important role to change the flow of power from ac grid to dc grid[11][12]. This is done to provide power to the dc loads & the energy storage systems.

In renewable energy system, the bipolar or unipolar PWM strategies may be applied for single-phase full-bridge converter to achieve bidirectional power flows & also to obtain better sinusoidal ac current shaping & DC voltage regulation. As compared with the conventional SPWM techniques, the simplified PWM strategy requires only one active switch status to be changed during switching period of the charging & discharging of the ac side inductor current. Thus, reducing the switching losses in the proposed simplified PWM strategy also by providing the higher conversion efficiency.

A feed-forward control scheme is developed to improve the control ability of the system by providing fast output voltage response & improved ac current shaping in both the rectifier & inverter mode of the single-phase bidirectional ac/dc converter.

2.2 Simplified PWM Strategy

The simplified PWM strategy requires only one active switch status to be changed during the switching period of charging & discharging of the ac side inductor current. The Table-1 & 2 shows the switching states of the proposed simplified PWM strategy used in rectifier & inverter mode operation respectively.

Table1: Rectifier Mode Switching combination in the Proposed simplified PWM

Status	TA+	TA-	TB+	TB-	VL	IL
A	OFF	OFF	ON	OFF	VS	IL>0
B	OFF	ON	OFF	OFF	VS	IL>0
E	OFF	OFF	OFF	OFF	VS-Vdc	IL>0
C	ON	OFF	OFF	OFF	VS	IL<0
D	OFF	OFF	OFF	ON	VS	IL<0

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E	OFF	OFF	OFF	OFF	VS+Vdc	IL< 0

Table 2: Inverter Mode Switching Combination in the Proposed Simplified PWM

Status	TA+	TA-	TB+	TB-	VL	IL
F	ON	OFF	OFF	OFF	VS	IL< 0
G	OFF	OFF	OFF	ON	VS	IL< 0
H	ON	OFF	OFF	ON	VS – Vdc	IL< 0
I	OFF	ON	OFF	OFF	VS	IL>0
J	OFF	OFF	ON	OFF	VS	IL> 0
K	OFF	ON	ON	OFF	VS+ Vdc	IL> 0

2.2.1 Rectifier Mode:

Assume that the internal impedance of the single-phase ac grid system as shown in fig.1 is highly inductive which is represented by L. The equivalent series resistance of L is neglected. When AC grid voltage source, vs> 0,the circuit operates according to the switching combination of states A & B as shown in Table 1. In the A & B states, the voltage across the inductor is vs, thus the inductor current is in charging state. While the converter operating as in status E, all the switches are turned OFF. In this case, the inductor voltage becomes vs – Vdc, that decreases the inductor current, which shows that the inductor is in the discharging state.

When AC grid voltage vs<0, the circuit operates with switching combination as given in status C or D. In these cases, the voltage across the inductor L is given by vs.The inductor current is found to be decreasing in both these states, therefore the Inductor current is in the discharging state. When the converter is in status E, all the switches are turned OFF & inductor voltage becomes vs + Vdc, that increase the inductor current. Thus, in this condition the inductor current is in charging state.

2.2.2 Inverter Mode:

When the converter is operated in the inverter mode, the switching combination is as listed in Table 2. In this mode the actual inductor current is in the reverse direction compared to the AC grid voltage. Consider the AC grid voltage, vs > 0, the input current is in the reverse direction, i.e. IL< 0. Both the status F & G gives inductor L positive voltage to charge theinductor current & status H gives negative voltage to inductor L to discharge the inductor current.

While AC grid voltage source, vs< 0, the input current is in the reverse direction, IL > 0. Both the statuses I & J give negative voltage to the inductor to discharge the inductor current & status K gives positive voltage to inductor L to charge the inductor current.

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

III. COMPARISON OF PWM STRATEGIES

Comparison of BPWM, UPWM & the proposed simplified PWM strategies are conducted, to understand the merits of simplified PWM strategies.

3.1 No. of switching status

BPWM has only two switching status (Table 3), as in bipolar control, the switches turn ON & OFF simultaneously & diagonally (i.e. TA+, TB+ or TA-, TB-) & each leg activates supplementary (i.e. TA+, TA-&TB+, TB-). In the UPWM, there are four switching status (Table 4), as in unipolar control, the switching signals of (TA+, TA) & (TB+, TB-) are controlled separately by comparing carrier waveform withoriginal & reverse control signal to get +Vdc, -Vdc & zero voltage levels. But from Table 1 & 2 one can find that simplified PWM needs only one switching status to be changed.

Table 3: Statuses of the Active Switches in BPWM

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

Table 4: Statuses of the Active Switches in UPWM

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

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3.2 Switching Loss

The switching time is defined as the number of changes in switching status regardless of whether the switch is turned ON or OFF. From Table 3, it can be observed that by considering the status change of active switches in BPWM,.it needs eight active switching times in a switching period. From Table 4, it can be observed that UPWM also needs eight active switching times in a switching period. From Table 1 & 2, it can be observed that proposed simplified PWM needs only two active switching times in a switching period. Thus, it implies that the switching losses in simplified PWM strategy are one-fourth to that of the conventional BPWM & UPWM strategies.

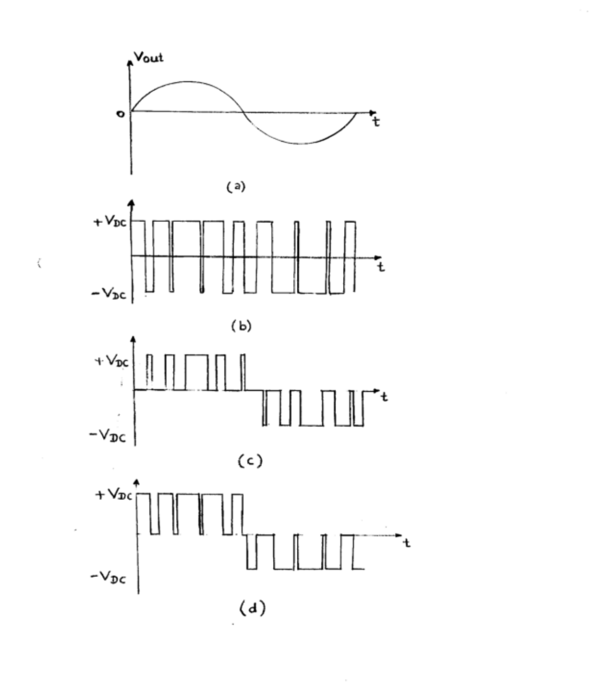

Fig. 2 (a)Inverter output (b)BPWM (c)UPWM (d)Simplified PWM

IV. FEEDFORWARD CONTROL SCHEME

In this section, the feed-forward control scheme is explained which is based upon the proposed simplified PWM strategy. For this, the rectifier mode operation of the converter is explained first. The switching combination in the rectifier mode of the converter operation is as shown in Table 1. One can choose operation statuses A & E during the condition vs> 0 & statuses C & E during the condition vs< 0. Instead of using status A the selection of status B is also allowed in case of charging the inductor & selection of status D instead of status C in case of discharging of the inductor current in the proposed simplified PWM strategy.

The duty ratio for state-space averaged equation for the proposed simplified PWM strategy is defined as Don = ton / T, where ton is the time duration when the switch is turned ON i.e. Son =1 & T is the time period of triangular waveform.

Similarly, the duty ratio Doff is defined as Doff = 1 - Don, when the switch is turned OFF.

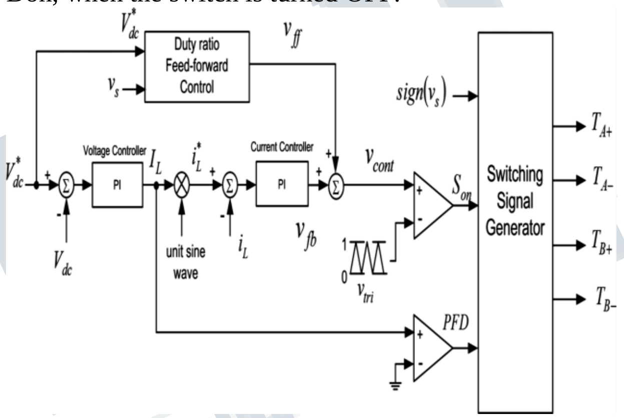

Fig.3: Proposed control scheme for the proposed simplified PWM strategy

For the positive half-cycle of the ac grid voltage source i.e. for vs> o, the duty ratio of status A & B is defined as Don & that of status E is defined as Doff . By applying the state-space averaged technique & volt-second balance theory to the status A & E, the state-space averaged eqn is derived as

$$Vs - (1\text{-}Don)\, Vdc = 0 \qquad (1)$$

During the steady state operation of the converter, the dc voltage is equal to the desired command Vdc = V*dc . Hence the eqn (1) becomes

$$Don = (1 - vs / V^*dc) \qquad (2)$$

Now, for the negative half-cycle of the ac grid voltage source i.e. vs < 0, the duty ratio for status E is Don& that of status C is Doff. Again by applying the state-space averaged technique & volt-second balance theory to status E & C, the state-space averaged eqn becomes

$$Vs + Don\ Vdc = 0 \quad (3)$$

Again for the steady state operation of the converter, the output voltage Vdc is equal to thedesired command i.e. Vdc = V*dc. Thus eqn (3) becomes

$$Don = - vs / V^*dc \quad (4)$$

According to the PWM properties, one can also express the switching duty ratio in terms of the control signal V'cont& the peak value Vtriof the triangular waveform.

$$Don = V'cont / Vtri \quad (5)$$

Substituting eqn (2) in eqn (4) & (5), the switching duty ratio for both conditions vs> 0 & vs< 0 i.e.

$$V'cont = \begin{cases} (1 - vs / Vo)\ Vtri, & \text{if } vs > 0 \\ -(vs / V^*dc)\ Vtri, & \text{if } vs < 0 \end{cases} \quad (6)$$

Now consider the inverter mode of the converter operation. The switching state combination is as shown inTable 2. Similar to the rectifier mode, the same process is done in the inverter mode of the converter operation. In this, for the positive half-cycle of the ac grid source voltage i.e. vs> 0, one can choose status F or status G for charging the inductor & status F or status G for discharging the inductor. Also for negative half-cycle of the ac grid source voltage i.e. vs< 0, one can choose status I or status J for discharging the inductor & status K for charging the inductor. Similar process is followed in inverter mode to obtain the eqn for the control signal V'cont as in the rectifier mode. The eqn for V'cont in the inverter & rectifier mode is same as described in eqn (6). As the control signal V'cont is directly proportional to the duty ratio Don, one can use the calculated control signal V'cont as the duty ratio of feed-forward control signal Vff. This is used to add into the dual-loop feedback control signal Vfb. The feed-forward control signal Vff improves the controllability which can provide fast output voltage response as well as it improves input current shaping.

The switching signal generator requires signals Son, the grid voltage sign (vs) & PFD combined with Tables 1 & 2 that generates the switching signals TA+, TA-, TB+,TB- . The proposed feed-forward control scheme is suitable for the proposed simplified PWM strategy & also for both the conventional BPWM & UPWM strategies.

V. PARAMETERS USED

The inductor & capacitor is the very important part of a bidirectional AC/DC converter. As inductor is used for bi-directional power flow & the capacitor is used to maintain the DC output voltage constant by reducing the output ripples. For PWM pulses the modulation index (M.I.) must be less than 1(say, M.I. =0.8), as the amplitude of modulating signal must be greater than that of the amplitude of carrier signal [8].
Input voltage:For sinusoidal ac voltage,

$$vs = Vs \sin \omega t \quad (7)$$

Input current:AC side peak supply current can be expressed as

$$Is = (2\ Po) / (vs \cos \varphi) \quad (8)$$

Output voltage: The output mode of the inverter can be written as

$$Vout = Vdc * m * \sin (2\pi\ f0\ t) \quad (9)$$

Where, Vout , Vdc , m, f0 represents the output voltage, input voltage, modulation factor & output frequency respectively.

Output current:

$$Io = Vout / R \quad (10)$$

Output Power: If an ideal lossless power converter is assumed, the output power Po is given by,

$$Po = (vs\ Is \cos \varphi) / 2 \quad (11)$$

Inductance:

$$L = \sqrt{(Vr2 - vs2) / (\omega Is)\ 2} \quad (12)$$

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Where, Vr is the fundamental component of PWM switch. It should varied from supply voltage at an angle of δ as the line is similar to that of transmission line.

Capacitance: The output capacitance is given by

$$C = P0 / (2\pi f V dc \Delta V) \quad (13)$$

Carrier Frequency: Carrier frequency should be of the order of 11 * fs , where fs is the supply frequency or fundamental frequency. For 50 Hz supply frequency it should be more than 550 Hz.

VI.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 .

For AC/DC conversion, the input voltage is assumedas 110√2 V, 50 Hz & the corresponding output voltage to be obtained is 300 V. In inverter mode, reverse operation should occur.

Table 5:Simulation Parameter values for the bidirectional AC/DC converter

Parameters	Values
Inductance (L)	1.65 mH
Capacitance (Co)	1400 µF
Output voltage command Vdc*	300 V
AC grid voltage vs	110√2 sin ωt (V)
Load	150 Ω
Switching frequency	40 kHz
DER (only inverter mode)	4 A

The Table 5, shows the simulation parameters for the bidirectional AC/DC converter system using MATLAB/ Simulink software.

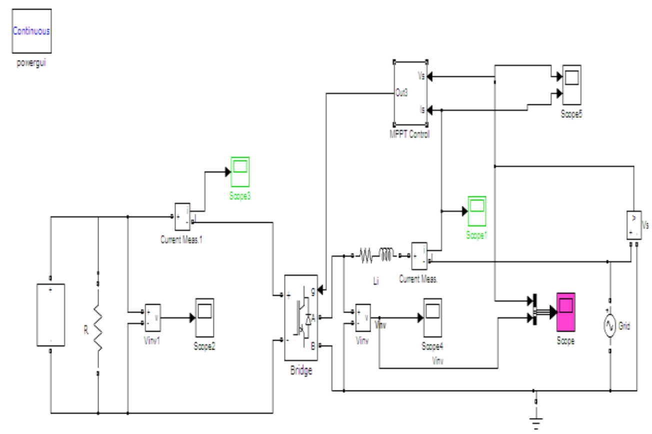

Fig.4 MATLAB Simulink Model of proposed PWM strategy inbidirectional single-phase ac/dc converter in renewable energy system

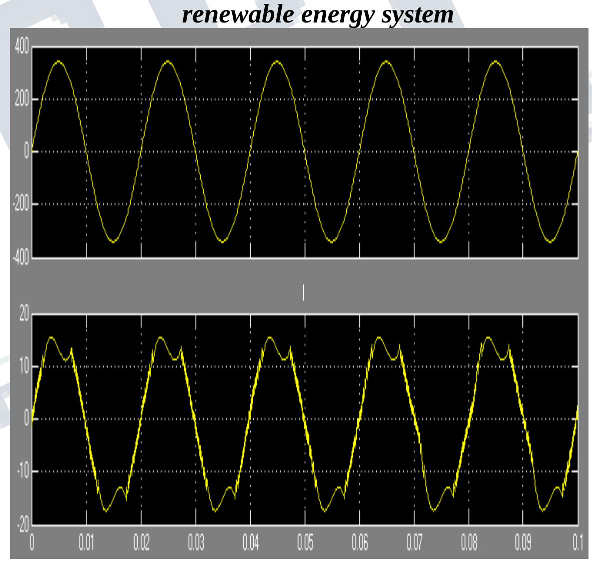

Fig.5 Measured grid voltage (VS) and line current (IS) waveforms of the converter using Feedforward control scheme in the proposed simplified PWM strategy operated in the rectifier mode

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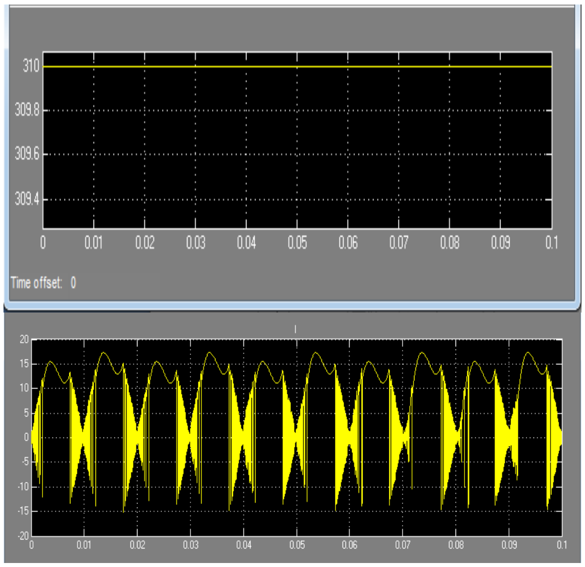

Fig.6 Measured DC Voltage (Vdc) & line current waveforms in the inverter mode

The simulation results of the proposed bidirectional AC/DC converter in rectifier & inverter mode are as shown in figures 4 & 5 respectively. In Rectifier mode, the input sinusoidal voltage 110√2 V, 50 Hz is converted into a DC output of 300 V. In the Inverter mode ,the DC output voltage of 300 V is converted to 113.42 V, 50 Hz sinusoidal voltage with THD of 4.83%.

Table 6:Simulation Results in Rectifier Mode

Rectifier Mode		
Control Scheme	THD	Power Factor
Dual-loop control	36.42%	0.91
Feedforward control	7.23%	0.974

Table 7: Simulation Results in Inverter Mode

Inverter Mode		
Control Scheme	THD	Power Factor
Dual-loop control	6.32%	-0.951
Feedforward control	4.53%	-0.982

From the Table 6 & 7 it is observed that feedforward control is superior than dual-loop control scheme in terms of both THD & power factor.

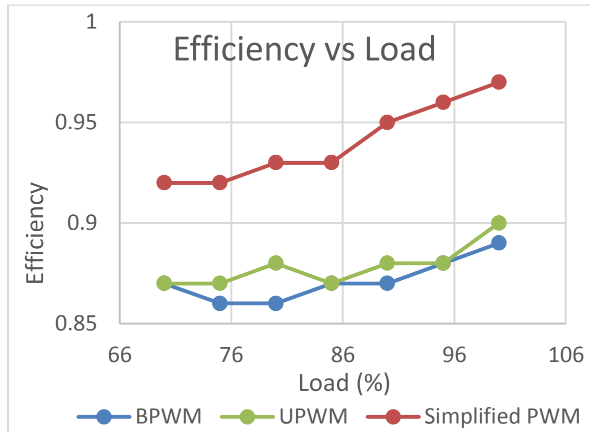

Fig.6 Measured efficiency of the ac/dc converter operated in BPWM, UPWM & simplified PWM

The efficiency of the AC/DC converter operated at full load of 600W using BPWM , UPWM & simplified PWM was measured & the results shown in figure shows that the efficiency of the simplified PWM strategy is higher than that of the UPWM & BPWM strategies because of the reduced switching losses. The efficiency at full load is found to be 0.968 using the simplified PWM strategy.

VII.EXPERIMENTAL STUDIES

In order to verify the effectiveness of the proposed simplified PWM strategy with feed-forward control scheme, a prototype was constructed as shown in figure . The adopted active switches were Metal Oxide Semiconductor Field Effect Transistor(MOSFET IRF540) with the body diodes used as the anti-paralleling diodes.

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Fig. 7 Completed Experimental Setup of the Bidirectional AC/DC PWM Converter

Table 6: Parameter Values for the experimental prototype

Parameters	Values
AC grid voltage (vs)	12 V, 50 Hz
DER (only inverter mode)	1 A
DC Voltage Command (Vdc)	12 V
Inductance (L)	1.65 mH
Capacitance (C)	104 µF
Load (R)	500Ω
Switching frequency (fs)	40kHz

The implemented actual AC grid voltage source was a distorted-sinusoidal-waveform voltage with Total Harmonic Distortion THDv = 5%. The prototype model shown in figure is designed for feeding 40W resistive load as given in Table 6. The ac grid supply voltage 230 V, 50 Hz is converted using a step-down transformer, to provide a 12 V DC output. The output is obtained from the experiment conducted on bidirectional AC/DC converter validates the theoretical findings

Conclusion

This paper presented the simplified PWM strategy with feed-forward control scheme for the bidirectional ac/dc converter. In this PWM strategy instead of using four active switch status as required in the UPWM & BPWM, only one active switch status is required in the switching period of the converter. Also efficiency of the ac/dc converter is improved than that of the UPWM & BPWM strategies. By using simplified PWM strategy in the rectifier & inverter mode of the ac/dc converter, output voltage regulation is achieved. The THD of the proposed simplified PWM strategy is less than that of the UPWM & BPWM strategies.

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