International Journal of Research
Available at https://edupediapublications.org/journals
p-ISSN: 2348-6848
e-ISSN: 2348-795X
Volume 03 Issue 12
August 2016

Intelligent Controller Based Feed Forward Control for AC to DC Converter PWM strategy With Reduced Switching Loss

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Abstract: A single-stage power factor correction (PFC) converter for feeding a bidirectional AC/DC converter. A simplified pulse width modulation (PWM) strategy is used for the bidirectional ac/dc single phase converter in a microgrid system. Then, the operation mechanism of the novel simplified PWM is clearly explained. The number of switching's of the simplified PWM strategy is one fourth that of the unipolar PWM and bipolar PWM. Based on the novel simplified PWM strategy, a feasible feedforward control scheme is developed to achieve better rectifier mode and inverter mode performance compared with the conventional dual loop control scheme. The requirement of continuous and controlled flow of voltage has met with the support of fuzzy logic controller and the capacitors present with the schematic design helps this requirement to be met in an efficient way. The conduction losses are reduced by using fuzzy logic controller in closed loop condition which reduces the switching losses and increases the output energy and the total harmonic distortion will be reduced. The proposed fuzzy logic controller based converter is implemented in MATLAB simulation platform and the output performance is analyzed.

Index Terms—Bidirectional ac/dc converter, simplified pulse width modulation (PWM) strategy, total harmonic distortion(THD).

I. INTRODUCTION

The single-phase ac/dc pulse width modulation (PWM) converter is widely used in many applications such as adjustable-speed drives, switch-mode power supplies, and uninterrupted power supplies. The single-phase ac/dc PWM converters [1] are usually employed as the utility interface in a grid-tied renewable resource system, To utilize the distributed energy resources (DERs) efficiently and retain power system stability, the bidirectional ac/dc converter plays an important role in the renewable energy system. When DERs have enough power, the energy from the dc bus can be easily transferred into the ac grid through the bidirectional ac/dc converter. In contrast, when the DER power does not have enough energy to provide electricity to the load in the dc bus, the bidirectional ac/dc converters can simultaneously and quickly change the power flow direction (PFD) from ac grid to dc grid and give enough power to the dc load and energy storage system. There are many requirements for ac/dc PWM converters as utility interface in a grid-tied system; for instance, providing power factor correction functions [2], low distortion line currents, high quality dc output voltage, and bidirectional power flow capability. Moreover, PWM converters are also suitable for modular system design and system reconfiguration. In this paper, a novel PWM control strategy with feed forward control scheme of a bidirectional single-phase ac/dc converter is presented.

In particular, Recurrent Fuzzy Systems [3, 4] represent the system dynamics approximately by means of linguistic rules, in which the conclusion part consists of the state derivative beingdescribed simply as a constant. Thus, Recurrent Fuzzy Systems may also be interpreted as zeroth-order Takagi-Sugeno fuzzy systems. In contrast to the more general Takagi-Sugeno fuzzy systems, the main benefit of Recurrent Fuzzy Systems relies on the possible linguistic interpretability of the rules obtained. Having obtained a recurrent fuzzy system, the question arises on how to control this particular system class. In [5, 6] it was shown how to derive stabilizing feedback for these dynamic fuzzy systems by means of static fuzzy control or switching polynomial controllers for known equilibria.

In the existing PWM control strategies of a single-phase ac/dc converter, the converter switches are operated at higher frequency than the ac line frequency so that the switching harmonics can be easily removed by the filter [7], [8], [9]. The ac line current waveform can be more sinusoidal at the expense of switching losses. Until now several PWM strategies have been utilized in a single-phase ac/dc converter such as bipolar PWM (BPWM), unipolarPWM(UPWM)[10]–[12],hybridPWM(HPWM) and Hysteresis switching [7].UPWM results in a smaller ripple in the dc side current and significantly lower ac side harmonic content compared to the BPWM. The UPWM effectively doubles the switching frequency in the ac voltage waveform harmonic spectrum allowing the switching harmonics to be easily removed by the passive filter. The HPWM utilizes two of the four switches modulated at high frequency and utilizes the other two switches commutated at the (low) output frequency to reduce the switching frequency and achieve better quality output.However, the switching loss in the HPWM is still the same as that of the UPWM [13].

II. OPERATION PRINCIPLE OF THE PROPOSED SIMPLIFIED PWM STRATEGY

A bidirectional single-phase ac/dc converter is usually utilized as the interface between DERs and the ac grid system to deliver power flows bidirectional and maintains 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.

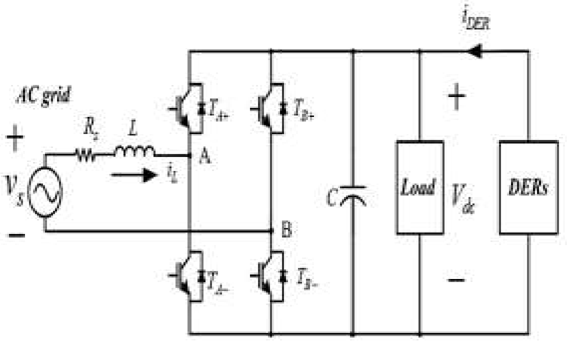


Fig.1. Application of a bidirectional single-phase ac/dc converter in the renewable energy system.

TABLE I
Rectifier Mode Switching Combination in the Proposed Simplified PWM

	Status	T_{A+}	T_{A-}	T_{B+}	T_{B-}	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 THE PROPOSED SIMPLIFIED PWM

	Status	T_{A+}	T_{A-}	T_{B+}	T_{B-}	Inductor status
$v_s > 0$	F	ON	OFF	OFF	OFF	$v_L > 0$
	G	OFF	OFF	OFF	ON	
	H	ON	OFF	OFF	ON	$v_L < 0$
$v_s < 0$	I	OFF	ON	OFF	OFF	$v_L < 0$
	J	OFF	OFF	ON	OFF	
	K	OFF	ON	ON	OFF	$v_L > 0$

To achieve bidirectional power flows in a renewable energy system, a PWM strategy may be applied for the single-phase full-bridge converter to accomplish current shaping at the ac side and voltage regulation at the dc side. Generally, BPWM and UPWM strategies are often utilized in a single-phase ac/dc converter. In this Project, a novel simplified PWM strategy is proposed. The proposed simplified PWM only changes one active switch status 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 also provides high conversion efficiency. The switching statuses of the proposed simplified PWM are listed in Tables I and II for rectifier mode and inverter mode operation, respectively.

Both the rectifier and inverter mode operations of the simplified PWM strategies are explained in this section as follows.

A. Rectifier Mode

Consider the single-phase system shown in Fig. 1 and assume the ac grid system internal impedance is highly inductive and, therefore, represented by L. The equivalent series resistance of L is neglected. Consider the converter is operated in the rectifier mode. While ac grid voltage source is operating in the positive half-cycle vs > 0, the operating circuits of Statuses A and B listed in Table I of the proposed simplified PWM are shown in Fig. 2(a) and (b), respectively. Using Kirchhoff's voltage law in the circuit operation shown in Fig. 2(a) and (b), the voltage relationship can be obtained as follows:

$$v_s - L\frac{d}{dt}i_L = 0. \tag{1}$$

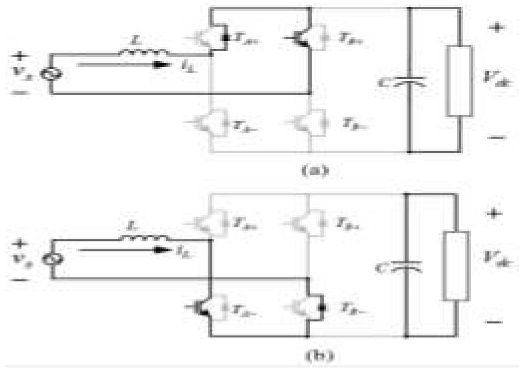


Fig. 2. Operation circuit of the proposed simplified PWM operated in the rectifier mode under (a) Status A and (b) Status B, while vs > 0 and iL > 0.

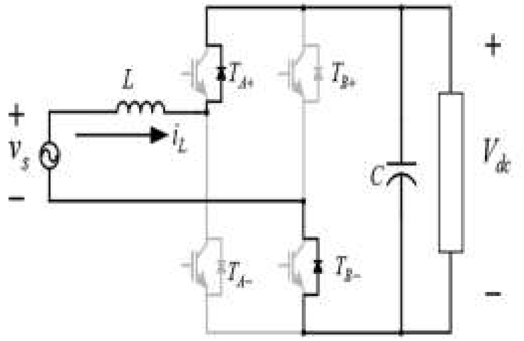


Fig.3. Operation circuit of the proposed simplified PWM operated in the rectifier mode under Status E, while vs > 0 and iL > 0.

One can see that while vs > 0, the inductor current is increasing in both Statuses A and B, and the voltage across the inductor is vs. Therefore, in this condition, the inductor current is in the charging state. While the converter is in Status E, as shown in Fig. 3, all of the switches are turned OFF. Using Kirchhoff's voltage law in the circuit operation shown in Fig. 3, the voltage relationship can be obtained as follows:

$$v_s - L\frac{d}{dt}i_L - V_{\mathrm{dc}} = 0 \tag{2}$$

The inductor voltage is vs − Vdc, which decreases the inductor current. Therefore, in this condition, the inductor current is in the discharging state.

Consider the ac grid voltage source during the negative half cycle vs < 0 in Fig. 1. The operating circuits of Statuses C and D of the proposed simplified PWM are shown in Fig. 4(a) and (b), respectively. Using Kirchhoff's voltage law in the circuit operation shown in Fig. 4, the voltage relationship can be obtained as follows:

$$v_s - L\frac{d}{dt}i_L = 0. \tag{3}$$

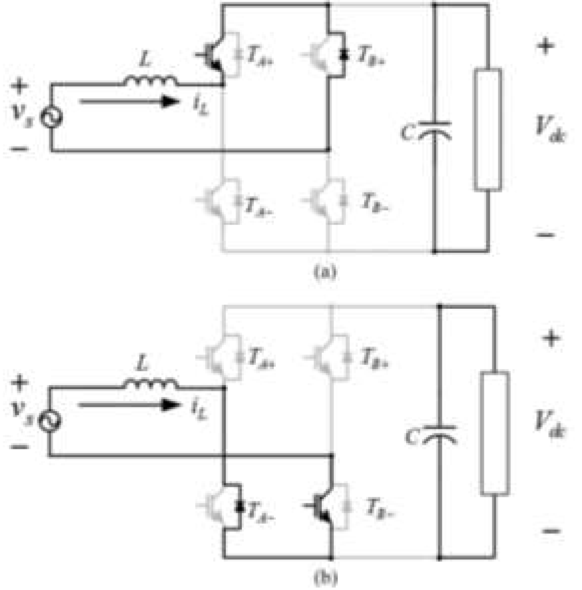


Fig. 4. Operation circuit of the proposed simplified PWM operated in the rectifier mode under (a) Status C and (b) Status D, while vs < 0 and iL < 0.

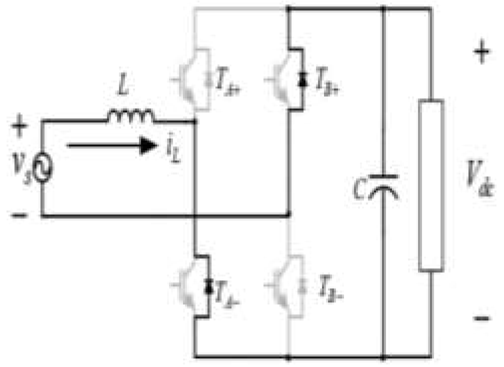


Fig. 5. Operation circuit of the proposed simplified PWM operated in the rectifier mode under Status E, while vs < 0 and iL < 0.

One can see that while the ac grid voltage source is operating in the negative half-cycle vs < 0, the inductor current is decreasing in both Statuses C and D. The voltage across the inductor L is vs. Therefore, in this condition, the inductor current is in the discharging state.

While the converter is in Status E, as shown in Fig. 5, all of the switches are turned OFF. Using Kirchhoff's voltage law in the circuit operation shown in Fig. 5, the voltage relationship can be obtained as follows:

$$v_s - L\frac{d}{dt}i_L + V_{\mathrm{dc}} = 0 \tag{4}$$

The inductor voltage is Vs + Vdc, which increases the inductor current. Therefore, in this condition, the inductor current is in the charging state.

In summary, while ac grid voltage source is operating in the positive half-cycle vs > 0, both Statuses A and B increase the inductor current and Status E decreases the inductor current to achieve ac current shaping and dc voltage regulation. While the

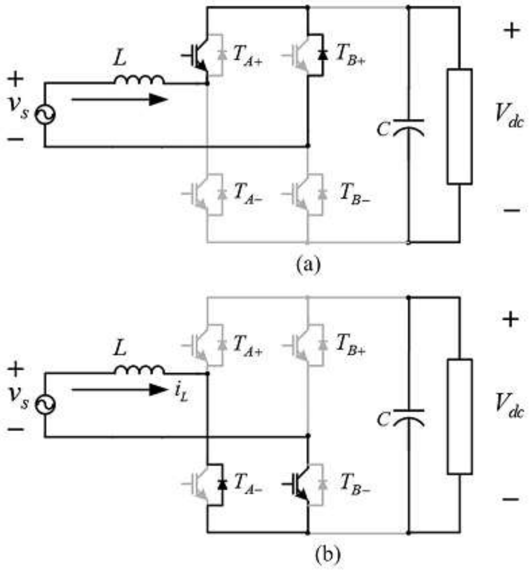


Fig. 6. Operation circuit of the proposed simplified PWM operated in the inverter mode under (a) Status F and (b) Status G, while vs > 0and iL < 0.

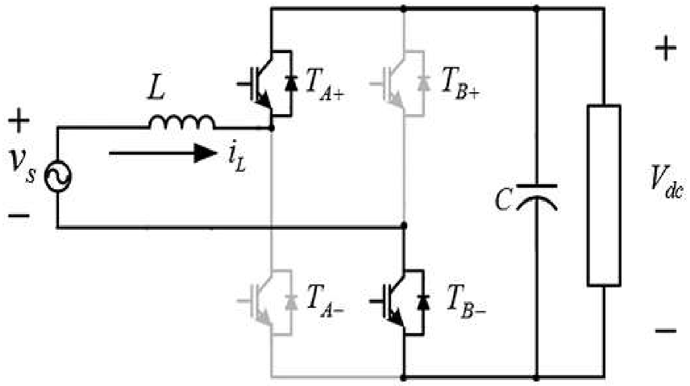


Fig. 7. Operation circuit of the proposed simplified PWM operated in the inverter mode under Status H, while vs > 0 and iL < 0.

ac grid voltage source is operating in the negative half-cycle vs < 0, both Statuses C and D decrease the inductor current and Status E increases the inductor current to accomplish ac current shaping and dc voltage regulation. Regardless whether the ac grid voltage source is operating in the positive half-cycle vs > 0 or negative half-cycle vs < 0, the converter inductor current can be increased or decreased properly in the proposed simplified PWM operated in the rectifier mode.

B. Inverter Mode

The switching combination of the proposed simplified PWM operated in the inverter mode is listed in Table II. When the converter is operated in the inverter mode, the actual inductor current is in the reverse direction compared to the ac grid voltage. Consider the ac grid voltage source is operating in the positive half-cycle vs> 0; the input current is in the reverse direction iL <0. Both Statuses F and G give inductor L positive voltage to charge the inductor current. The corresponding circuit operation of Statuses F and G is shown in Fig. 6. Status H gives inductor L negative voltage to discharge the inductor current, as shown in Fig. 7.

While the ac grid voltage source is operating in the negative half-cycle vs < 0, the input current is in the reverse directioniL > 0.

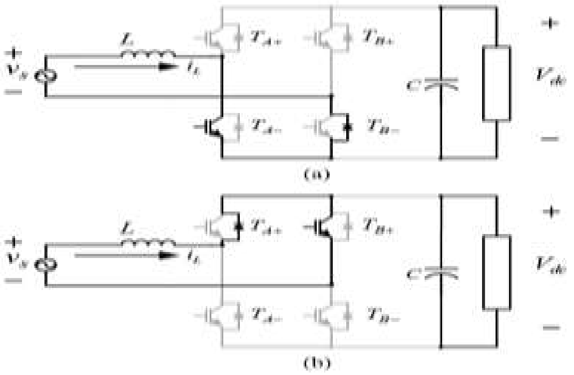


Fig. 8. Operation circuit of the proposed simplified PWM operated in the inverter mode under (a) Status I and (b) Status J, while vs < 0 and iL > 0.

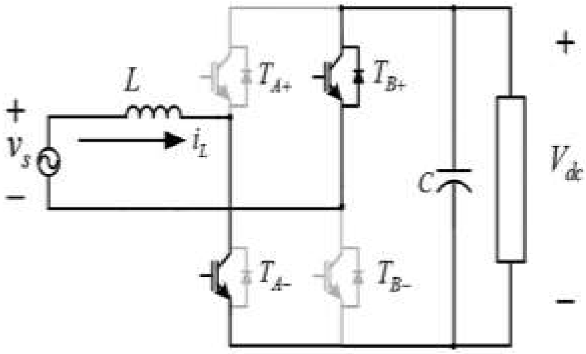


Fig.9. Operation circuit of the proposed simplified PWM operated in the inverter mode under Status K, while Vs< 0 and iL > 0.

Both Statuses I and J give inductor L negative voltage to discharge the inductor current. The corresponding circuit operation of Statuses I and J is shown in Fig. 8. Status K gives inductor L positive voltage to charge the inductor current, as shown in Fig. 9. Regardless of whether the ac grid voltage source is operating in the positive half-cycle vs > 0 or the negative half cycle vs<0, the converter inductor current can be increased or decreased properly to achieve ac current shaping and dc voltage regulation in the proposed simplified PWM operated in the inverter mode.

According to the previous discussion, the ac grid line current of a single-phase ac/dc PWM converter could be increased and decreased easily in both rectifier and inverter mode to achieve bidirectional power flows and proper line current shaping and voltage regulation in the proposed simplified PWM strategy.

III PROPOSED FEED FORWARD CONTROL SCHEME

However, the conventional dual-loop control scheme applied to the proposed simplifiedPWM cannot produce good performance in a single-phase bidirectional ac/dc converter. In this section, based on the proposed simplified PWM strategy, a feed forward control scheme is also developed to provide better line current shaping and better output voltage regulation compared with the conventional dual-loop control scheme.

A. Conventional Dual-Loop Control Scheme

In the conventional dual-loop control scheme applied to the single-phase bidirectional ac/dc converter, the inner current loop and outer voltage loop are utilized as shown in where Vdc is the dc voltage command, Vdc is the actual dc voltage; i_L^* is the ac current command, and IL is the actual ac current. The voltage controller calculates the voltage error and generates the current amplitude command IL multiplied by the unit sinusoidal waveform, obtained from the phase lock loop to generate the current commandi_L^*. In general, a proportional-integral controller is adopted as the voltage controller and current controller to achieve power factor correction at the ac side and voltage regulation at the dc side.

B. Proposed Feed forward Control Scheme

Based on the proposed simplified PWM, a novel feed forward control scheme is presented in this section. For a convenient explanation, the converter operated in the rectifier mode is discussed first. The rectifier mode switching combination is listed in Table I. One can choose operation Statuses A and E during the condition vs > 0, and Statuses C and E during the condition vs <0. It should be noted that the selection of Status A or B for increasing inductor current and Status C or D for decreasing inductor current is all allowable in the proposed simplified PWM strategy. To derive the state-space averaged equation for the proposed simplified PWM strategy, the duty ratio Don is defined as Don=ton/T , where ton is the time duration when the switch is turned ON, i.e., Son = 1, and T is the time period of triangular waveform. The duty ratio Doff is defined as Doff = 1 − Don, which is the duty ratio when the switch is turned OFF. While the ac grid voltage source is operating in the positive half-cycle vs > 0, the switching duty ratio of Status A is defined as D on and that of Status E is defined as Doff. The corresponding circuit equations of Statuses A and E were obtained in (1) and (2), respectively. By introducing the state-space averaged technique and volt–second balance theory, the state-space averaged equation is derived as follows:

$$v_s - (1 - D_{\text{on}})\, V_{\text{dc}} = 0. \tag{5}$$

When the converter is operated in the steady state, the dc voltage is equal to the desired command Vdc = Vdc ∗ ; (5) can also be expressed in the following form:

$$D_{\text{on}} = \left(1 - \frac{v_s}{V_{\text{dc}}^*}\right) \tag{6}$$

While the ac grid voltage source is operating in the negative half-cycle vs < 0, the duty ratios corresponding to Statuses E and C are D on and Doff , respectively. The corresponding circuit equations for Statuses E and C were obtained in (4) and (3), respectively. By introducing the state-space averaged technique and volt–second balance theory, the state-space averaged equation is derived as follows, while the ac grid voltage source is

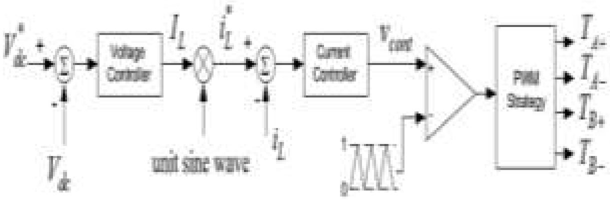


Fig.10. Conventional dual-loop control scheme for a single-phase bidirectional ac/dc converter.

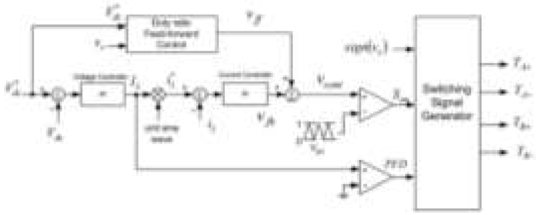


Fig.11. Proposed control scheme for the proposed simplified PWM strategy. operating in the negative half-cycle Vs < 0:

$$v_s + D_{\text{on}} V_{\text{dc}} = 0. \tag{7}$$

Similarly, when the converter is operated in the steady state, the output voltage is equal to the desired command Vdc = V_{dc}^* . Equation (7) can be expressed in the following form:

$$D_{\text{on}} = -\frac{v_s}{V_{\text{dc}}^*}. \tag{8}$$

According to the PWM properties, the switching duty ratio can be expressed in terms of the control signal vcont and the peak value vˆtri of the triangular waveform

$$D_{\text{on}} = \frac{v'_{\text{cont}}}{\hat{V}_{\text{tri}}}. \tag{9}$$

Substituting (6) and (8) into (9), the switching duty ratios in both conditions vs > 0 and vs < 0 are derived

$$v'_{\text{cont}} = \begin{cases} \left(1 - \dfrac{v_s}{V_{\text{dc}}^*}\right) \hat{V}_{\text{tri}}, & \text{if } v_s > 0 \\ -\dfrac{v_s}{V_{\text{dc}}^*} \hat{V}_{\text{tri}}, & \text{if } v_s < 0. \end{cases} \tag{10}$$

Consider that the converter is operated in the inverter mode with the switching combination listed in Table II. One can choose Statuses F and H for increasing and decreasing the inductor current, respectively, during condition Vs > 0, and Statuses I and K for decreasing and increasing the inductor current, respectively, during the condition vs < 0. Note that selecting Status F or G for increasing the inductor current and Status I or J for decreasing the inductor current is all allowable in the proposed simplified PWM strategy. While the converter is operated in the inverter mode, the control signal vcont can be obtained using a similar manner in the rectifier mode. After calculation, the control signal vcont operated in the inverter mode is the same as that in the rectifier mode, as described in (10).Because the control signal vcont is proportional to Don, one can regard the calculated signal vcont in (10) as the duty ratio feed forward control signal Vff to add into the dual-loop feedback control signal Vfb. The feed forward control signal Vff can enhance the control ability to provide fast output voltage response as well as improve current shaping. Thus, the developed control scheme for the proposed simplified PWM is presented in Fig. 11.

IV.FUZZY LOGIC CONTROL

L. A. Zadeh presented first on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to power system [5]. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of converter. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of compensator.

The basic scheme of a fuzzy logic controller is shown in Fig 12 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

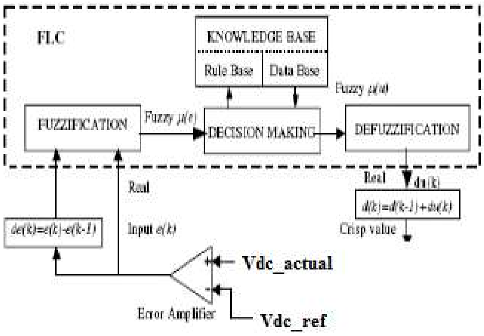


Fig.12 Block diagram of the Fuzzy Logic Controller (FLC) for proposed converter.

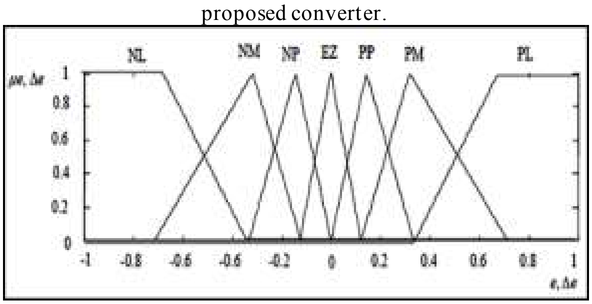


Fig.13 Membership functions for Input, Change in input, Output.

Rule Base:the elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse in-put/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table III, with '*Vdc*' and '*Vdc-ref*' as inputs

Δe \ e	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	NL	NM	NS	EZ	PS	PM	PL

V.MATLAB/SIMULINK RESULTS

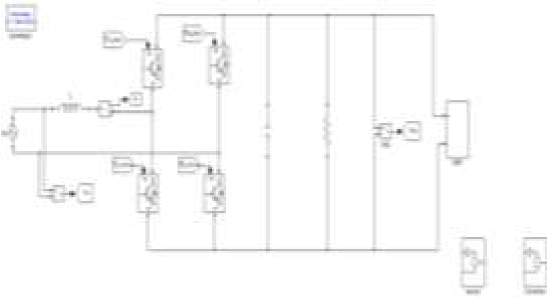
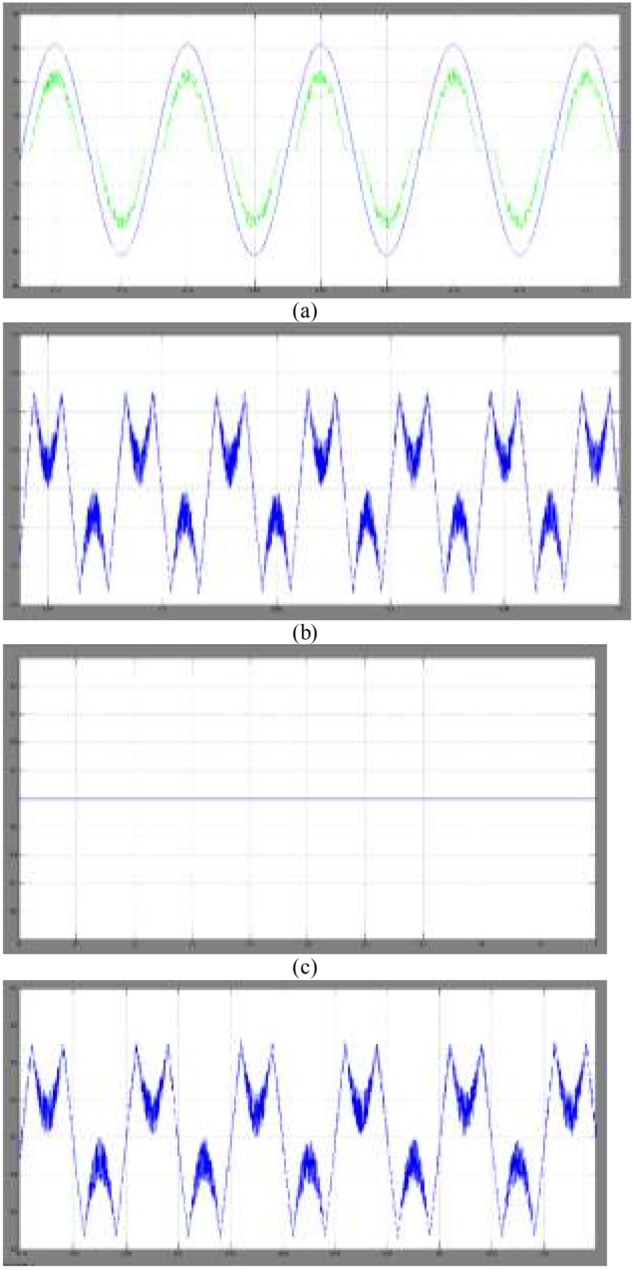


Fig.14.Simulink model of proposed simplified PWM operated in the inverter mode.



(a)

(b)

(c)

(d)

Fig. 15. Simulation results with distorted ac grid voltage (a) vs and iL , (b)vcont , (c) vf f , and (d) vf b using the dual-loop control scheme in the proposedsimplified PWM strategy operated in the rectifier mode.

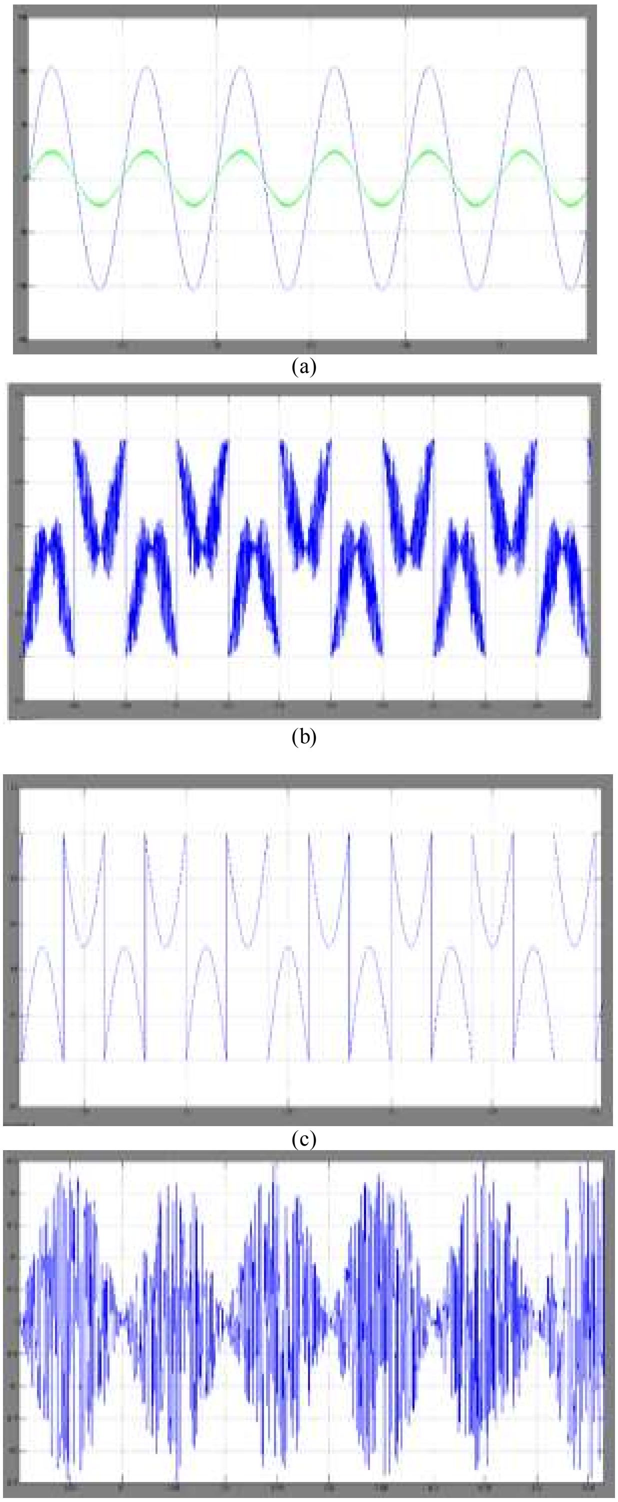

(a)
(b)
(c)
(d)

Fig. 16. Simulation results with pure sinusoidal ac grid voltage (a) vs and iL ,(b) vcont , (c) vff , and (d) vf b using the feedforward control scheme in theproposed simplified PWM strategy operated in the rectifier mode.

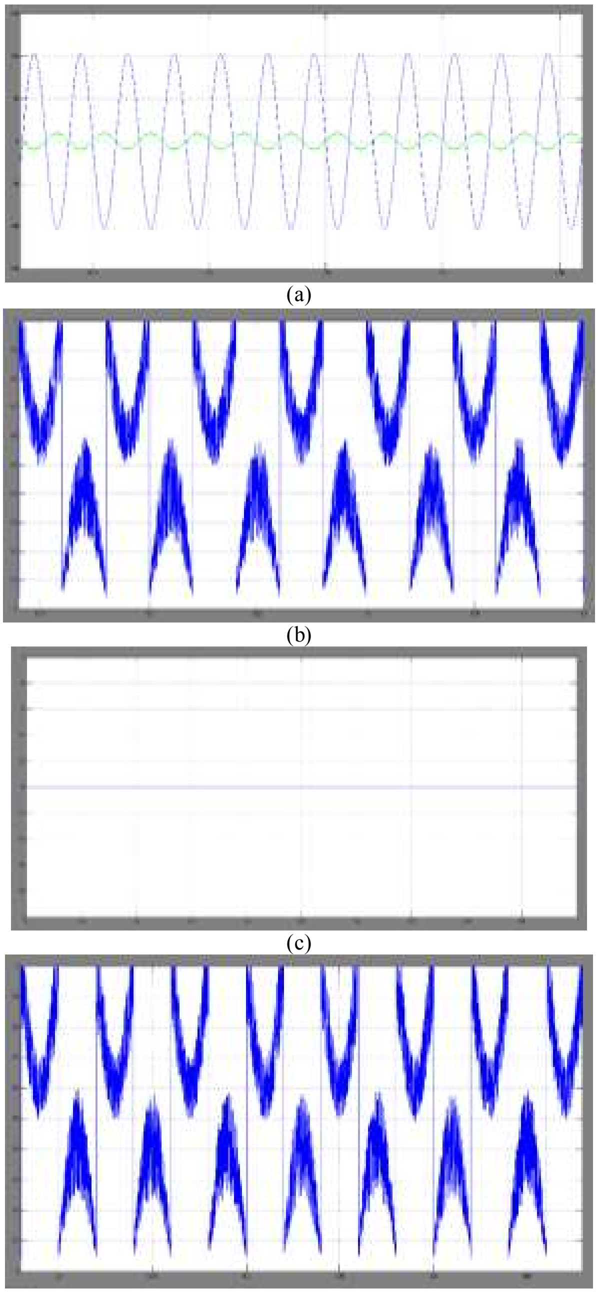
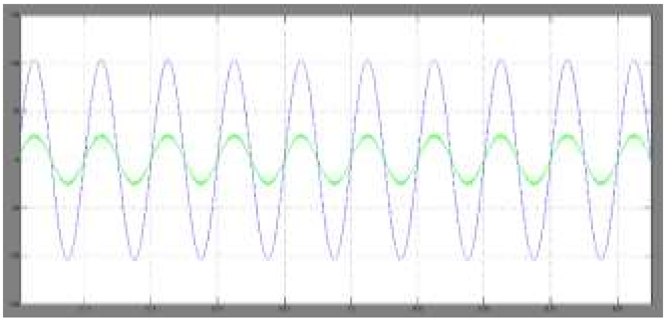
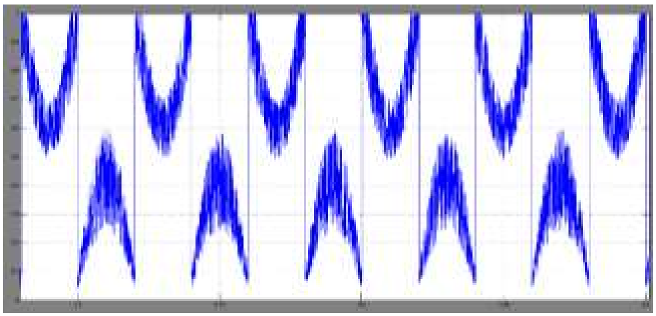

(a)
(b)
(c)
(d)

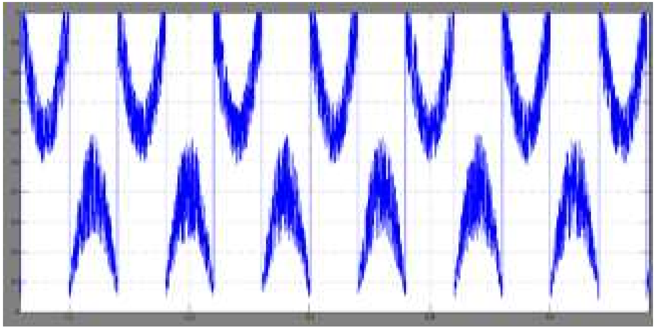
Fig. 17. Simulation results with pure sinusoidal ac grid voltage (a) vs andiL , (b) vcont , (c) vff , and (d) vf b using the dual-loop control scheme in theproposed simplified PWM operated in the inverter mode.


(a)



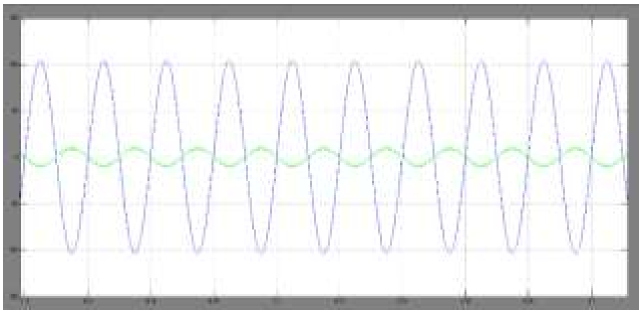
(b)

(c)

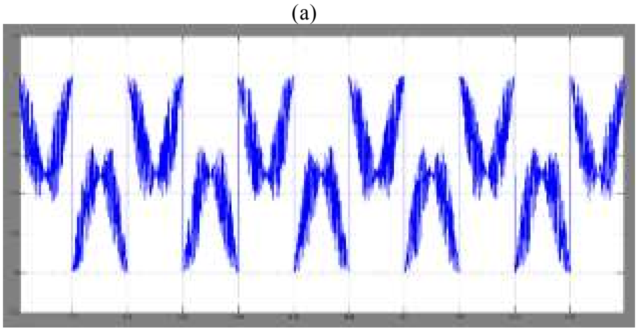


(d)

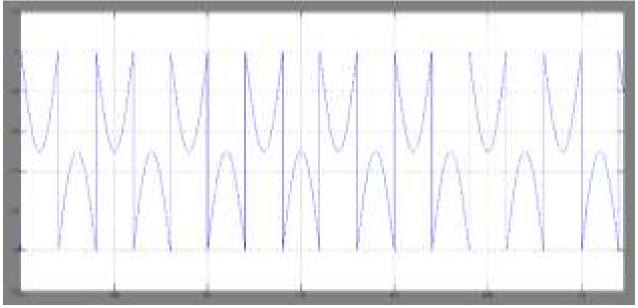
Fig.18. Simulation results with pure sinusoidal ac grid voltage (a) vs andiL , (b) vcont , (c) vf f , and (d) vf b using the dual-loop control scheme in theproposed simplified PWM operated in the rectifier mode.



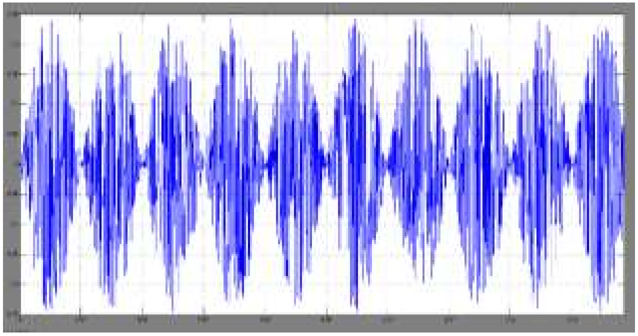
(a)



(b)

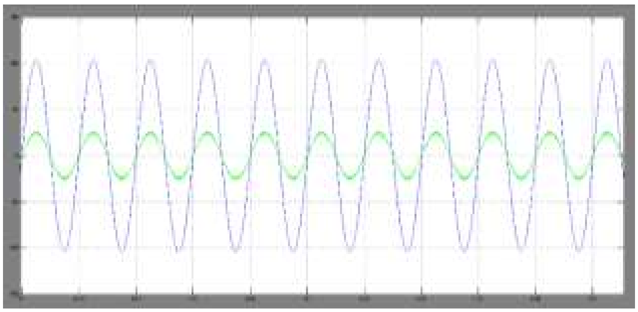


(c)

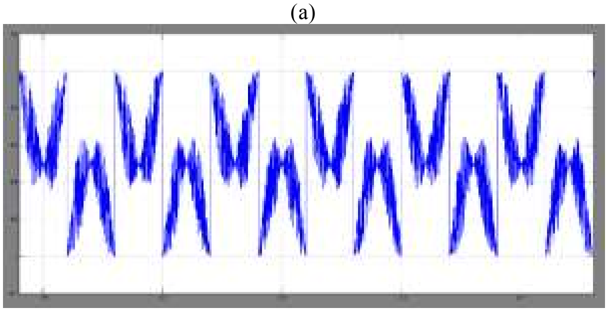


(d)

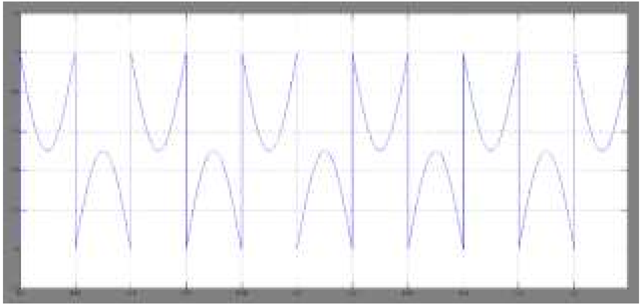
Fig. 19. Simulation results with pure sinusoidal ac grid voltage (a) vs and iL ,(b) vcont , (c) vf f , and (d) vf b using the feedforward control scheme in theproposed simplified PWM strategy operated in the inverter mode.



(a)



(b)



(c)

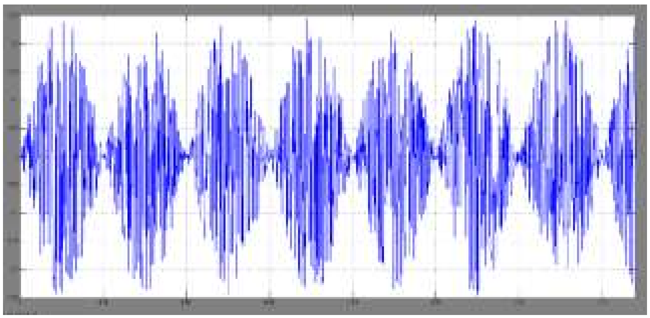
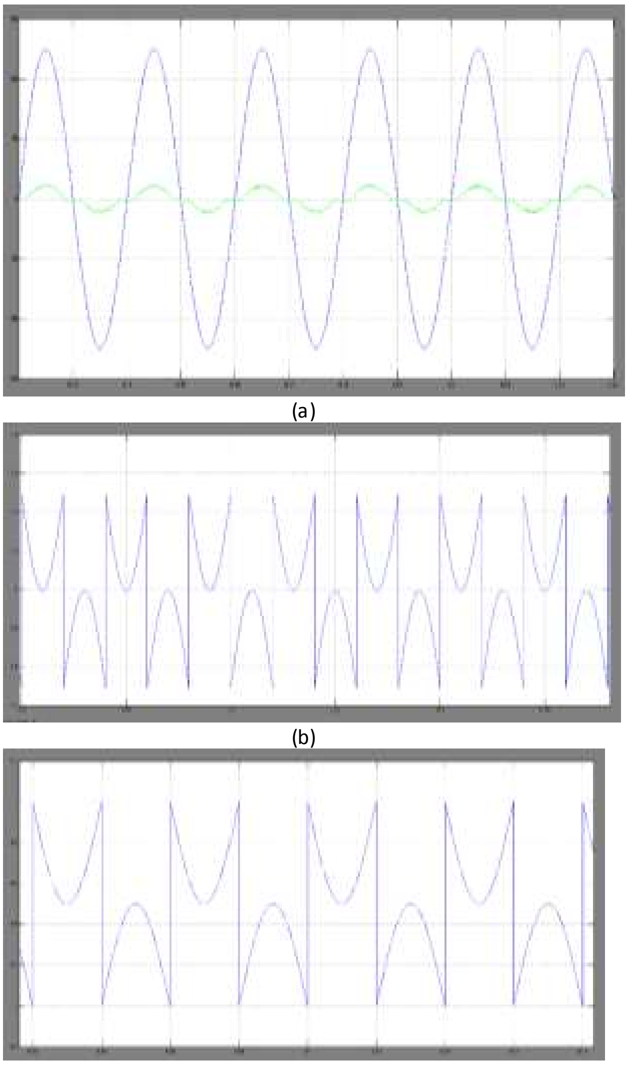

(d)

Fig. 20. Simulation results with distorted ac grid voltage (a) vs and iL , (b)vcont , (c)vf f , and (d)vf b using the feedforward control scheme in the proposedsimplified PWM strategy operated in the rectifier mode.


(a)

(b)

(c)

Fig. 21. Simulation results with pure sinusoidal ac grid voltage (a) vs and iL , (b) vcont , (c) vf f with fuzzy logic controlle.

VI.CONCLUSION

The controller based feedforward control presented a novel simplified PWM strategy using a feed forward control scheme in the bidirectional single-phase ac/dc converter. The proposed simplified PWM strategy only requires changing one active switch status in the switching period instead of changing four active switch statuses as required in the UPWM and BPWM strategies. The efficiency of an ac/dc converter operated in the proposed simplified PWM strategy is higher than that in the UPWM and BPWM strategies. Based on the proposed feed forward control scheme, both ac current shaping and dc voltage regulation are achieved in both the rectifier and inverter operating modes. By using fuzzy logic we can reduce more conduction losses and total harmonic distortions when compared to PI controllers.

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