Near Unity Power Factor Using Non-inverting Boost-Buck Converter with Programmed PWM

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***Abstract*-- This paper presents how to implement non-inverting boost-buck converter to achieve near unity power factor application. The advantage of the proposed converter is that it has continuous currents at both input and output, and its gain can be adjusted to higher or lower than unity. Steady state operation of the converter is also described by using circuit simplification. Since its input current is continuous, it can be applied for power factor correction. This work shows how to make the input current to have the current from ac source close to sinusoidal waveform with the same phase. In order to achieve that, programmed PWM technique is used to control the switches in the converter. Computer simulation is also given to confirm the work.**

***Index Terms*-- power factor correction, boost-buck converter, current programmed control.**

I. INTRODUCTION

Many research works introduced boost-buck or Cuk converter [1]-[4] in the past. This type of converters has only one switch and gives a wide range of gain from below to over unity. However, this converter gives inverting output and may not suitable for many applications that require common ground with the voltage source. Recently, non-inverting boost-buck converter that uses two switches was introduced [5,6]. Both boost-buck topologies provide continuous currents at both input and output. Therefore, they can be used for several applications, such as PV array and power factor correction etc. The concepts of using power converters for power factor correction were proposed [7]-[13]. However, these works are quite complicated.

This paper will describe the process of how to use boost-buck converter for power factor correction. The process will be done by using programmed PWM technique. In most cases, PWM converters are operated in continuous conduction mode, so the steady state operation of the proposed converter will be described for continuous conduction mode in this paper.

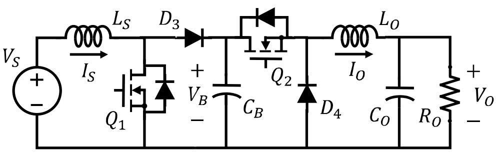


Fig. 1. Circuit diagram of noninverting boost-buck converter.

II. CONCEPT FOR POWER FACTOR CORRECTION

In general cases, in order to get a dc source from an ac source or power line, a bridge rectifier has to be utilized as indicated in the block diagram shown in Fig. 2. In this paper, non-inverting boost-buck converter is used power processing from ab terminal to the load. The expectation from this work is to have the waveform of i_a be the same as that of v_{ab} as indicated in Fig. 2.

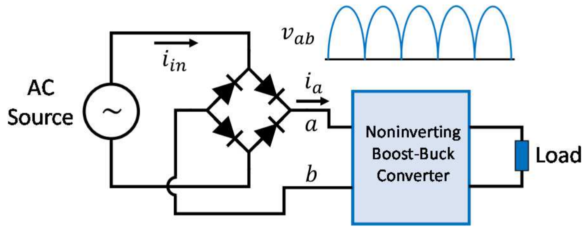


Fig. 2. Block diagram of getting power from ac source to dc load.

In most practical cases, passive components are used after the bridge rectifier. These passive components mainly are inductive filter and capacitive filter circuits etc. If L_O used in the circuit in Fig. 3 is large enough, current i_L will become almost constant. The wave forms of v_{ab}, v_O and i_L are shown, accordingly, in Fig. 4. From the definition of power factor denoted by *pf*, the power factor of the circuit in Fig. 3 can be approximated lower than 90%. In this case, the input current from the ac source becomes square wave rather than sinusoidal.

$$pf = \frac{\text{Real Power}}{V_{rms} I_{rms}} \tag{1}$$

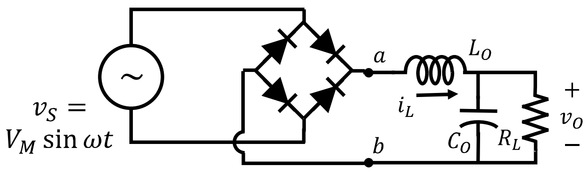


Fig. 3. Inductive filter circuit used after rectifier.

The other passive component circuit that are commonly used to obtain dc voltage is capacitive filter circuit. This circuit is shown in Fig. 5. The waveforms of this circuit are shown, accordingly, in Fig. 6. In this case, the input current from the ac source becomes pulsating rather than continuously sinusoidal. From the definition in (1), this type of circuit will have power factor worse than 50%.

Hence, most electric power providers will suffer from this situation if many users use this circuit for voltage rectification.

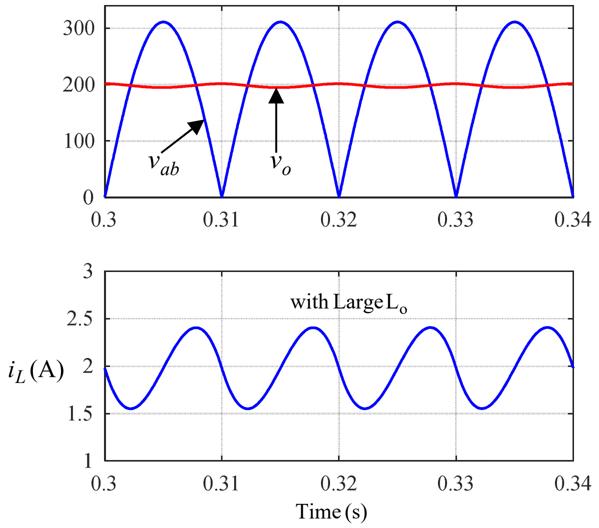


Fig. 4. Waveforms of rectifier with inductive filter circuit in Fig. 3.

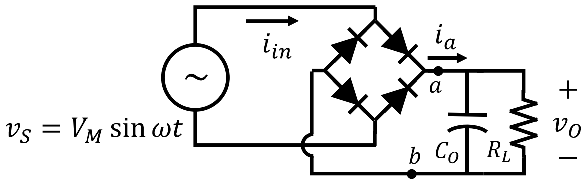


Fig. 5. Capacitive filter circuit used after rectifier.

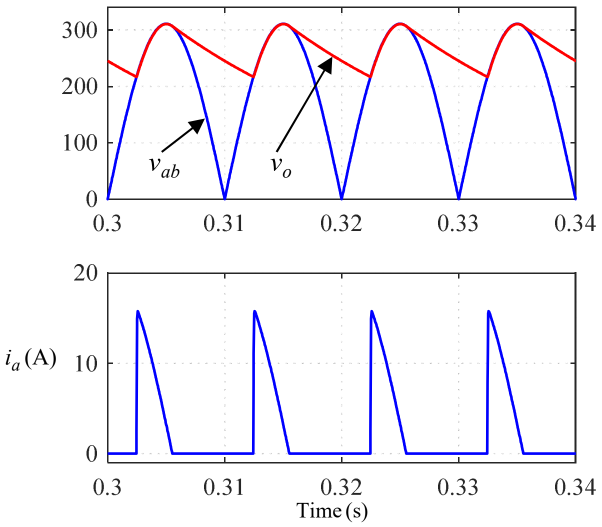


Fig. 6. Waveforms of rectifier with capacitive filter circuit.

In this paper, non-inverting boost-buck converter, indicated in Fig. 2, is used after the full-bridge rectifier to make the input current from the ac source to be close sinusoidal as much as possible. The usage can be as a preprocessing to convert ac voltage to a dc bus or as a converter providing dc voltage directly to load.

III. Steady State Operation of Noninverting Boost-Buck Converter

Since continuous currents are required, the mode of operation has to be in continuous conduction mode (CCM). ComponentsL_S, L_O and C_B is Fig. 1 are assumed to be large enough, so I_S, I_O and V_B can be treated constant. In this case, the circuit in Fig. 1 can be simplified, and its simplified circuit is given in Fig. 7. Voltage V_B is the voltage buffer that will receive and transfer energy. On the other hand, current I_O is the current sink that can only receive energy. Since I_S in Fig, 1 is almost constant, V_S and L_S can be combined and equivalently replaced by current source I_S as shown in Fig. 7.

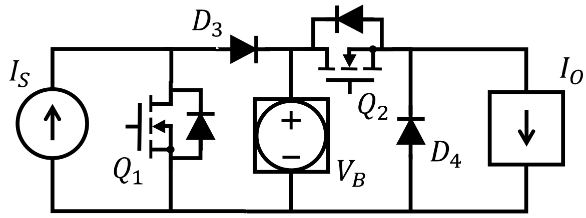
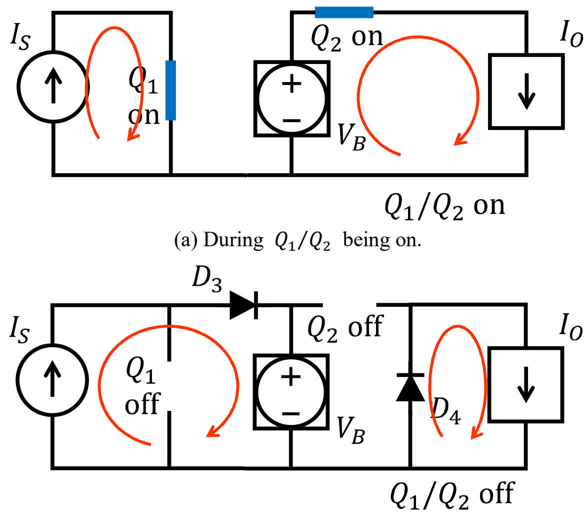


Fig. 7. Simplifies circuit of the proposed converter.



(a) During Q_1/Q_2 being on.

(b) During Q_1/Q_2 being off.

Fig. 8. Equivalent circuit and directions of current flows.

Duty ratio control with constant switching frequency is initially used for the proposed converter. Switching frequency and switching period are denoted by f_s and T_s, respectively, in this paper. MOSFETs Q_1 and Q_2 in Fig. 1 are turned on and off synchronously with turn-on time given as DT_s and turn-off time given as $(1-D)T_s$, where D is the duty ratio. Using the simplified circuit given in Fig. 7, the equivalent circuit of the converter during turn-on and turn-off times are given, accordingly, in Fig. 8. This figure also indicates the directions of current flows for each time interval. When Q_1/Q_2 are on (Fig. 8(a)), I_S is flowing in its own loop through Q_1. In fact, inductor L_S is being charged by V_S. Voltage buffer V_B also charges energy to I_O, which is the output circuit. When Q_1/Q_2 are off (Fig. 8(b)), I_S transfers energy to

V_B, and I_O is flowing in its own loop through D_4.

During steady state, energies that V_B receives and transfers out in a switching period have to be the same amount. Hence, the following relation can be obtained,

$$(1-D)I_S = DI_o \tag{2}$$

Using conservation of energy with the converter being assumed lossless, $V_S I_S = V_O I_O$ can be achieved. Therefore, the converter gain can be derived from (2) as

$$m = \frac{V_o}{V_S} = \frac{I_S}{I_o} = \frac{D}{1-D} \tag{3}$$

IV. Using the Proposed Converter as Power Factor Correction

As mentioned earlier, current i_a in Fig. 2 should have the same waveform as v_{ab} in the same figure in order to have unity power factor. In this case, L_S in Fig. 1 cannot be too large, so its current can change along with v_{ab}. In terms of frequency response, the size of L_S should not be too large, so that the current with twice frequency of ac source can get through. On the other hand, the sizes of C_B and L_O should be large enough to have the voltage across and the current flowing through, respectively, constant. Looking closely at v_{ab}, one period of it (half period of ac line) is shown in Fig. 9. This shape will be the reference of the current drawn from the rectifier. This paper shows three concepts of power factor correction. This will start from the simplest one by providing constant duty ratio to MOSFET. Secondly, the method would be a little more complicated by using programmed PWM. Finally, current programmed control is proposed. This concept can give power factor close to unity. However, all of these concepts are considered as open-loop control.

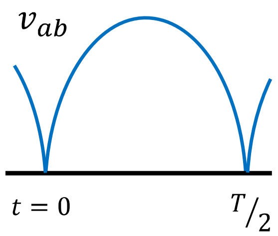


Fig. 9. Waveforms of rectifier with capacitive filter circuit.

A. Constant Duty Ratio Control

The input voltage of the converter for each half of ac source cycle is shown in Fig. 9. At the time $t = 0$ and a little after, the level of input voltage is small. This is the same as that at the time before T/2. If applying a constant duty ratio to MOSFETs, the current flowing through L_S will be proportional to input voltage, but may not be linearly proportional. However, this concept is quite easy to implement. The logic diagram of how to implement 50% duty cycle is show in Fig. 10. The saw tooth signal has the peak value as V_{peak}. Then v_{ref} with constant value at $0.5V_{peak}$ is applied to the comparator to be compared with the saw tooth signal. As a result, 50% duty ratio PWM signal is generated.

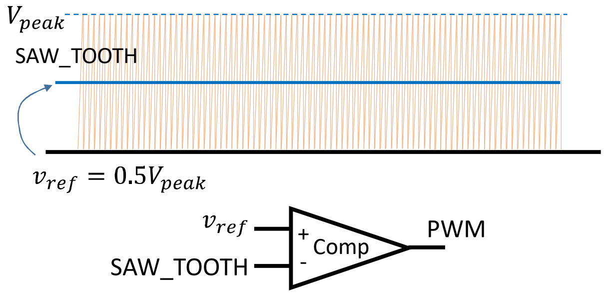


Fig. 10. Logic diagram of how to implement 50% duty ratio.

A converter circuit with detail below is used to do computer simulation for checking currents and voltages:

$L_S = 16$ mH, $C_B = 40$ µF,
$L_O = 400$ mH, $C_O = 200$ µF,
$R_L = 100$ Ω.

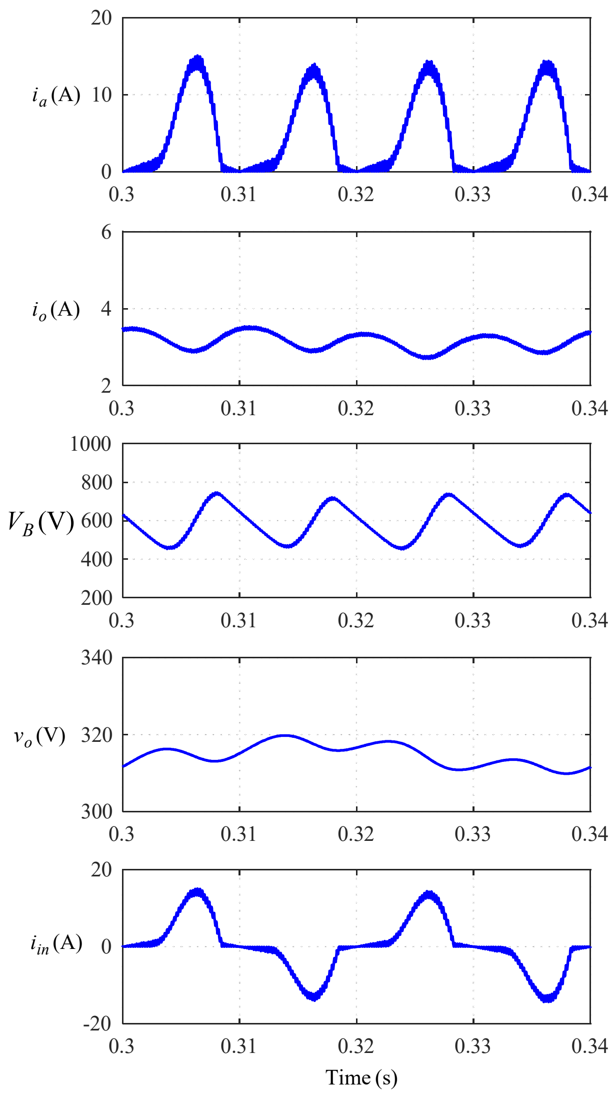


Fig. 11. Computer simulation results of the converter connected after ac line rectifier using 50% duty ratio.

The input voltage used is $220\sqrt{2} = 311\,\mathrm{V_{peak}}$ with 50 Hz frequency. The simulation results of this converter circuit using 50% duty ratio are given in Fig. 11. It can be seen from the simulation results that the input current is more close to sinusoidal.

Looking at each period of i_a in Fig. 11, it can be noticed that the current is too low at the beginning and at the end of the period and too high at the middle of the period. What can be done is to compensate at the PWM signal to the waveform of the current look sinusoidal. This will be described in the following subsections.

B. Programmed PWM Control Using Sinusoidal Signal

Since the duty ratio at each time is linearly proportional to v_{ref}. Programming PWM signal can be done by setting the desired function to v_{ref}. Since the current is too low at the beginning and the end of each period of i_a. Signal v_{ref} should be made higher at both sides. Sinusoidal signal with frequency at $2f$ can be added in v_{ref}, where f is the frequency of ac source. The waveform of this is shown in Fig. 12. A computer simulation of this control scheme has been done with the same converter circuit and the same ac source. The simulation results are given in Fig. 13.

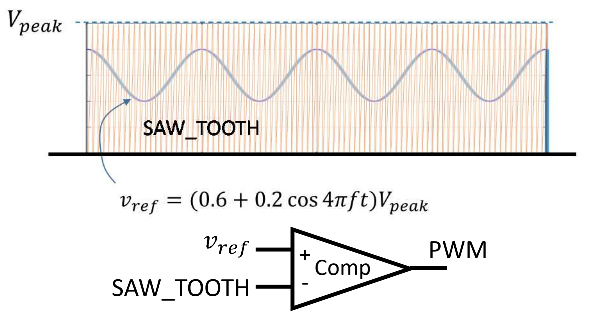


Fig. 12. Logic diagram of programmed PWM with sinusoial portion in v_{ref} .

From the simulation results shown in Fig. 13, the current at the beginning of each period of i_a is still too low and at the end of the period is a bit too high. Therefore, a compensation should be added to v_{ref} function. This will be explained in the next subsection.

C. Programmed PWM Control Using Compensated Sinusoidal Signal

In order to boost up the current at the beginning of each period of i_a, the sinusoidal signal mentioned in the previous subsection should be compensated. This compensation is to add a negative ramp function for each period of i_a to v_{ref} function. This compensation and the waveform of v_{ref} is shown in Fig. 14.

A computer simulation has been done with the same converter circuit using this control scheme. The simulation results are given in Fig. 15. This figure shows that i_{in}, which is the input current from the ac source, becomes very close to sinusoidal.

D. Current Programmed Control

For this scheme, a constant switching frequency is still used for PWM signal. The conceptual diagram of current programmed control is given in Fig. 16.

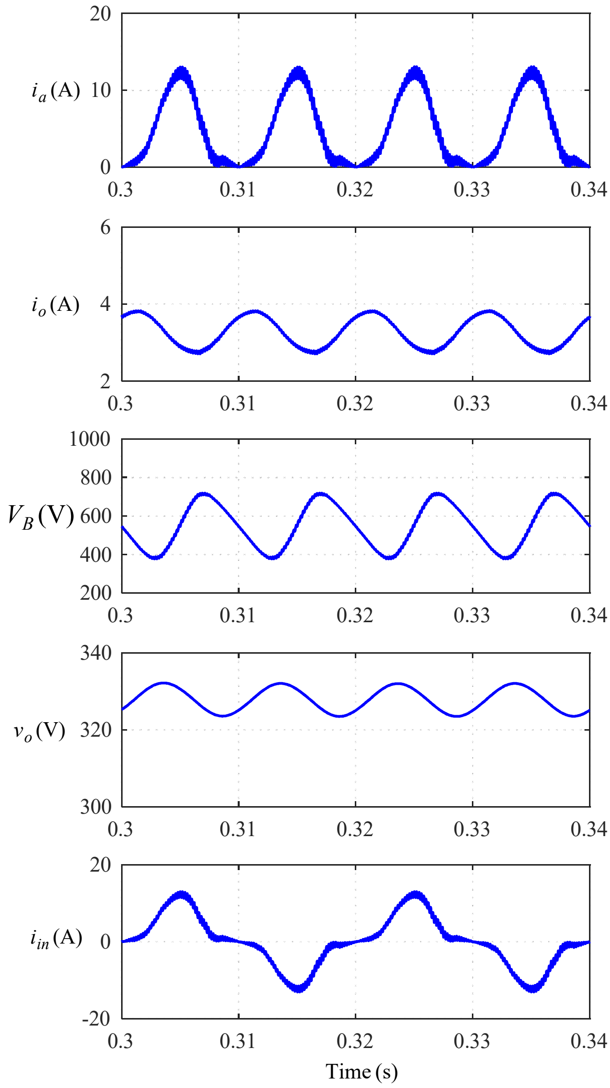


Fig. 13. Computer simulation results of the converter connected after ac line rectifier using programmed PWM including sinusodal portion.

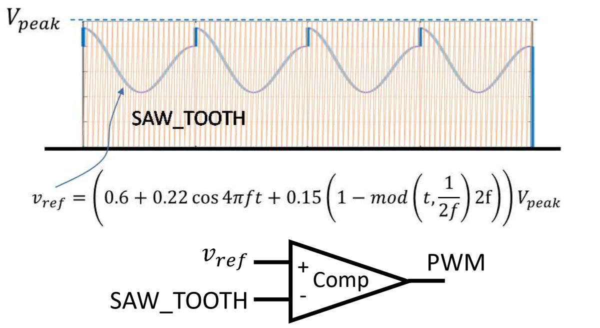


Fig. 14. Logic diagram of programmed PWM with compensated sinusoial portion in v_{ref} .

Fig. 16 shows that the PWM signal that drives MOSFETs is generated by SR flip-flop. This flip-flop is set by a pulse train with frequency equal to switching frequency (f_S), so PWM signal will have constant frequency. Voltage v_{ab}, which is $|v_{ac}|$, and current i_a are monitored and multiplied by coefficients k_v and k_i becoming $k_v|v_{ac}|$ and $k_i i_a$, respectively. These two signals will be compared by a comparator as indicated in

Fig. 16. Once $k_i i_a$ reaches $k_v|v_{ac}|$, the flip-flop will be reset and turn the MOSFETs off. The SR flip-flop will be set again by the pulse of the pulse train. The movements of $k_i i_a$ and $k_v|v_{ac}|$ can be graphically described by Fig. 17.

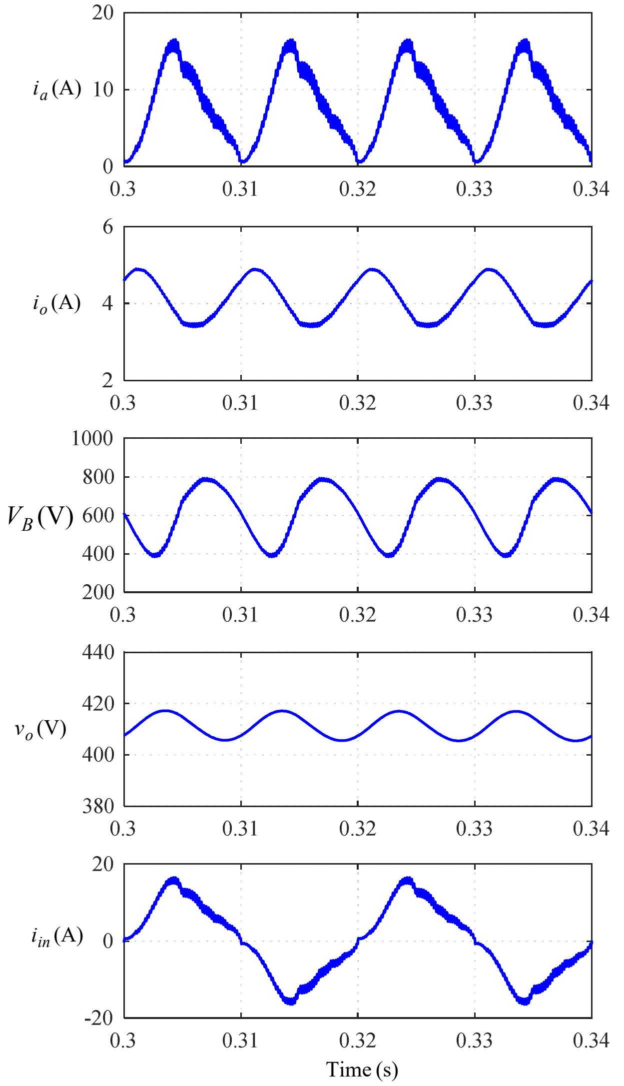


Fig. 15. Computer simulation results of the converter connected after ac line rectifier using programmed PWM including compensated sinusodal portion.

When the SR flip-flop is set by a pulse of the pulse train, the MOSFETs are turned on. While the MOSFETs are on, the current through L_S through increases linearly due to positive voltage bias; hence $k_i i_a$ increases. Once $k_i i_a$ reaches $k_v|v_{ac}|$ the output of the comparator will reset the SR flip-flop and make the MOSFETs turned off. Then L_S will have negative voltage bias, and its current decreases linearly; hence, $k_i i_a$ decreases. The SR flip-flop will be set again in the next switching cycle. By doing this, signal $k_i i_a$ can be approximately equal to $k_v|v_{ac}|$. Due to this, the following relation can be obtained,

$$I_{a,peak} = \frac{k_v}{k_i} V_{ac,peak} \tag{4}$$

where $I_{a,peak}$ and $V_{ac,peak}$ are the peak values of i_a and v_{ac}, respectively.

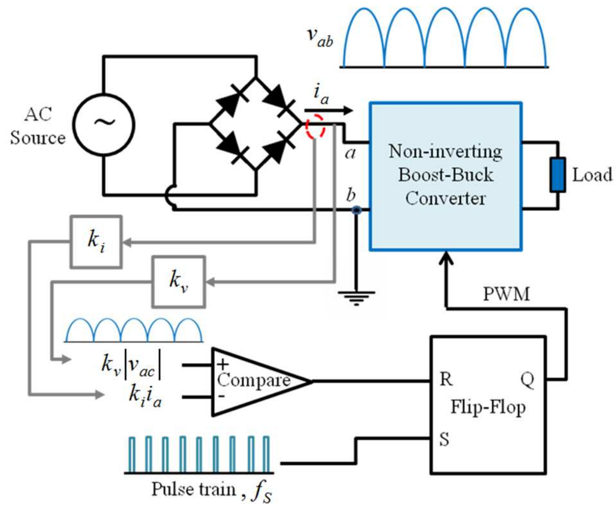


Fig. 16. Logic diagram of programmed PWM with compensated sinusoial portion in v_{ref} .

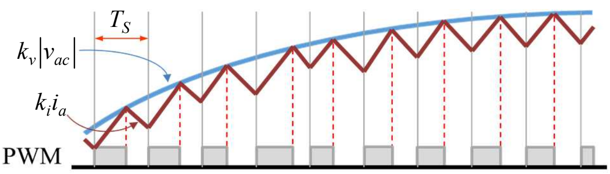


Fig. 17. Waveforms of $k_i i_a$ and $k_v|v_{ac}|$ showing how the current programmed works

Using the conceptual block diagram in Fig. 16 to work on a computer simulation using the same converter circuit, the simulation results can be obtained and given the signal response as shown in Fig. 18 and Fig. 19. Both figure show that i_a moves along $|v_{ac}|$ with linearly proportional ratio. This makes i_{in}, which is the current from the ac source, become purely sinusoidal.

The amount of electric power of the system can be calculated by

$$\text{power} = \frac{V_{ac,peak} I_{a,peak}}{2} \tag{5}$$

Using relation in (4), the power of the system becomes

$$\text{power} = \frac{k_v V_{ac,peak}^2}{2k_i} \tag{6}$$

In addition to having near unity power factor, this current programmed control also provides power that can be controlled by parameters k_v and k_i. This would be suitable for the applications that require exact amount (or controllable amount) of power transferred to the load, such as battery charger etc.

Fig. 20 shows the performance comparison of each method. In all the proposed methods, the input current (i_{in}) is in-phase with the source voltage (v_S) but distort from the sinusoidal waveform except in the current-programmed control method. The current signals in all methods after using non-inverting boost-buck converter with programmed PWM to improve the power factor is better than without using a converter. The input current of the current-programmed control method gives the best performance. This method give the input current close to sinusoidal waveform and is in-phase with the source voltage. In addition, the input current in this method gives the amplitude current less than other methods.

TABLE 1 shows the performance of each method which is expressed with the total harmonic distortion percentage (%THD) of the input current. The %THD value shows that each method resulted in a smaller %THD value compared with the system that does not use a non-inverting boost-buck converter for power factor improvement. The current programmed control method for the programmed PWM control provides the best performance and makes the input current closer to the sinusoid signal waveform than other methods.

V. Conclusion and Future Work

In this paper, how to implement near unity power factor by using non-inverting boost-buck converter has been described. The concept is to make the current from ac source to be close to sinusoidal as much as possible. The technique (in this paper) called programmed PWM is presented. The advantage of this method is being simple and using open loop control, so compensation circuit is required. Several concepts of this method have been presented. Computer simulation for each one has been done to confirm the idea. All the proposed methods can improve the waveform of the current. The one that would be the most effective is current programmed control. This concept can provide controllable and adjustable amount of power to the load.

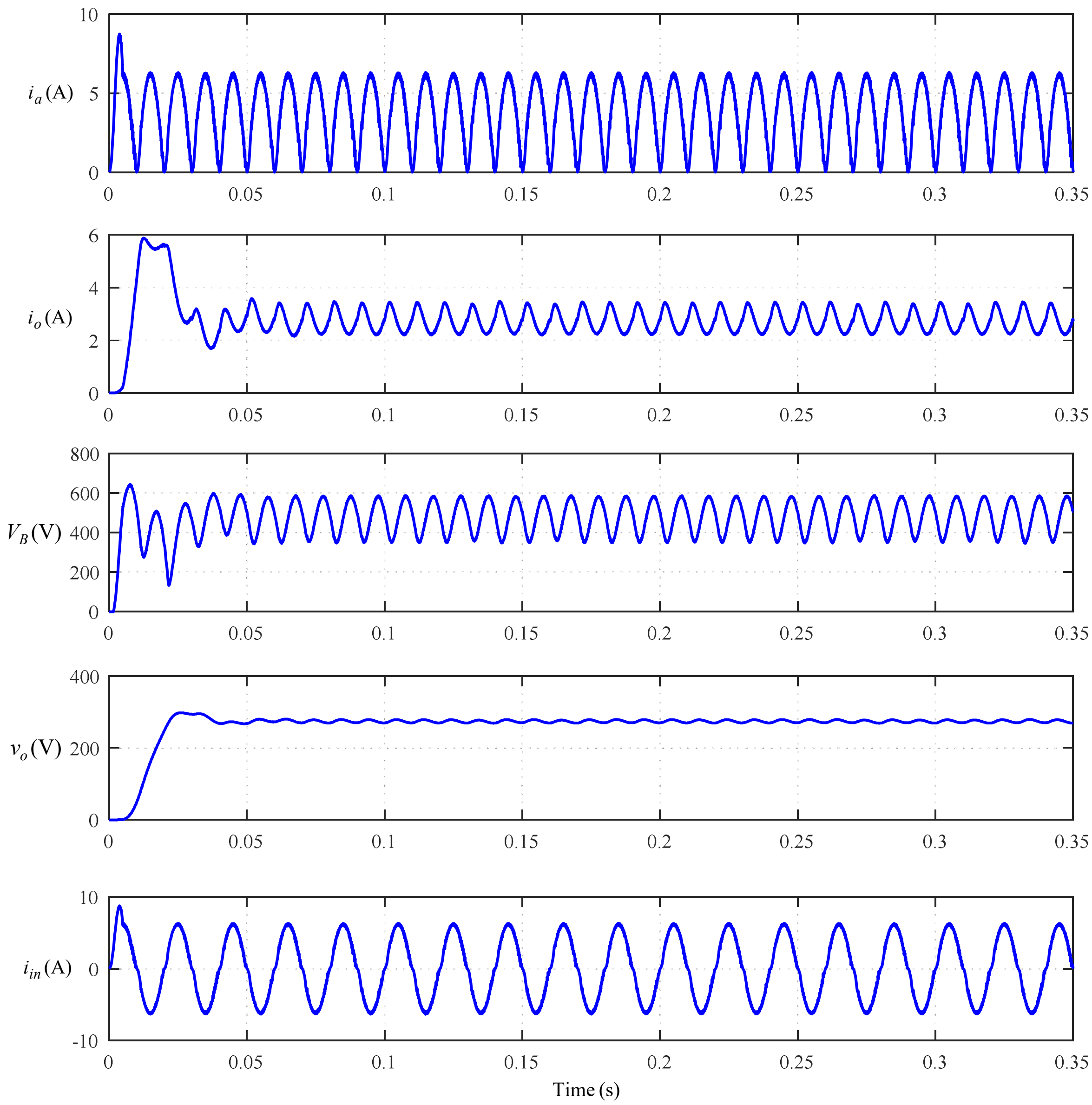


Fig. 18. The simulation results of the converter connected after ac line rectifier using current programmed control.

The future work should apply with the closed loop control and include the real experiment of the proposed concepts for several applications. Implementing other converter topologies is also included.

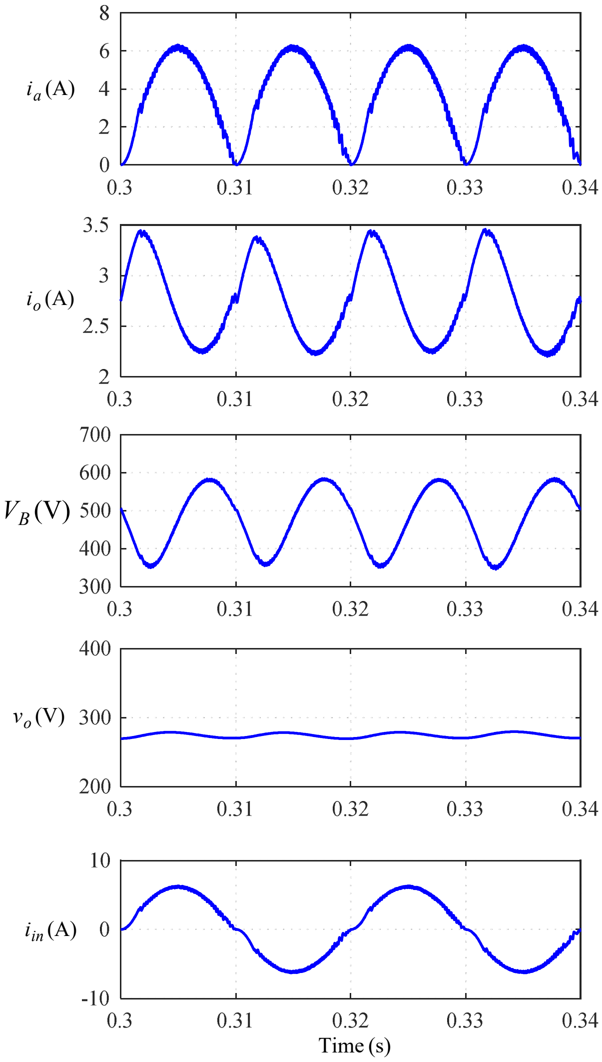


Fig. 19. Computer simulation results of the converter connected after ac line rectifier using current programmed control.

TABLE I
THE PERFORMANCE AFTER IMPROVE WITH NON-INVERTING BOOST-BUCK CONVERTER USING PROGRAMMED PWM.

Method	**%THD** of i_{in}
Without boost-buck converter	110.24
Using Constant Duty Ratio Control	54.35
Using Sinusoidal Signal	41.28
Using Compensated Sinusoidal Signal	19.60
Using Current programmed Control	6.24

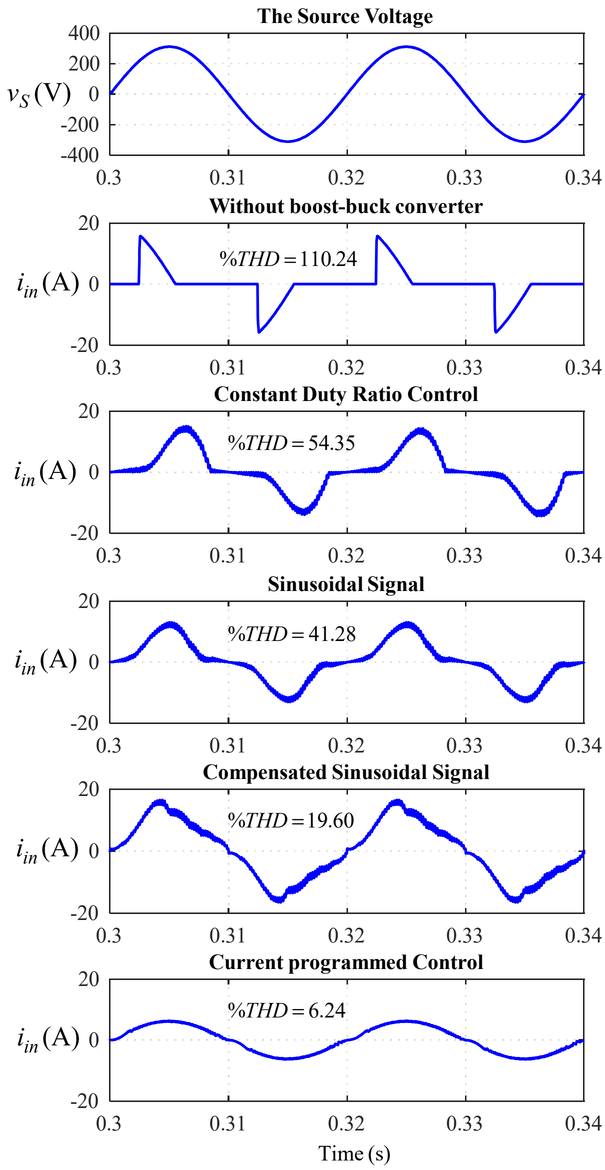


Fig. 20. Compare the simulation results of the input current i_{in} for the programmed PWM control between all method.

REFERENCES

[1] K. M. Smedley and S. Cuk, "Dynamics of one-cycle controlled Cuk converters," *IEEE Transactions on Power Electronics*, vol. 10, no. 6, pp. 634-639, Nov. 1995, doi: 10.1109/63.471282.

[2] A. Anand and B. Singh, "Modified Dual Output Cuk Converter-Fed Switched Reluctance Motor Drive With Power Factor Correction," *IEEE Transactions on Power Electronics*, vol. 34, no. 1, pp. 624-635, Jan. 2019, doi: 10.1109/TPEL.2018.2827048.

[3] B. -R. Lin and Y. -S. Huang, "ZVS Double-Ended Ćuk Converter," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 57, no. 11, pp. 908-912, Nov. 2010, doi: 10.1109/TCSII.2010.2068112.

[4] A. Lekić and D. M. Stipanović, "Hysteresis Switching Control of the Ćuk Converter," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 63, no. 11, pp. 2048-2061, Nov. 2016, doi: 10.1109/TCSI.2016.2600199.

[5] S. Busquets-Monge, S. Alepuz and J. Bordonau, "A Bidirectional Multilevel Boost–Buck DC–DC Converter," *IEEE Transactions on Power Electronics*, vol. 26, no. 8, pp. 2172-2183, Aug. 2011, doi: 10.1109/TPEL.2011.2105508.

[6] T. Srimonthon and S. Sooksatra, “Universal Non-Inverting PWM Converter with Circuit Simplification Approach,” Presented at 19th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), pp. 1-4, May, 2022.

[7] Bo-Tao Lin and Yim-Shu Lee, "Power-factor correction using Cuk converters in discontinuous-capacitor-voltage mode operation," *IEEE Transactions on Industrial Electronics*, vol. 44, no. 5, pp. 648-653, Oct. 1997, doi: 10.1109/41.633463.

[8] Kyu-Chan Lee, Hang-Seok Choi and Bo Hyung Cho, "Power factor correction converter using delay control," *IEEE Transactions on Power Electronics*, vol. 15, no. 4, pp. 626-633, July 2000, doi: 10.1109/63.849032.

[9] C. K. Tse and M. H. L. Chow, "Theoretical study of switching power converters with power factor correction and output regulation," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 47, no. 7, pp. 1047-1055, July 2000, doi: 10.1109/81.855460.

[10] V. Bist and B. Singh, "A Unity Power Factor Bridgeless Isolated Cuk Converter-Fed Brushless DC Motor Drive," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 7, pp. 4118-4129, July 2015, doi: 10.1109/TIE.2014.2384001.

[11] R. Kushwaha and B. Singh, "A Power Quality Improved EV Charger With Bridgeless Cuk Converter," *IEEE Transactions on Industry Applications*, vol. 55, no. 5, pp. 5190-5203, Sept.-Oct. 2019, doi: 10.1109/TIA.2019.2918482.

[12] Xueshan Liu, Wenhan Liu, Mingzhi He, Wei Wang, Qun Zhou and Jianping Xu, “Boost-Type Single-Stage Step-Down Resonant Power Factor Correction Converter,” *IEEE Transactions on Industrial Electronics*, Vol. 68, no. 9, pp. 8081-8092, September 2021, doi: 10.1109/TIE.2020.3013766.

[13] Enver Candan, Nathan C. Brooks, Andrew Stillwell, Rose A. Abramson, Johan Strydom and Robert C. N. Pilawa-Podgurski, “A six-Level Flying Capacitor Multilevel Converter for Single-Phase Buck-Type Power Factor Correction,” *IEEE Transactions on Power Electronics*, Vol. 37, No. 6, pp. 6335-6348, June 2022, doi: 10.1109/TPEL.2021.3122739.