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Closed Loop Operation of High Efficiency Ac-Dc Step-Up Converter Using Fuzzy Logic Controller

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ABSTRACT
The conventional power electronic converters used in the micro generator based energy harvesting applications has two stages: a diode bridge rectifier and a dc-dc converter. But it is less efficient and can't be used for electromagnetic micro generators, as the diode bridge rectification is not normally feasible due to extreme low output voltage of the micro generators. In this paper a direct ac-dc power electronic converter topology is proposed for efficient and maximum energy harvesting from low voltage micro generators. The single stage ac-to-dc power conversion is achieved by utilizing the bidirectional conduction capability of MOSFETs. This converter uses a boost converter and a buck-boost converter to process the positive and negative half cycles of the ac input voltage, respectively. The detailed analysis of this ac-dc step up converter is carried out to obtain the relations between power, circuit parameters, and duty cycle of the converter. The present model is proposed with the fuzzy logic controller for better performance. Furthermore, using this converter, maximum energy harvesting can be implemented effectively. The simulation results are obtained using MATLAB/SIMULINK software
***Keywords* -** AC-DC convertion ,boost converter, buck-boost converter, energy harvesting,Fuzzy logic controller, low voltage, low power.

I. INTRODUCTION

The recent development of compact and efficient semi conductor technologies has enabled the development of low-power wireless devices. Typical applications for such devices are wireless sensor nodes for structural monitoring, data transfer, biomedical implants etc. Batteries have been traditionally used as the energy source for such low-power wireless applications. However, they are inherently limited by capacity and size considerations. Therefore, they need to be recharged and replaced periodically. For low-power requirement of a few milli watts, harvesting energy from the environment has become feasible option.

Vibration based energy harvesting is a popular way of extracting electrical energy from the environment. In particular, electromagnetic micro generators work on the principle of faraday's law of electromagnetism. They utilize ambient vibrations to enable movement of a permanent magnet which induces an electromotive force in a stationary coil. The amount of harvested energy can be controlled by changing the load resistance connected to the coil. Unlike other popular vibration-based generators like piezo-electric micro generators, electromagnetic generators have to be specifically designed for a particular environment Many types of micro generators, used in the self-powered devices, are reported in the literature for harvesting different forms of ambient energies [1],[2]. The power level of the inertial -micro-generators is normally very low ranging from few microwatts to tens of mill watts. Based on the energy conversion principle, the inertial micro-generators can be classified mainly into three types: electromagnetic, piezoelectric, and electrostatic [5], [6], among them, the electromagnetic micro-generators have the highest energy density [7]. The electromagnetic generators are typically spring-mass damper- based resonance systems „as shown in Fig.1 in which the small amplitude ambient mechanical vibrations are amplified into larger amplitude translational movements and the mechanical energy of the motion is converted to electrical energy by electromagnetic coupling.

An electromagnetic power generator consists of a copper coil, a permanent magnet (also acting as a mass), and a spring, the permanent magnet is attached to the coil through the spring. This generator works when there is a vibration input, the coil cuts through the magnetic flux formed by the permanent magnet due to the relative displacement between the permanent magnet and the coil.

A sinusoidal electromotive force (EMF) in the coil can be generated and thus transfers mechanical energy into electrical energy. Since the output power of the power generator is very low, ranging from few micro-watts to tens of mill-watts, an energy harvesting interface circuit with high power transfer efficiency need to recharge and store the electrical power into the energy storage elements.

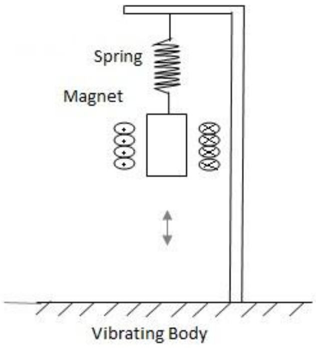


Fig .1 Schematic diagram of an inertial micro generator.

In the electromagnetic micro-generators, due to practical size limitations, the output voltage level of the generators is very low (few hundreds of mill volts), whereas the electronic loads require much higher dc voltage(3.3V). The conventional power converters, reported for energy harvesting [2], [6] mostly Consist of two stages, a diode bridge rectifier and a standard buck or boost dc-to-dc converter. However, there are major disadvantages in using the two-stage power converters to condition the outputs of the electromagnetic micro generators. For very low-voltage electromagnetic micro generators, rectification is not feasible by the use of conventional diodes.

A direct ac-to-dc converter is in shown in Fig. 2, it consists of a boost converter (inductor L_1, switch S_1, and diode D_1) in parallel with a buck– boost converter (inductor L_2, switch S_2, and diode D_2). In this converter, the negative output to input voltage gain of a buck–boost converter is utilized to step-up the negative half input voltage of the micro generator to a positive high-dc output voltage. The output dc bus is realized by using a single capacitor. The output capacitor is charged by the boost converter in the positive half cycle and by the buck–boost converter in the negative half cycle. Therefore, it resolves the problems present in a dual-polarity boost converter.

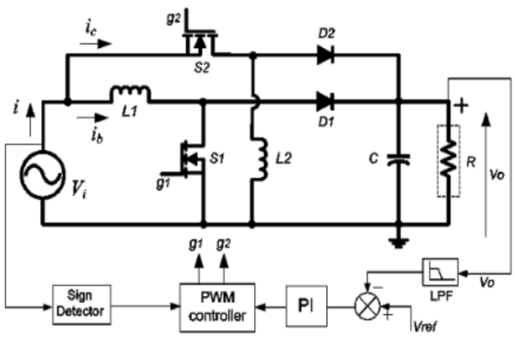


Fig. 2. Direct ac-to-dc converter with PI controller.

The direct AC- DC converter with PI-controller in the closed loop will not give zero steay state error and it has slow dynamic response. These Problems can be overcome by using FLC (fuzzy logic controller). The Proposed ac-dc converter with FLC is shown in figure.3.

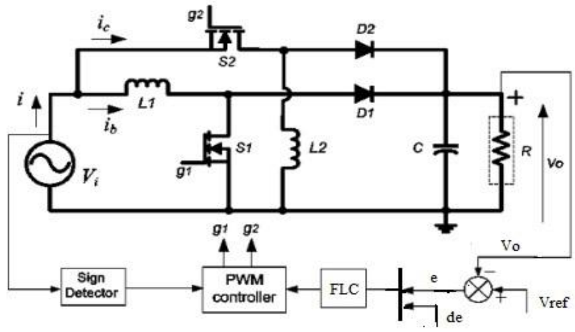


Fig 3. Direct ac-to-dc converter with Fuzzy logic controller.

II. DIRECT AC-TO-DC CONVERTER

The electromagnetic micro generators typically consist of a moving permanent magnet, linking flux with a stationary coil (see Fig. 1). The variation of the flux linkage induces ac voltage in the coil. The typical output voltage of an electromagnetic micro generator is sinusoidal. Hence, in this study, the micro generator is modeled as a sinusoidal ac voltage source. Furthermore, electromagnetic micro generators with low output voltages (few hundreds of milli volts) are only considered in this study for energy harvesting.

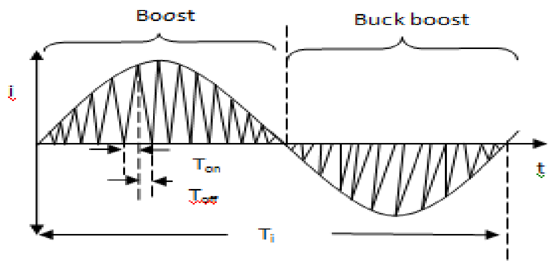
The proposed direct ac-to-dc power conditioning circuit, as shown in Fig. 3, consists of one boost converter in parallel with one buck–boost converter. The output capacitor C of this converter is charged by the boost converter (comprising inductor L_1, switch S_1, and diode, D_1) and the buck–boost converter (comprising inductor L_2, switch S_2, and diode D_2) during the positive half cycles and the negative half cycles of the sinusoidal ac input voltage (v_i), respectively. N channel MOSFETs is utilized to realize the switches S_1 and S_2. It can be noted that the MOSFETs are subjected to reverse voltage by the ac output of the microgenerator. To block the reverse conduction, the forward voltage drop of the body diodes of the MOSFETs is chosen to be higher than the peak of the input ac voltage. Two Schottky diodes (D_1 and D_2) with low forward voltage drop are used in the boost and the buck–boost converter circuits for low losses in the diodes. It can be mentioned that the diodes can be replaced by MOSFETs to further improve the efficiency of the converter.

The proposed converter is operated under discontinuous mode of operation (DCM). This reduces the switch turn ON and turn OFF losses. The DCM operation also reduces the diode reverse recovery losses of the boost and buck–boost converter diodes. Furthermore, the DCM operation enables easy implementation of the control scheme. It can be noted that under constant duty cycle DCM operation, the input current is proportional to the input voltage at every switching cycle; therefore, the overall input current will be in-phase with microgenerator output voltage. The converter operation can be divided mainly into four modes. Mode-1 and Mode-2 are for the boost converter operation during the positive half cycle of the input voltage. Under Mode-1, the boost switchS1 is ON and the current in the boost inductor builds. During Mode-2, the switch is turned OFF and the output capacitor is charged. The other two modes: Mode-3 and Mode-4 are for the buck–boost converter operation during the negative half cycle of the input voltage. Under Mode-3, the buck–boost switchS2 is ON and current in the buck–boost inductor builds. During Mode-4, the buck–boost switchS2is turned OFF and the stored energy of the buck–boost inductor is discharged to the output capacitor.

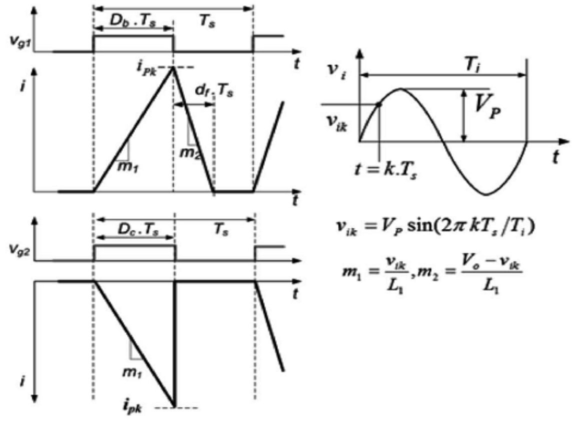
A. Converter Analysis:

Consider the input current waveform of the converter as shown in Fig. 4(a). It can be noted that during the boost converter operation, the input current I and the boost inductor current (i_{L1}) are equal, but during the buck–boost converter operation, the input current I and the current in buck–boost inductor (i_{L2}) are not equal. This is because, in the buck–boost converter the input current becomes zero during the switch turn OFF period (T_{OFF}). Therefore, in a switching cycle, the energy transferred to the output by a buck–boost converter is equal to the energy stored in the inductor, whereas, in the boost converter, the energy transferred to the output is more than the energy stored in the inductor. In this section, analyses of the converters are carried out and the relations between the control and circuit parameters of the boost and the buck–boost converters pertaining to the input power and the output power are obtained. Consider any k^{th} switching cycle of the boost and the buck– boost converter as shown in Fig. 4(b), where Ts is the time period of the switching cycle, D_b is the duty cycle of the boost converter, d_fT_s is the boost inductor current fall time (or the diodeD$_1$ conduction time),D_c is the duty cycle of the buck– boost converter, vi is the input voltage of the generator with amplitude V_p, and V_o is the converter output. Assuming the switching time period (T_s) of the converter is much smaller than the time period of the input ac cycle (T_i), the peak value of the inductor current (i_{Pk}) in the boost converter can be obtained from the following equation

$$v_{ik} = L_d \frac{di}{dt} = L_d \frac{i_{pk}}{T_{on}}$$



(a)



(b)

Fig.4.(a) Input current waveform of the converter.(b) Input currents, gate drive signals and input voltage during a switching cycle of boost and buck–boost converter.

. Therefore,

$$i_{pk} = m_1 D_b T_s = \frac{v_{ik} D_b T_s}{L_d} \quad (1)$$

where

$$v_{ik} = V_p \sin(wkT_S)$$

After the boost converter switch is turned OFF, the current in the inductor starts to fall (see Fig. 4). The slope (m_2) of this current is decided by the voltage across the inductor. In a kth switching cycle, the voltage across the inductor during the inductor current fall time is: V_o–v_{ik}. Therefore, the inductor current fall time can be found as in (2)

$$d_f T_s = \frac{i_{PK}}{m_2} = \frac{i_{pk} L_1}{V_0 - v_{ik}} \quad (2)$$

During this kth switching cycle, the average power supplied in the boost switching cycle is

$$P_{kb} = \frac{v_{ik} i_{pk} (D_b + d_f)}{2} \quad (3)$$

The number of switching cycles during the time period of one input ac cycle is defined as $N = T_i/T_s$. In the proposed power electronics converter topology, the boost converter is operated for the half time period of the input ac cycle ($T_i/2$). The average input power P_{ib} of the boost converter over this half cycle time period can be obtained as in (4)

$$P_{ib} = \left(\frac{2}{N}\right)\sum_{k=1}^{N/2} P_{kb} = \left(\frac{2}{N}\right)\sum_{k=1}^{N/2} \frac{v_{ik} i_{pk} (D_b + d_f)}{2} \quad (4)$$

For large N, the discrete function in (4) can be treated as a continuous function. The average input power of the boost converter P_{ib} (4) can be obtained by integrating the term in the summation over the half cycle ($T_i/2$) period of the input ac voltage and then taking its mean value. The average power of the boost converter expressed in the integration form can be obtained as in (5)

$$P_{ib} = \left(\frac{2}{T_i}\right)\int_0^{T_i/2} \frac{D_b^2 T_s}{2L_1} V_P^2 \sin^2(wt) \times V_0 \left(V_0 - V_P \sin^2(wt)\right)^{-1} dt \qquad (5)$$

Where the microgenerator input voltage is defined as: $V_i = V_p \sin(wt)$.

Simplifying (5), the average input power for the boost converter P_{ib} is found to be as follows:

$$P_{ib} = \frac{V_P^2 D_b^2 T_s}{4L_1}\Delta \qquad (6)$$

Where

$$\Delta = \left(\frac{1}{\frac{\Pi}{2}}\right)\int_0^{\pi} \frac{1}{1-(V_P/V_0)\sin\phi} d\phi$$

and

$$\phi = wt$$

It can be noted that in (6), Δ is constant for fixed values of V_p and V_o. Also, it is seen that for large switching frequency of the converter, the average power is independent of the micro generator output voltage frequency. In steady state, the average input power of the converter is equal to the sum of the average output power and the various converter losses. Hence, by defining the converter efficiency as η for a load resistance R, the input power and the output power can be balanced as in (7).

$$\frac{V_P^2 D_b^2 T_s}{4L_1}\Delta = \frac{V_0^2}{R}\frac{1}{\eta} \qquad (7)$$

From (7), the duty cycle of the boost converter (D_b) can be obtained as

$$D_b = \frac{2V_0}{V_p}\sqrt{\frac{L_1}{RT_s\eta}\frac{1}{\Delta}} \qquad (8)$$

Further, consider the operation of the buck–boost converter; in this case the input power is supplied only during the ON period of the switch S_2(see Fig. 2). During the OFF period of the switch S_2, the input current is zero [see Fig. 4(a)]. Hence, for any kth switching cycle, the average power supplied by the buck–boost converter P_{kc} can be obtained as

$$P_{kc} = \frac{V_{ik} i_{pk} D_c}{2} \qquad (9)$$

Applying similar approach, used earlier for the boost converter, the average power can be expressed in the integration form as

$$P_{ic} = \left(\frac{2}{T_i}\right)\int_0^{T_i/2} \frac{D_b^2 T_s}{2L_1} V_P^2 \sin^2(wt)dt = \frac{V_P^2 D_b^2 T_s}{4L_1} \qquad (10)$$

The duty cycle D_c can be obtained as in (11)

$$D_c = \frac{2V_0}{V_p}\sqrt{\frac{L_2}{RT_s\eta}} \qquad (11)$$

B. Converter Control Scheme:

Using (8) and (11), the duty cycle of the boost converter D_b and the duty cycle of the buck–boost converter D_c can be related as

$$\frac{D_b}{D_c} = \sqrt{\frac{L_1}{L_2\Delta}} \qquad (12)$$

Based on (12), two different control schemes can be proposed for the boost and buck–boost-based converter to deliver equal average input power. In scheme 1, the values of the inductors are kept to be equal ($L_2=L_1$) and the converters are controlled with different duty cycles such that it satisfies the condition: $Dc = D_b\sqrt{\beta}$. In scheme 2, both the boost and the buck–boost converters are controlled with same duty cycle ($D_b = D_c$), whereas the inductor values are chosen to satisfy the condition: $L_1=\Delta L_2$.

In Fig. 5, the variable Δ from (6) is plotted as a function of the step-up ratio (V_o/V_p). It can be seen from this plot that for large values of voltage step-up ratio, the value of Δ approaches to 1. Hence, for higher voltage step-up ratio applications, the boost and the buck–boost converters can be designed with inductors of equal values and they can be controlled with the same duty ratio to successfully deliver the required average power to the output.

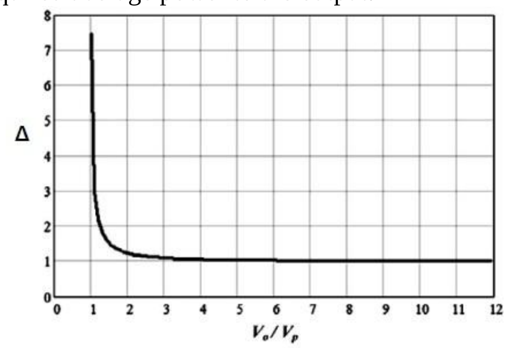


Fig. 5. Δ versus V_o/V_p (step-up ratio>1) plot

This is assistive for the target application of this study, where the very low voltage is stepped up to a much higher dc output voltage. The proposed simplified control and design of the converter is later validated by simulation and experimentation. It can be mentioned that the value of Δ approaches to infinity for $V_o/V_p \rightarrow 1$. Therefore, from (6), the input power for the boost converter may seem to approach infinity as well. But in this case, the duty cycle of the boost converter Db approaches to zero for $V_o/V_p \rightarrow 1$.

Therefore, no power is transferred from the input to the output and the equation remains valid even when V_o/V_p =1.

It can be mentioned that there could be two possible energy harvesting scenarios. One ,in which the converter is controlled to harvest maximum power available from the vibrating body and the micro generator system and store it in an energy storage component (like battery) at the output. In this case, the output voltage is mainly decided by characteristics of the energy storage component. In the second scenario, the converter is controlled to harvest the amount of power demanded by the load while maintaining the desired output voltage.

III. FUZZY CONTROLLER

The internal structure of the control circuit is shown in figure 6. The control scheme consists of Fuzzy controller, limiter, PWM Controller and generation of switching signals. The actual capacitor voltage is compared with a set reference value. This fuzzy controller takes error and change in error as inputs, the output of fuzzy controller is given to PWM controller, which generates gating pulses of desirable pulse width to MOSFETS in the AC-DC Step up converter.

(a) **Definition of a fuzzy set**: Assuming that X is a collection of objects, a fuzzy set A in X is defined to be a set of ordered pairs:

$$A = \{(X,\mu_A(X))/X\epsilon X\}$$

Where $/\mu_A$ (x) is called the membership function of x in A.The numerical interval X is called Universe of Discourse.The membershipfunction $\mu_A(^X)$ denotes the degree to which x belongs to A and is usually limited to values between 0 and 1.

(b) **Fuzzy set operation:** Fuzzy set operators are defined based on their corresponding membership functions. Operations like AND, OR, and NOT are some of the most important operators of the fuzzy sets. It is assumed that A *and* B are two fuzzy sets with membershipFunctions $\mu_A(x)$*and* $\mu_B(x)$ respectively.

A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. Firstly, input voltage *Vdc* and the input reference voltage *Vdc-ref* have been placed of the angular velocity to be the input variables of the fuzzy logic controller.

To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) as shown in Fig.7.

The fuzzy controller is characterized as follows:

1) Seven fuzzy sets for each input and output;
2)Fuzzification using continuous universe of discourse;
3) Implication using Mamdani's 'min' operator;
4) De-fuzzification using the 'centroid' method.

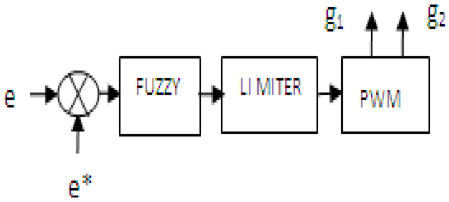


Fig.6 Conventional fuzzy controller

Fuzzification: The process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.

De-fuzzification: The rules of FLC generate required output in a linguistic variable (Fuzzy Number), according to real world requirements, linguistic variables have to be transformed to crisp output (Real number).

Database:The Database stores the definition of the membership Function required by fuzzifier and defuzzifier.

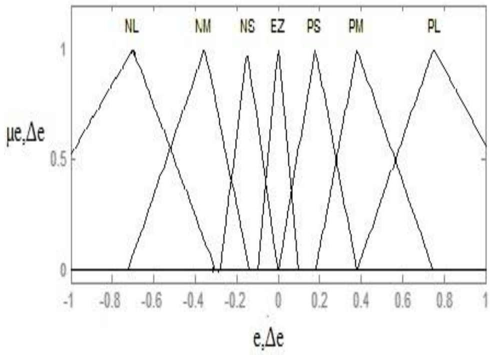


Fig.7. Membership functions for Input, Change in input, and Output.

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 1, 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

Table-1: Rules table

IV. MATLAB MODELING AND SIMULATION RESULTS

Here simulation is carried out in different conditions, in that

1. Open loop operation of AC-DC Step up converter.
2. Closed Loop Operation of AC-DC Step up Converter using Conventional PI Controller.
3. Closed Loop Operation of AC-DC Step up Converter using Fuzzy Controller.

Case 1: Open Loop Operation of AC-DC Step up Converter

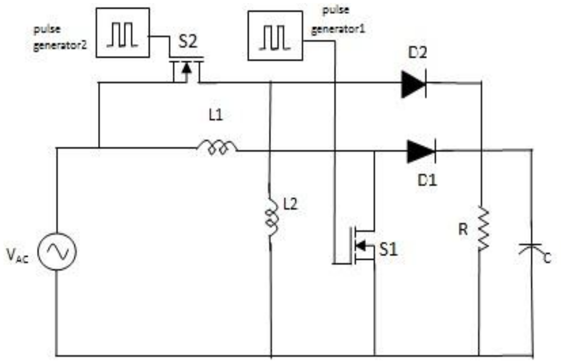


Fig.8.Circuit diagram of Open loop operation of AC-DC Step up converter

Fig.8 shows the Circuit diagram of open loop operation of AC-DC Step up converter.

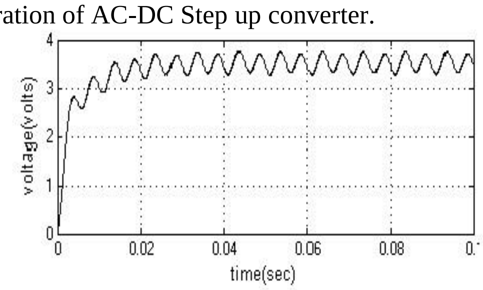


Fig.9. Output Voltage

Fig.9. Output Voltage of Open Loop Operation of AC-DC Step up Converter.

Case 2: Closed Loop Operation of AC-DC Step up Converter using Conventional PI Controller

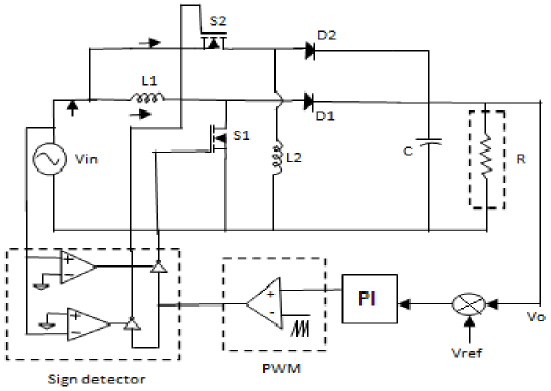


Fig.10 Circuit diagram of closed loop operation of AC-DC Step up converter using conventional PI controller

Fig.10 shows the Circuit diagram of closed loop operation of AC-DC Step up converter using conventional PI controller.

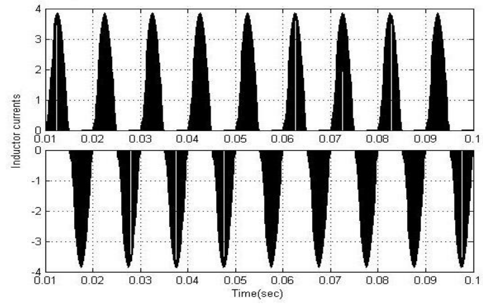


Fig.11 Inductor Currents

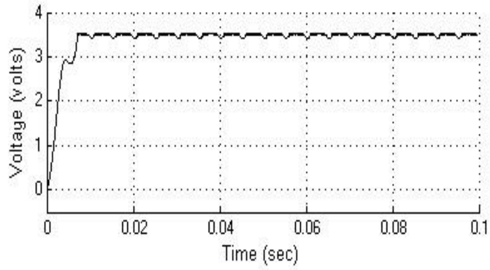


Fig.12 Output Voltage

Fig.12 Output Voltage of Closed Loop Operation of AC-DC Step up Converter using Conventional PI Controller.

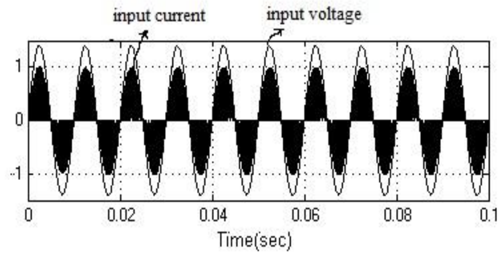


Fig.13 Source Side Power Factor

Fig.13 shows the Source Side Power Factor of AC-DC Step up Converter using Conventional PI Controller.

Case 3: Closed loop operation of AC-DC step up converter using Fuzzy controller.

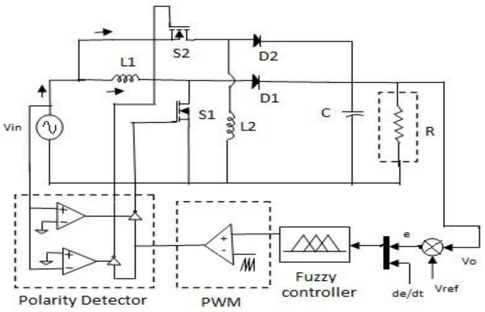


Fig.14.Circuit diagram of closed loop operation of AC-DC step up converter using Fuzzy controller

Fig.14 shows the Circuit diagram of closed loop operation of AC-DC Step up converter using Fuzzy Controller using using Matlab/Simulink Platform.

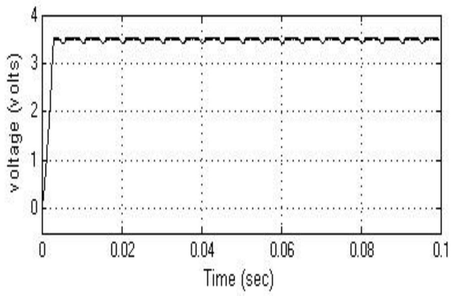


Fig.15. Output Voltage

Fig.15,Output Voltage of Closed Loop Operation of AC-DC Step up converter using Fuzzy Controller.

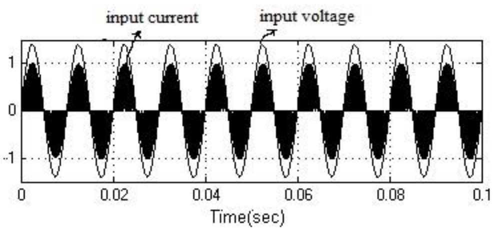


Fig.16 Source Side Power Factor

Fig.16 shows the Source Side Power Factor of AC-DC Step up Converter using Fuzzy Controller.

V. CONCLUSION

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 ac-to-dc converter and performance of proposed controllers. 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 ac-to-dc converters. The presented direct ac-to-dc low voltage energy-harvesting converter avoids the conventional bridge rectification and achieves higher efficiency. The proposed converter consists of a boost converter in parallel with a buck–boost converter. The negative gain of the buck–boost converter is utilized to boost the voltage of the negative half cycle of the micro generator to positive dc voltage. Here simulation is performed with conventional controller as well as fuzzy controller gets best output value, fast response, steady state error goes to zero.

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