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Design and Implementation of FPGA based Digital Controller for High Efficiency DC-DC Converter

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Abstract

This paper presents a novel method for design and simulation of a high efficiency DC-DC converter using discrete control system in Field Programmable Gate Array device (FPGA). The digital designed controller is more advanced, beneficial and therefore produces a better response, as compared to the analog controller. Digital control of switching power supplies is becoming more and more common in industry today because of the availability of low cost, high performance. The newest generation of processors for embedded applications requires high performance power supplies. As a matter of fact, the new generation of power supplies are based on high speed switching DC/DC converters. The latest constraint makes very difficult task to implement a real time control system based on low performance controllers. This is the reason why digital control is becoming more and more popular for the construction of real time control systems. However, the main problem of using digital control is the requirement of having a good knowledge of the internal architecture and the associated languages for the development applications. The design of DC-DC converter operates at the switching frequency of 1MHz.This system can be implemented on system-on-chip devices easily. MATLAB Xilinx system generator toolbox based on Fixed-Point Arithmetic is used to design the discrete controller. Experimental results show that the proposed system leads to attain high efficiency.

Keywords: FPGA, Discrete controller, System generator, DC-DC converter

1. Introduction

Nowadays, power supplies are required and ever increasing demands being placed in power sector which increases demand of power consumption and available power source is less. So now moving towards the renewable energy source like solar power, wind power, biomass, geothermal, etc. The Solar PV module is one of the promising technology and the solar generation is preferred over other renewable sources because it is efficient, inexhaustible. This proposed system needs high frequency transformers which are applicable, so we choose buck – boost high efficiency DC- DC converter. Digital controllers [1] are in pervasive use in power electronics because of the different advantages offered by digital controllers and it will be increasingly used even in low to medium power. It is possible to execute the complicated control laws easily in digital controllers with lesser parts than analog controller. In analog controller, the changes in control logic requires the hardware to be changes or restructured, whereas the digital controllers [2] offers the flexibility to the designer to change the control strategy or to entirely reprogram it without any hardware modifications. The high frequency switching power supplies are used in digital controller. The traditional analog controllers are currently preferred because of cost and performance. In this proposed system digital controller for a power supply are used that operates at the switching frequency of 1 MHz .The digital control has attracted attention in order to save the energy because the power consumption tends to increases. It has more advantages such as high performance control, monitoring task and etc.

This paper presents a design consideration of high performance digital control dc-dc converter [4] based on the high frequency characteristics. In addition, the frequency characteristics of proposed method and conventional PID control [3] are compared. Switched mode voltage regulators are an important part of low-voltage battery operated in electronic systems, complex communications systems, processors and microcontrollers which require a well regulated voltage to work efficiently.

This system is implemented using digital controller in a dedicated FPGA. The new generation of application requires better performance and less processing time which is obtained by this system. The FPGA [20] is a quality alternative to mask programmed ASICs. Microprocessor, Microcontrollers and Digital Signal Processors (DSPs) can no longer pace with the new generation due to longer processing time.

The paper is organized as follows: Continuous and discrete control system which is explained in session 2. Overview of the proposed contribution of research which is explained in session 3. Design and implementation of FPGA based digital controller for high efficiency dc-dc converter which is discussed in session 4. The simulation results are discussed in session 5. The conclusion is drawn in session 6. Finally we conclude the paper with the reference.

2. Continuous and Discrete Control System

A continuous time system is the one in which the inputs and outputs are defined for all values of time rather than just for discrete values of time. Continuous control systems are real, they can’t be realized and Proportional –Integral-Derivative (PID) controller. A signal that is continuous in time, with infinite precision and minuscule time spacing between indication points. The input and the output are continuous signal. Figure1. Shows the schematic diagram of continuous controller diagram. An analog plant model can be controlled again by a controller that produces outputs as an analog signal. Figure 1 shows a schematic diagram of continuous controller diagram.

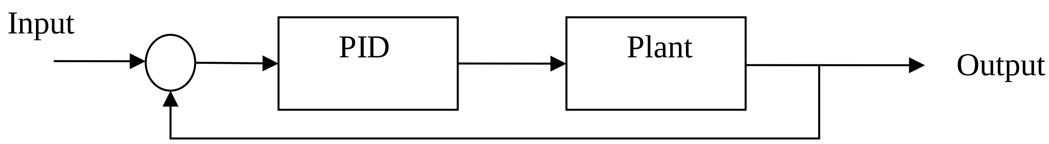

Fig. 1 - A schematic diagram of continuous controller

The plant operators understood the analog controller which has a simple control structure and it was easy for working. While other control system was not as good as the proposed digital controller which is implemented via FPGA [18].

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(t)d\tau + T_d\frac{de(t)}{dt}\right) \qquad (1)$$

A signal with finite precision and discrete spacing between indication points and discrete control systems [6] have two unique features the signals in these systems are either in the form of digital code and controlled process often contain analog components.

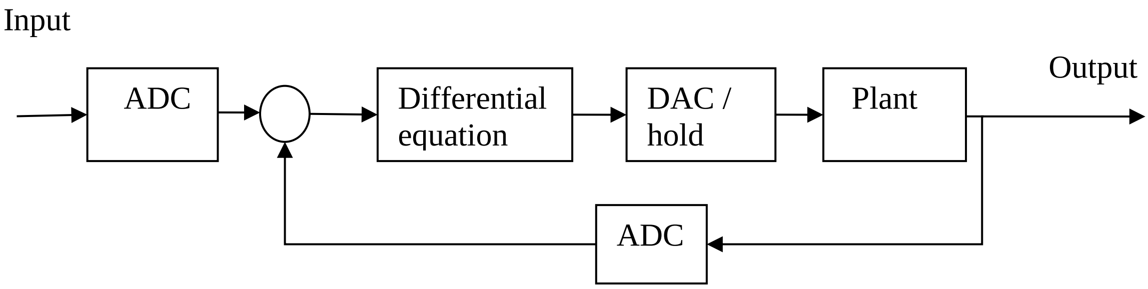

Fig. 2 - A Schematic Diagram of Discrete Controller

In figure 2. A schematic diagram of continuous controller diagram. The discrete-data system can be represented by a number sequences with the numbers separated by the sampling period *T*. The digital – to –analog converter can be represented by a sample-and –hold device, which consists of a sampler and a data - hold device for linear operation. The analysis of discrete-data systems consists of an ideal sampler which is most often used in the sample- and hold. Analog – to –Digital converter is not instantaneous and wants two-step process. First step a delay between the analog input voltage and the output digital word. The analog signal is first converted to a sampled signal and then converted to a sequence of binary numbers ie., the digital signal is called analog- to digital converter. It has more pros including advanced control strategy, low sensitivity to variations and ability to use digital design tools. Figure 2, shows the digital controller consists of three blocks: Analog-to-Digital (A/D) Converter (ADC) [11], Control Law and Digital- to-Analog Converter (DAC).

3. Overview of the Proposed Contribution of Research

In this proposed system design and simulation of a digital controller for a high frequency switching power supply is been described. The strategy for the minimum required resolution of the analog- to –

digital converter, the digital pulse width modulator, fuzzy logic and the fixed-point computational unit are derived. A solar PV array fed high efficiency DC-DC converter [5] which is used to fluctuate solar panel voltage to higher constant DC voltage. This system is implemented in Xilinx block sets in MATLAB/SIMULINK software integrated with Xilinx System Generator. The main motivation of this work is intended to develop a generic methodology for the development of control systems using discrete control system. We choose high efficiency DC-DC converter operating at the switching frequency of 1 MHz which is presented. The advantage of using multi- bit sigma digital pulse width modulator (DPWM) for DC-DC converters with switching frequencies [8] up to multiple MHz include improved resolution. DPWM [14] has implemented with minimal additional hardware that achieves improved output voltage and leads to improve significant power consumption. Diode bridge rectifier provides the same output polarity for either input polarity. In this rectifier is used for converting an alternating current (AC) into a direct current (DC) and it provides full wave rectification from a two wire AC input, therefore resulting in power factor maintenance, lower weight and cost. HEV battery [17] capacity is less important to the other types and the battery can be much smaller, saving weight, it delivers higher current and boost efficiently. The implementation results are shown to validate the design approach and achieved high efficiency. Simulation is done using MATLAB/SIMULINK and the results were discussed in this paper. Figure 3. represents the block diagram of the proposed methodology.

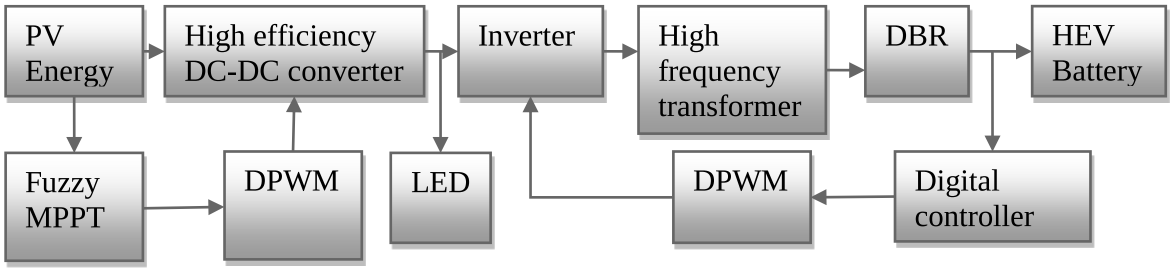

Fig. 3 - The Block diagram of the Proposed Methodology

4. Design and Implementation of FPGA based Digital Controller for High Efficiency DC-DC Converter

In figure 4. Simulation diagram for high efficiency DC-DC converter without control system is shown .This simulation system consists of high efficiency DC-DC converter, high frequency inverter, high frequency transformer, Diode bridge rectifier and battery.

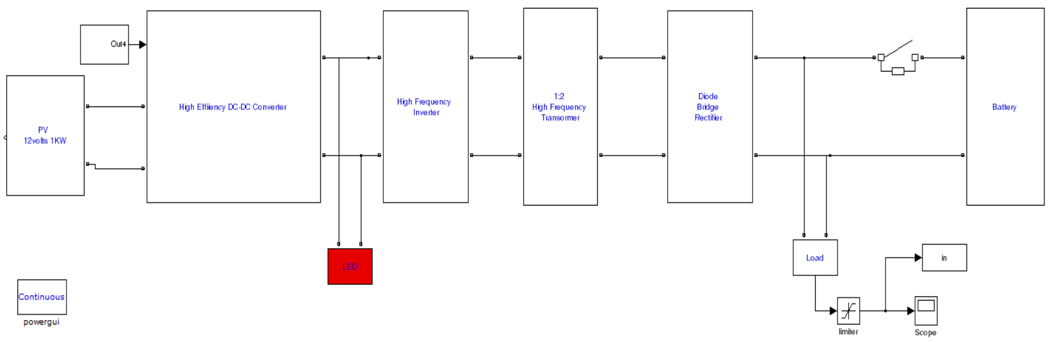

Fig. 4 - Simulation diagram for high efficiency DC-DC converter without control system

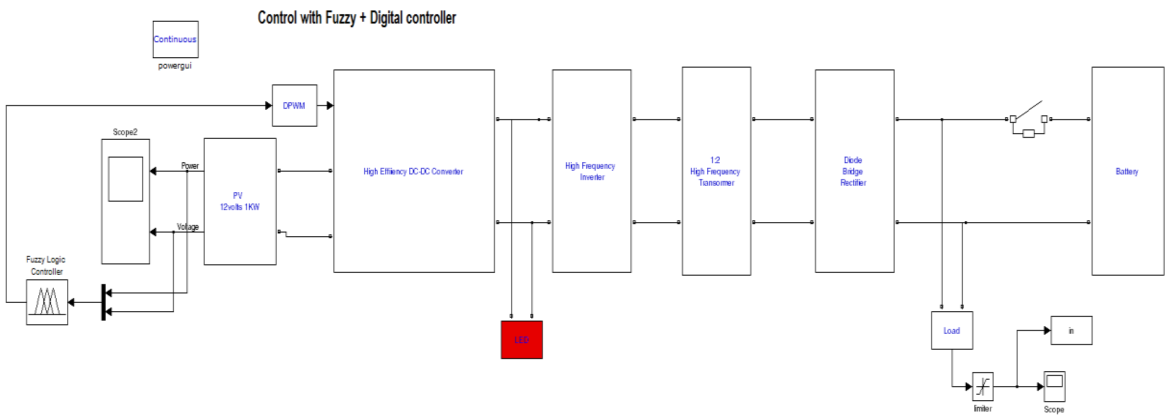

Fig. 5 - Simulation diagram for high efficiency DC-DC converter with control system

In figure 5. Simulation diagram for high efficiency DC-DC converter with control system is shown. This simulation system consists of high efficiency DC-DC converter [9], high frequency inverter, high frequency transformer, Diode bridge rectifier, battery, Digital control system and Fuzzy MPPT.

A. Inductor Selection

The higher inductor value [10] is the possible maximum output current because of the reduced ripple current and normally when the inductor value is low, the smaller is the solution size

$$L > \frac{V_{out}*(V_{inmax}-V_{out})}{K_{ind}*F_{sw}*V_{inmax}*I_{out}} \tag{2}$$

Where:

V_{inmax} = maximum input voltage

Vout = desired output voltage

Iout = desired maximum output current

Fsw = switching frequency of the converter

K_{ind} = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current.

B. Maximum Switch current

The maximum switch current is to calculate the duty cycle must be derived from this application. There are two operating cases to consider for these calculations ie., buck mode and boost mode. Derive the maximum switch current [10] for both cases; the maximum switch current is obtained when the input voltage is at its maximum.

$$I_{swmax} = \frac{\Delta Imax}{2} + I_{out} \tag{3}$$

$$\Delta Imax = \frac{(V_{in}-V_{max})*Dbuck}{F_{SW}*L} \tag{4}$$

Where,

Vinmax = maximum input voltage

Vout = desired output voltage

Iout = desired output current

ΔImax = maximum ripple current through the inductor

Iswmax = maximum switch current

Dbuck = minimum duty cycle for buck mode

Fsw = switching frequency of the converter

L = selected inductor value

The converter can deliver the maximum current using equation 5. I_{maxout} must be greater than I_{outmax}. I_{outmax} is specified as the maximum output current.

$$I_{maxout} = I_{lim} - \frac{\Delta Imax}{2} \qquad (5)$$

Where:

Imaxout = maximum deliverable current through inductor by the converter

Ilim = switch current limit, specified in converter datasheet

ΔImax = Ripple current through the inductor calculated in equation 3.

C. Capacitor Selection

To calculate the minimum output capacitor value [10] for a desired output voltage ripple and for the minimum output capacitance the maximum value from equation 5 is been used .

$$C_{outmin} = \frac{K_{ind} * I_{out}}{8 * F_{sw} * Vout_{ripple}} \qquad (6)$$

Where,

Coutmin = minimum output capacitance

Fsw = switching frequency of the converter

= desired output voltage ripple

I out = desired maximum output current

K ind = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current.

D. Duty cycle

The operating parameter of the converter is to calculate the minimum duty cycle [10] for buck mode [16] and maximum duty cycle for boost mode. These duty cycles are important because at these duty cycles the converter is operating at the extreme of its range and this system need 6v so only buck mode is chosen. The duty cycle is positive and always less than 1.

$$D_{Buck\ (6v)} = \frac{V_o}{V_i} = \frac{6}{12} = 0.5 \quad (7)$$

E. Fuzzy Logic Controller

Fuzzy logic [21] is capable of making valuable decisions and this technique is widely applied today. To implement fuzzy logic to an application requires the following three steps. The first step is called fuzzification, it is changing of real values into fuzzy values. Fuzzy inference process is the second step which combines the fuzzy variables with the control rules to obtain the fuzzy output. The final step is defuzzification it is reconverted fuzzy variables into real world signal. Table 1. Shows the fuzzy control rule.

V / P	NB	NS	Z	PS	PB
NB	PB	PB	Z	PB	PB
NS	PS	PS	Z	Z	NB
Z	Z	Z	Z	Z	Z
PS	PB	NS	Z	NS	NS
PB	PB	PS	Z	NS	NB

Table 1 - Fuzzy Control Rule

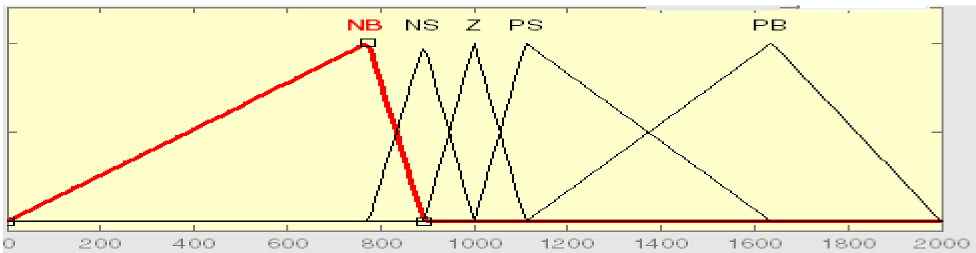

Fig. 6 - Fuzzy Control Rule Diagrammatic Representation for Pmax

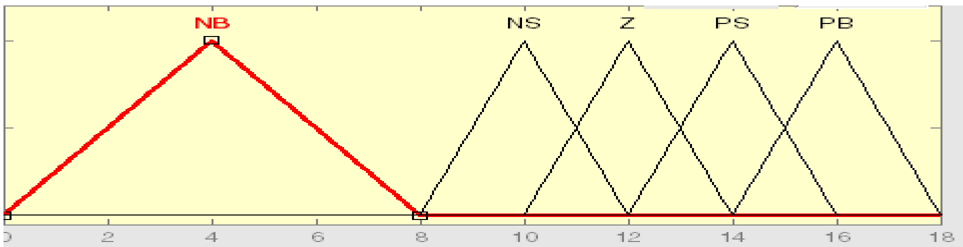

Fig. 7 - Fuzzy Control Rule Diagrammatic Representation for Vmax

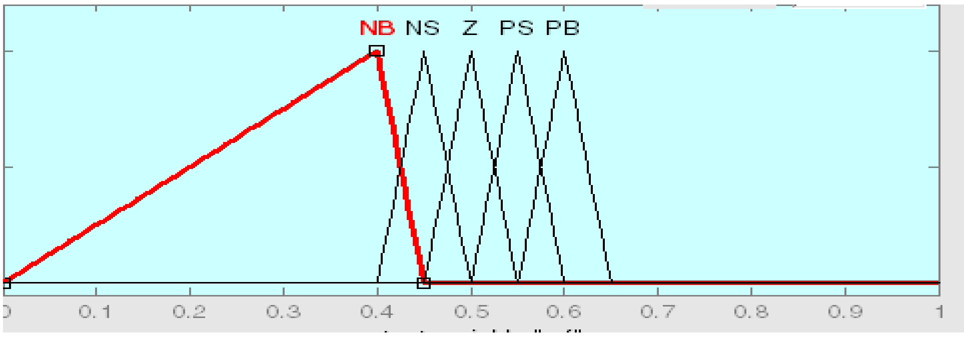

Fig. 8 - Fuzzy Control Rule output Diagrammatic Representation

From figure 6,7 and 8 represents the fuzzy control rule for power, voltage and the output. The input to the fuzzy logic is an power (Pmax) and voltage (Vmax) and the output acquired is the active component of current. Both Pmax and Vmax are transformed from continuous variables to fuzzy variables by using four member functions. The four member functions are named as Z – Zero, PS – Positive Small, PB – Positive Big, Negative Small (NS) and Negative Big (NB). The output of the fuzzy logic controller is estimated using fuzzy rule shown in table 1 for five membership function. Fuzzy sets of power and voltage are combined to produce a rule for the system. These rules are known as rule base system.

F. Digital controller system

Design of discrete controller has different types of methods, they are Inverse dynamics method, Dead beat and dead beat with constraint on manipulated variable, Stable Time –optimal control (TOC), Finite TOC, Constrained Finite TOC, Feed Forward and Quadratic Controller. Figure 9.shows the simulation diagram for digital control system.

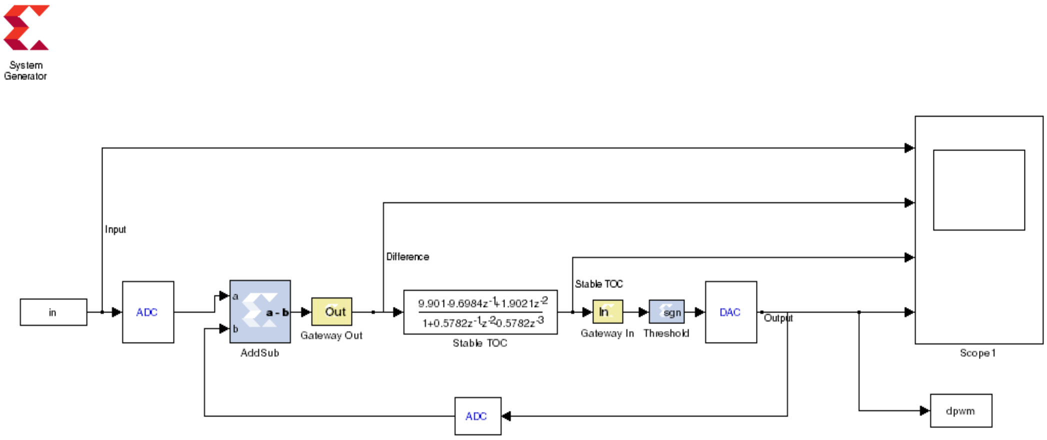

Fig. 9 - Simulation diagram for Digital control system

Table. 2 - Transfer function of Digital Controller

METHOD	$G_R(z)$
Stable TOC	$\frac{9.901-9.6984z^{-1}+1.9021z^{-2}}{1+0.5782z^{-1}-z^{-2}-0.5782z^{-3}}$
Finite TOC	$\frac{6.2735-6.1449z^{-1}+1.205z^{-2}}{1-0.6336z^{-2}-0.3664z^{-3}}$
Constrained Finite TOC ($u \leq 6$)	$\frac{6-5.6035z^{-1}+0.8847z^{-2}+0.0525z^{-3}}{1-0.606z^{-2}-0.378z^{-3}-0.016z^{-4}}$
Feedforward	$\frac{9.901}{1+1.5577z^{-1}+0.5663z^{-2}}, \frac{-7.5972+1.863z^{-1}}{1+1.5577z^{-1}+0.5663z^{-2}}$
Quadratic Controller	$\frac{1-0.9795z^{-1}+0.1921z^{-2}}{0.101+0.0584z^{-1}-0.101z^{-2}-0.0584z^{-3}}$
Inverse Dynamics	$\frac{2.1026-2.0795z^{-1}+0.4323z^{-2}}{1-z^{-1}}$
Dead Beat	$\frac{6.2735-6.1449z^{-1}+1.2051z^{-2}}{1-0.6336z^{-2}-0.3664z^{-3}}$
Constrained Dead Beat ($u \leq 5.5$)	$\frac{5.5-4.6082z^{-1}+0.2997z^{-2}+0.1486z^{-3}}{1-0.555z^{-2}-0.3993z^{-3}-0.0452z^{-4}}$

In this proposed system, we choose Stable TOC because they attain maximum efficiency compared to the other methods and it produces less running time.

5. Simulation Result

A simulation model of FPGA based digital controller for high efficiency dc- dc converter is designed using MATLAB Xilinx system generator toolbox. The Simulink model consists of Solar PV, high efficiency DC-DC converter, battery, inverter, high frequency transformer, fuzzy MPPT and LED. The above simulink model has been designed using the following parameters as shown in table 3 and 4.

Table 3 - PV Specification

Units	Value	Parameter
volts	12	Voc
Amps	83	Isc
Kwatts	1	Pmax

Table 4 - High Efficiency DC-DC Converter

Units	Value	Parameter
Volts	12	Input Voltage
Volts	6	Output voltage
Kwatts	1	Output power
uH	0.06	Inductor
uF	62.5	Capacitor
MHz	1	Switching frequency

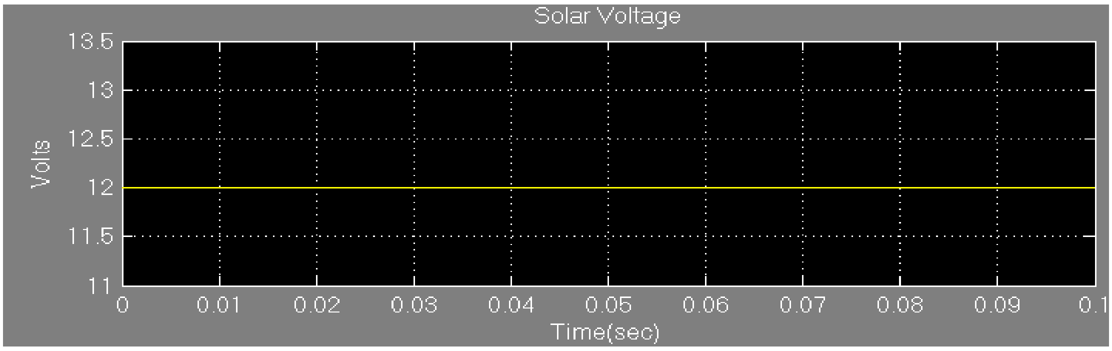

Fig. 10 - Solar Input voltage

In figure 10. The solar panel input voltage of 12V are shown and the figure 11.shows the solar output power 1Kwatts.

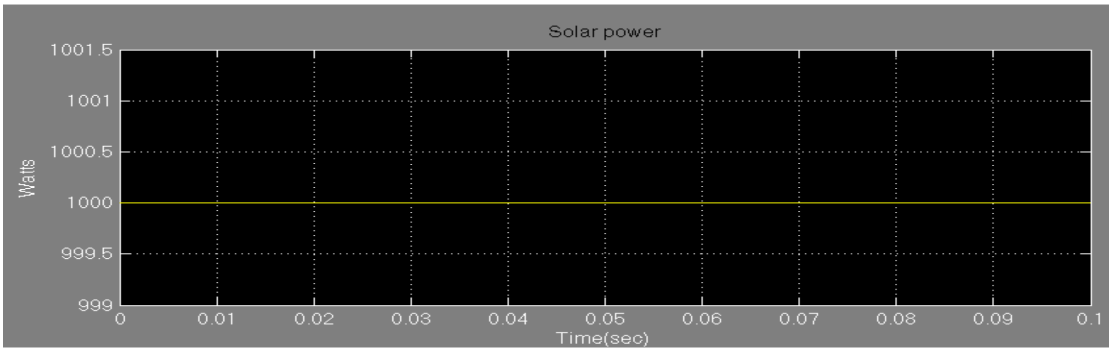

Fig. 11 - Solar output power

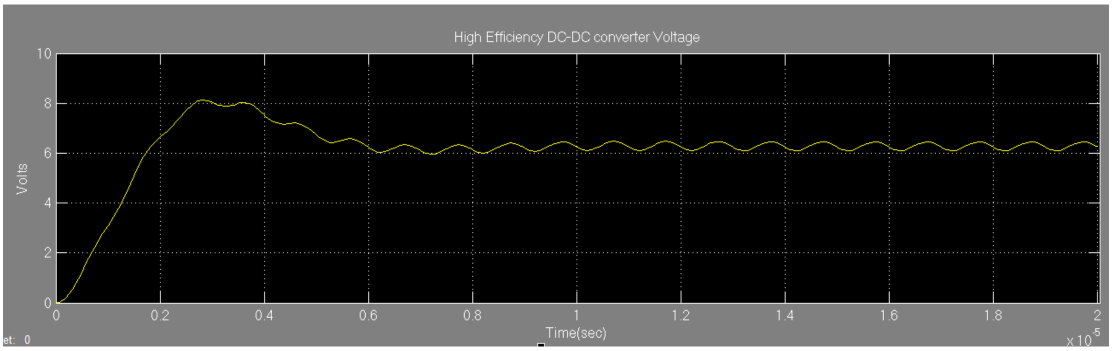

Fig. 12 - High efficiency DC-DC converter voltage

The figure 12 represents the high efficiency DC- DC converter voltage of 6v and the figure 13 represents the high efficiency DC-DC converter power of 1Kwatts.When the solar voltage is 12V, 1 KWatts is input of the high efficiency DC- DC converter and it is transformed into the output of the high efficiency DC-DC converter which produces 6v, 1Kwatts.

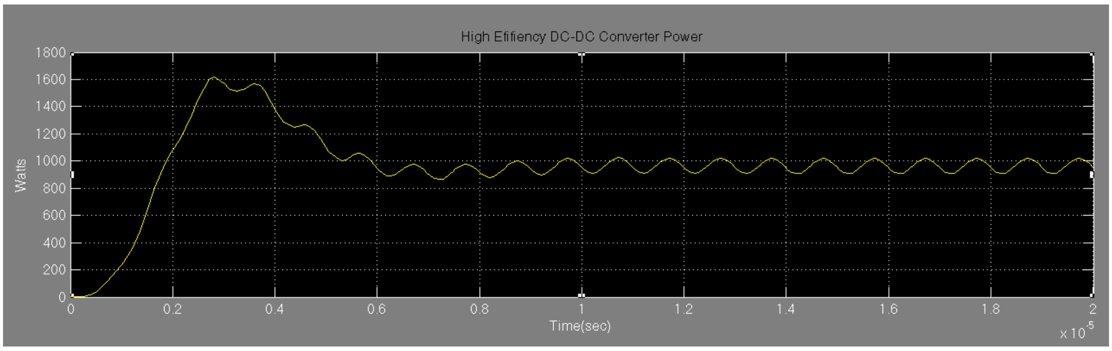

Fig. 13 - High efficiency DC- DC Converter power

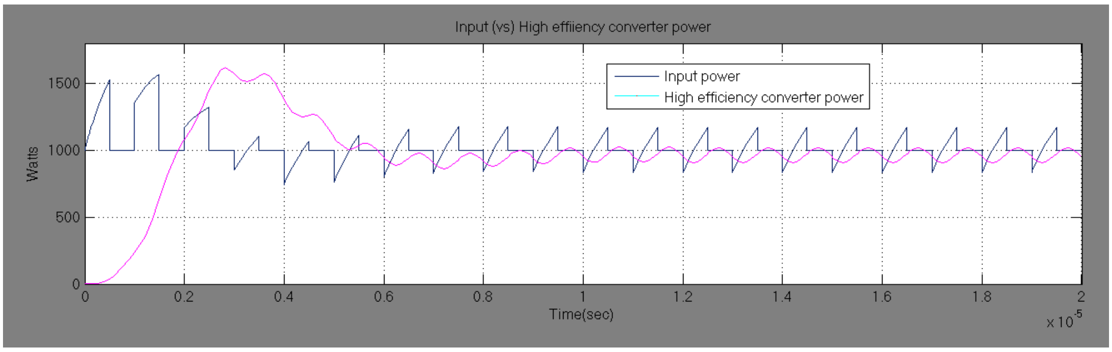

Fig. 14 - Input power compared with high efficiency converter power

Figure 14 shows the input power compared with high efficiency converter power.

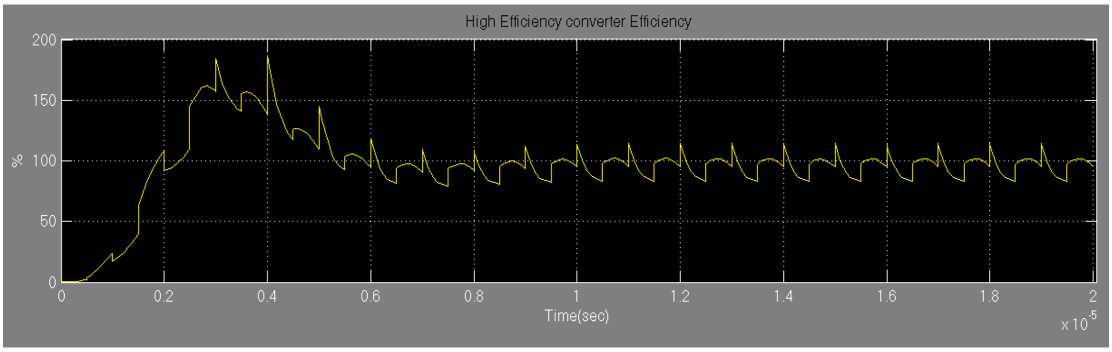

Fig. 15 - Efficiency of the high efficiency converter

From the figure 15. The efficiency of the converter is achieved approximately 100%. While the normal buck – boost converter produces 70- 77% efficiency.

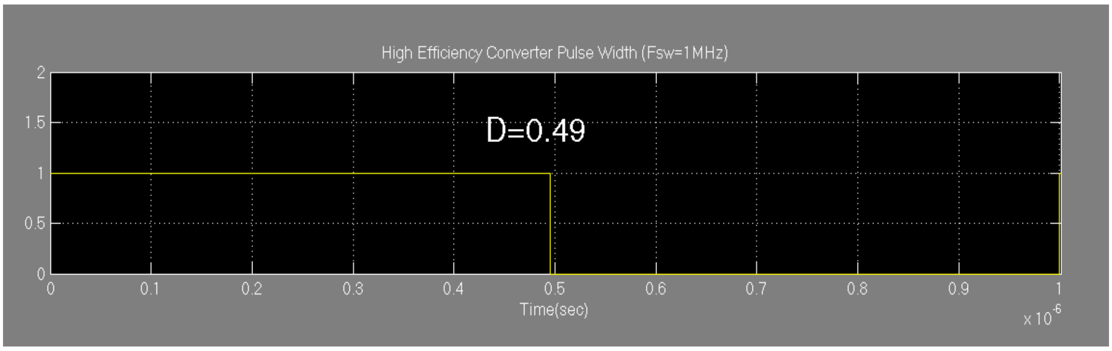

Fig. 16 - High efficiency converter – Pulse Width

The figure 16. Represents the high efficiency converter pulse width, duty cycle 0.49 approximately 50% of the duty cycle for 1MHz switching frequency.

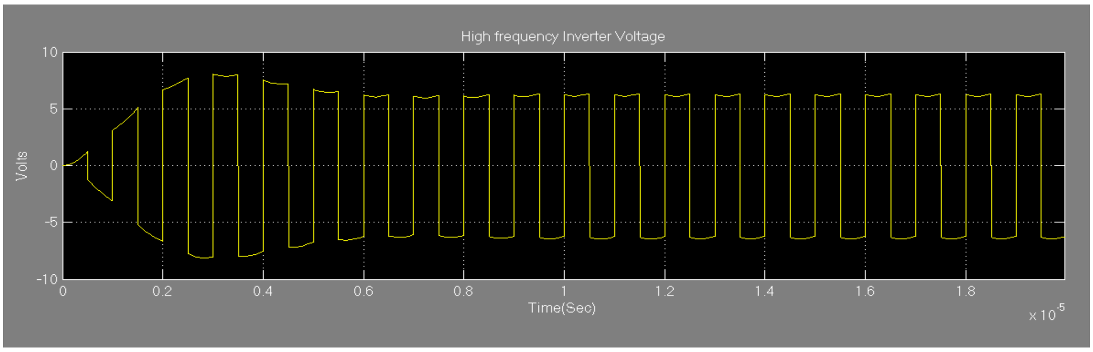

Fig. 17 - High frequency inverter voltage

The figure 17. Represents the high frequency inverter voltage. When the input voltage is DC 12v, 1 Kwatts and the high efficiency converter output voltage is 6v. Then the next stage is high frequency inverter, it produces AC 6v. Because only AC voltage is applied to the input of the next block of high frequency transformer, so here inverter is used to invert the voltage.

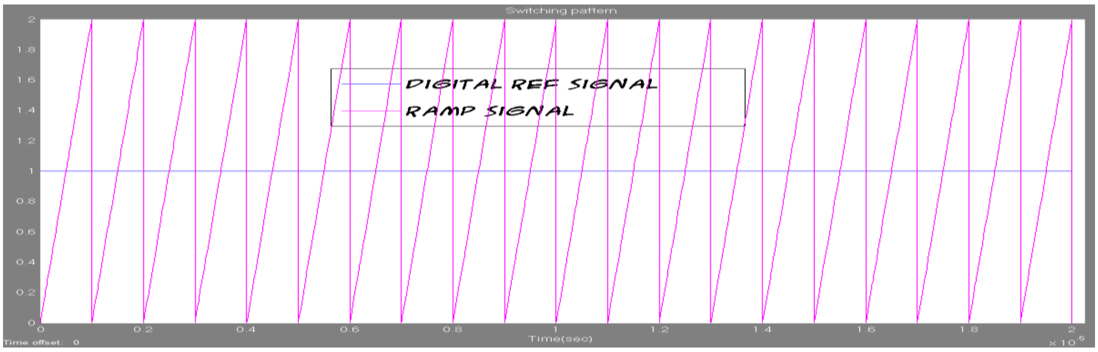

Fig. 18 - Digital reference signal across the ramp signal

Figure 18. Represents the digital reference signal across the ramp signal.

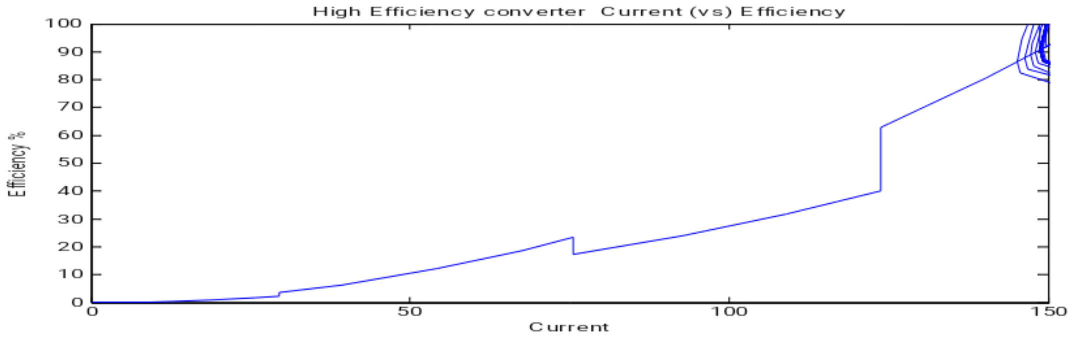

Fig. 19 - High Efficiency Converter Current (A) verses Efficiency (%)

Figure 19. Represents the high efficiency converter current verses efficiency. The x-axis shows the current in amps and the y-axis shows efficiency. Let's include our samples in the graph see what sort of efficiency they would get with this current. This proposed have attained high efficiency at 80% to 100%.

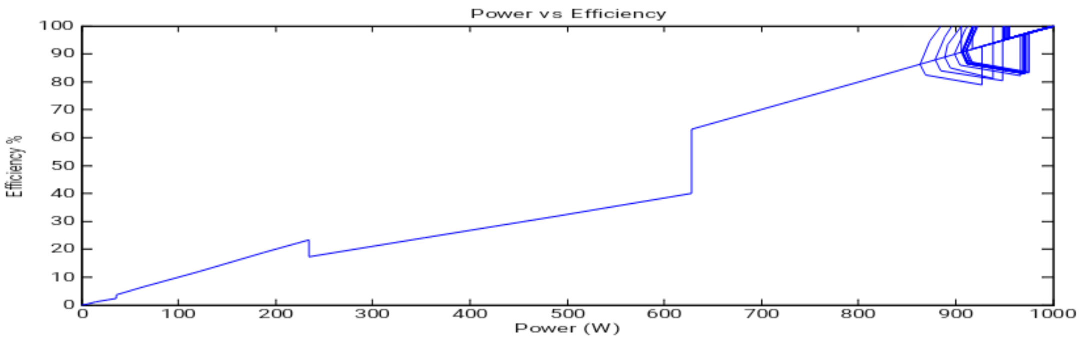

Fig. 20 - Power (W) verses Efficiency (%)

In figure 20 power verses efficiency is represented. Efficiency is the output power divided by the input power. The x-axis shows the power supply load in watts and the y-axis shows efficiency. Let's include our samples in the graph see what sort of efficiency they would get with this power supply. This system causes high-performance power supply to 80% to 100% efficiency, although occurs at the maximum load 1 K watts. Figure 21 represents the inverter switching pulse.

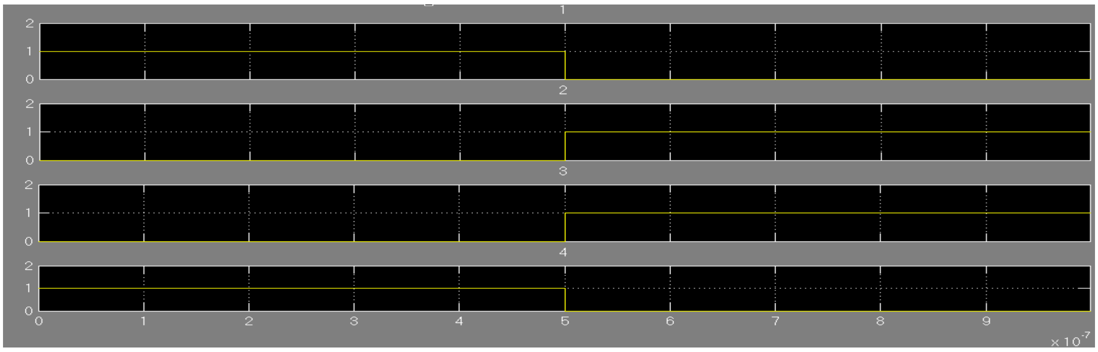

Fig. 21 - Inverter Switching Pulse

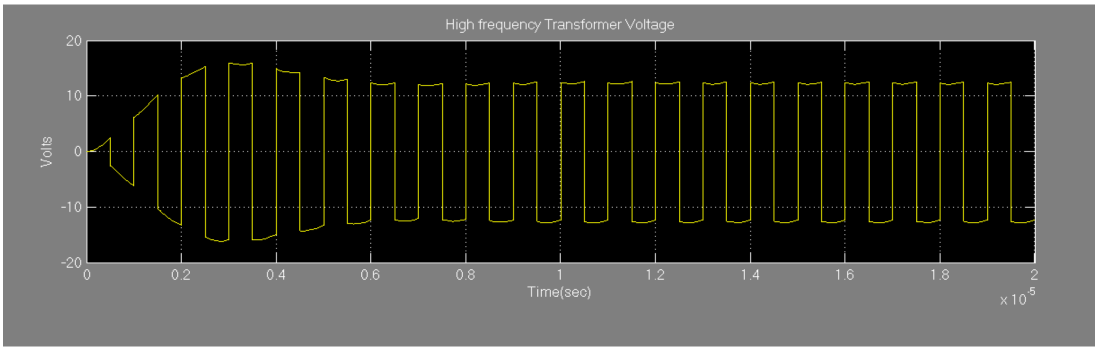

Fig. 22 - High frequency transformer voltage

In the figure 22. Shows the high frequency transformer voltage is shown and the figure 23. Represents the digital control system output. When the digital controller input is 12V and the figure 23 shows the stable TOC input, stable TOC output and digital to analog output signal. This system required high efficiency so we choose stable TOC.

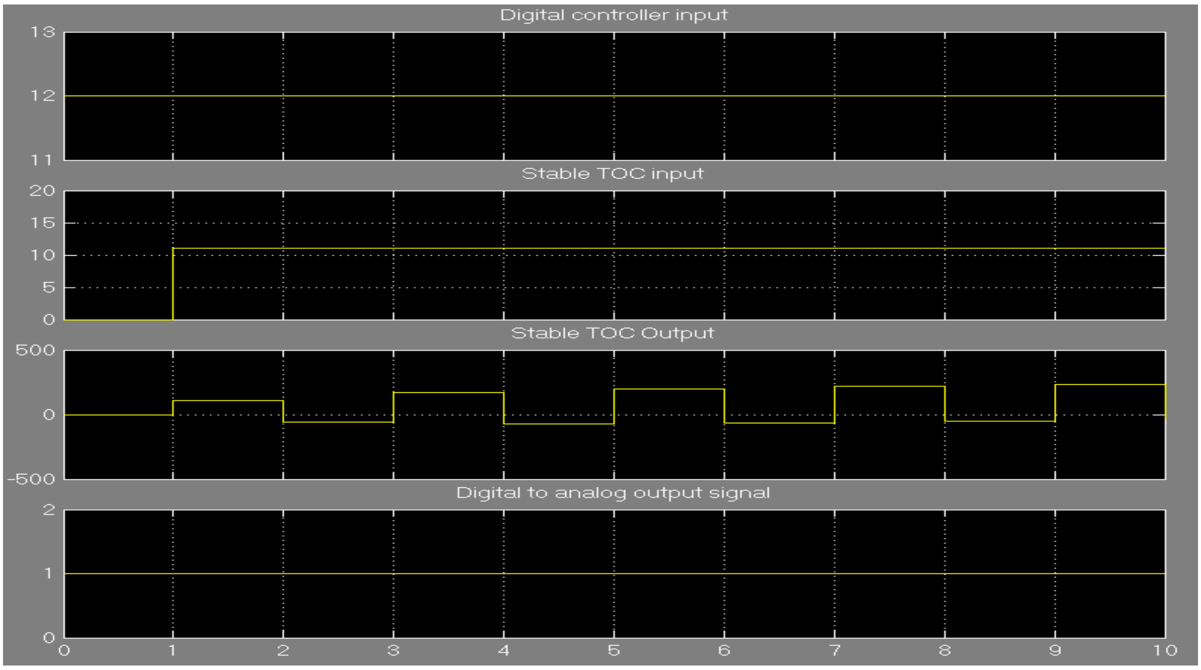

Fig. 23 - Digital control system output

Fuzzy Logic Controller

The fuzzy logic controller [21] uses Pmax and Vmax and the input signals and the output is the reference of the high efficiency converter. In this system, five fuzzy levels are used Zero (Z), Positive Small (PS), Positive Big (PB), Negative small (NS) and Negative Big (NB). So it has twenty numbers of states.

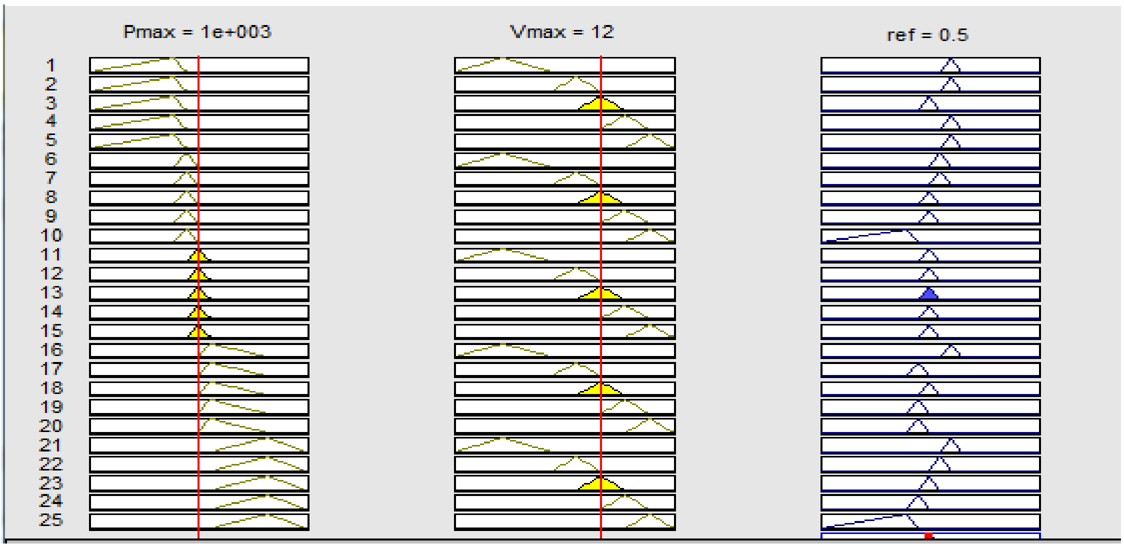

Fig. 24 - .Fuzzy Rules Relating Inputs and Outputs Parameters in Fuzzy Logic System

Figure 24. Shows the fuzzy rules relating inputs and outputs parameters in the fuzzy logic system. The membership function of the input power (Pmax) is 1 e+003, Voltage (Vmax) is 12V and the output is 0.5.

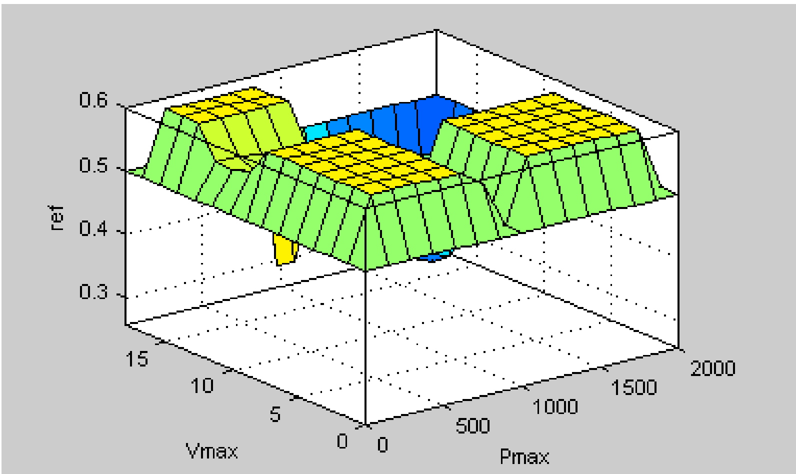

Fig. 25 - Surface Plot of Fuzzy Logic Control

In figure 25.the surface plot of fuzzy logic control are shown. The surface plot of the first input X-axis is Pmax =1e+003, second input y-axis is Vmax 12V and the output is 0.5.

6 Conclusion

In this proposed system the elements of a research program to design and implement FPGA based digital controller for high efficiency dc- dc converter. Continuous control, in which the variables and parameters are continuous and discrete control in which the variables and parameters are discrete. In continuous control, the aim is to maintain the value of an output variable at a desired level, similar to the operation of a feedback control system. In discrete control, the parameters and variables of the system are changed at discrete moments in time and the changes are typically binary (ON/OFF). Digital control systems are more suitable for modern control system and processing time is very low. The analog circuit output has some electrical stress but the digital circuit has stress free output. So this proposed system uses digital controller. Normal buck – boost converter achieved only 70% efficiency and the high efficiency buck- boost converter achieved 80 to 100% efficiency. So, in this system to choose high efficiency DC-DC converter operating at the switching frequency of 1MHz.The converter is suitable for HEV plug-in –battery charges but also for automobile applications and particularly the results are high efficiency. MATLAB Xilinx system generator toolbox is used to implement the proposed system and the simulation result has achieved better performance and high system efficiency.

References

1. Nene, Hrishikesh, Chen Jiang & Shamim Choudhury (2017). Digital controller with integrated valley switching control for light load efficiency and THD improvements in PFC converter. Applied Power Electronics Conference and Exposition (APEC), 2017 IEEE. IEEE, 2017.
2. Shu, Zhang, et al. (2017). A single-switch LED driver based on Class-E converter with digital control. Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), 2017 11th IEEE International Conference on. IEEE, 2017.
3. Wu, Jing & Min Zhou (2016). Digital PID controller designed and realized based on state machine. Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC), 2016 IEEE. IEEE, 2016.
4. Suryanarayana, K. & Nagaraja, H. N. (2015). Modeling and design of 700W digital average current mode controlled multiphase bidirectional DC-DC converter. Microelectronics and Electronics (PrimeAsia), 2015 IEEE Asia Pacific Conference on Postgraduate Research in. IEEE, 2015.
5. Dashtestani, Ahmad & Bertan Bakkaloglu (2015). A Fast Settling Oversampled Digital Sliding-Mode DC–DC Converter. IEEE Transactions on Power Electronics 30.2, 1019-1027.
6. Paulusova, J. & Dubravska, M. Design Of Discrete Controller in MATLAB. Institute of Control and Industrial Informatics, Slovak Scientific Grant Agency, Grant No. 1/2256/12 and Grant No. 1/1241/12.
7. Dutta, Sumit, Samir Hazra & Subhashish Bhattacharya. A Digital Predictive Current Mode Controller for Single Phase High Frequency Transformer Isolated Dual Active Bridge DC to DC Converter.
8. Furukawa, Yudai & Fujio Kurokawa (2015). Design consideration of high performance digital control DC-DC converter based on frequency characteristics. Industrial Technology (ICIT), 2015 IEEE International Conference on. IEEE.
9. Gopinathan, Krishna & Mamatha, I (2016). Average current mode controlled DC-DC converter using digital controllers. Power and Energy Systems: Towards Sustainable Energy (PESTSE), 2016 Biennial International Conference on. IEEE.
10. Michael Green, Design Calculations for Buck-Boost Converters, Advanced Low Power Solutions, Texas Instrument
11. Jacinto, Bruno & Marcelino Santos (2015). Digital Sliding Mode Control with non-linear ADC. Design of Circuits and Integrated Systems (DCIS), 2015 Conference on. IEEE.
12. Kurokawa, Fujio, Ryuya Yoshida & Yudai Furukawa (2015). Digital fast P slow ID control DC–DC converter using A–D converters in different resolutions. IEEE Transactions on Industry Applications 51.1, 353-361.

13. Lee, Yoontaek, Juyun Lee & Jaeha Kim (2015). GaN FET-based synchronous buck converter with 10-bit 4-MHz digital pulse width modulator. Power Electronics and ECCE Asia (ICPE-ECCE Asia), 2015 9th International Conference on. IEEE.
14. Mooney, James et al. (2015). Dithered multi-bit sigma-delta modulator based DPWM for DC-DC converters. Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE. IEEE, 2015.
15. Pasternak, Sarah & Jason Stauth (2016). Design considerations for digitally controlled buck converters with large input transients. Control and Modeling for Power Electronics (COMPEL), 2016 IEEE 17th Workshop on. IEEE.
16. Stack, David, Anthony Kelly & Thomas Conway (2016). A high accuracy and high bandwidth current sense circuit for digitally controlled DC-DC buck converters. Applied Power Electronics Conference and Exposition (APEC), 2016 IEEE.
17. Sucameli, Matteo (2015). Design and performance evaluation of a digitally controlled 1 kW three-phase interleaved ZVS converter for plug-in EV and HEV battery charger. Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE.
18. Patel, Vipul, B., Singh, V. and Acharya, R. H. (2012). Design of FPGA-based all digital pid controller for dynamic systems. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering. 1.2.
19. Sustersic, John, et al. (2000). Design and implementation of a digital controller for DC-to-DC power converters. No. 2000-01-3603. SAE Technical Paper.
20. Zhao, Wei, et al. (2005). FPGA implementation of closed-loop control system for small-scale robot." Advanced Robotics, 2005. ICAR'05. Proceedings., 12th International Conference on. IEEE.
21. Benaissa, Amar, Boualaga Rabhi & Ammar Moussi (2014). Power quality improvement using fuzzy logic controller for five-level shunt active power filter under distorted voltage conditions. Frontiers in Energy 8.2, 212.