

# **Voltage Regulation and Over Voltage Protection for High Gain High-Efficiency DC-DC Converter**

N.T. Bakhtiyari<sup>1</sup>, B.R.Prabhu<sup>2</sup>, Shilpa Patil<sup>3</sup>

PG Student [Electronics], FRCRCE, Maharashtra, India<sup>1</sup>

Senior Member IEEE, Professor, Dept. of ECE, FRCRCE, Maharashtra, India<sup>2</sup>

Professor, Dept. of ECE, FRCRCE, Maharashtra, India<sup>3</sup>

**ABSTRACT** Due to increase in population, there is an increase in demand for consumption of electricity; renewables sources like Solar Photovoltaics [PV] and fuel cell stack are becoming popular. Solar PV and fuel stack are preferred as it operated at low voltages. Due to which, there is a need for a high voltage, a high-efficiency DC-DC converter for renewable applications requiring high DC link output voltage. The main objective of the project is to achieve a regulated output voltage at the DC link and also protect output filter from the fluctuation caused by the change in the output load. In a high voltage gain, DC-DC converter the output filter needs to be protected to avoid the filter potential to reach more than the rated voltage level of 380VDC in case of load fluctuation. It is necessary to protect the output smoothing filter from overcharging in order to avoid filter damage and eventual circuit breakdown. In this project in order to regulate and protect the same, a voltage feedback control technique used along with the help of microcontroller PIC16876P a circuit is designed which will sense the output voltage level, take corrective action and provide PWM signals to operate the power MOSFET which will, in turn, avoid filter damage.

**KEYWORDS:** High Gain DC-DC converter, voltage feedback control technique, PWM Control, Voltage Regulation.

## **I.INTRODUCTION**

With the increase in population, there is a very high demand for electricity which has led to extreme usage of fossil fuels, such as oil, gas, and coal results in a serious greenhouse effect and environmental pollution, which have a great influence in the world. Meanwhile, there is a big contradiction between the fossil supply and the global energy demand. Renewable energy is becoming very popular to meet the global power demand and to reduce environmental pollution. Renewable energy sources include solar, wind and tidal energy sources are becoming more mature and widely used. Solar PV is becoming a favourite choice amongst the other renewable sources and it will make one of the biggest contributions to electricity generation among the entire renewables energy candidate because it is clean, emission-free, and renewable electrical source with high reliability. Often these renewable sources have low-voltage output and must be pass through a set of high boost converter circuits to increase the voltage and then through a DC-AC inverter to convert AC voltage for the main supply. Therefore, a DC-DC high boost converter plays an important role in the overall efficiency of the system. The PV grid-connected power system in the residential applications is recently becoming a fast-growing segment in Europe, Japan, and the U.S. [1]. Unfortunately, the output voltage of the PV array is relatively low (24-48V). In order to satisfy the high bus voltage requirements for the full-bridge, half-bridge, or multilevel grid inverters, the PV series-connected configuration is the conventional solution [2]. However, the generated output power of the PV arrays is decreased greatly due to module mismatch and partial shading, especially in the urban areas [3]. In the residential PV grid-connected system, the PV arrays are usually installed on the roof. Thus, the generated power of the PV arrays is reduced greatly with PV series connected configuration when they are covered by the shadows, which may be caused by the clouds, trees, neighbour's house, and even the power line cables. In these situations, the PV parallel-connected configuration is more efficient than the series-connected configuration due to the

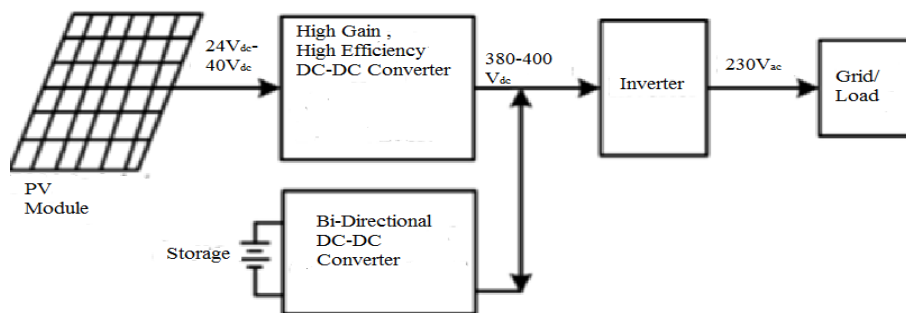
# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

PV performance [4]. On the other hand, only a low voltage is generated with the parallel-connected configuration, which makes it easy to satisfy the safety requirements in home applications. Thus, the new research trend is to employ the PV parallel-connected configuration rather than the series-connected configuration in the residential power generation system. Renewable energy such as Solar PV and fuel stack poses some other significant challenges such as optimal utilization of the sources due to their variable output. They are usually operated at low output voltage levels (typically 24-48V) when connected in parallel for residential application. This makes their application to grid-connected systems and even some standalone loads difficult because a large voltage boosting at the output is required. The converters need to raise the low DC voltage (24-48V) to high DC voltage (380-400 V) for the PV inverters. This indicates that a DC-DC converter with high output voltage is essential right across the solar power panel as shown in the fig.1.1.



**Fig1. Block diagram of a PV power conversion**

The block diagram of a PV power conversion is as shown in fig1. The output of the panel is fed to a High Gain High-Efficiency DC-DC converter. Various topologies of DC to DC step-up converter are available to achieve this high voltage gain. This high voltage of 380-400Vdc is then fed to an inverter. The inverter input which is the DC link bus voltage of 380-400Vdc is needed to be held constant for the inverter to invert the DC voltage to AC voltage. The inverter can either be grid tied or stand-alone. The converter filter capacitor is designed based on a fixed inverter rating and the filter capacitor is rated based on that load. Now there is a need to regulate the rated DC link voltage for the rated inverter in order to function properly. Due to fluctuation in the load or in cases when the inverter might fail and make the converter load go open. This will cause the output capacitor of the DC-DC converter to charge beyond its rated voltage this is because the constant current is being fed to the capacitor through the inductor. This may cause the damage to the output capacitor and breakdown of the whole DC-DC converter. So there is a need to regulate the DC link converter output voltage and also to protect the output filter capacitor from overcharging.

## II. LITERATURE SURVEY

In recent years, there has been extensive research going in the field of High Gain High-Efficiency DC-DC converter with the rising popularity of renewable energy. The renewable energy is operated at low voltage DC which is needed to be a boosted to a high voltage to feed to the inverter input. Various topologies are introduced in the following section.

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

## 2.1 Conventional Boost Converter

Conventional boost converters are widely used in power factor correction (PFC) application due to its simple topology structure. The conventional single switch topology is shown in fig. 2.

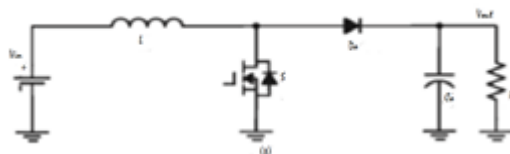


Fig2. Conventional boost converter

A conventional DC-DC boost converter can be used in order to increase the output voltage to a high level but as the duty ratio tends towards unity the efficiency of the converter drops. It also causes a large peak current to flow on the input side, which adversely affects the magnetic component and results in high losses. It also causes the large voltage to appear across the switch, as a result, of the on state resistance of a switch depends on its voltage rating, the conduction losses increase. Diode reverse recovery becomes a major concern.

Various topologies are developed and proposed in the past for renewable application. The following topology philosophy can be classified as follows: High step-up converter with the coupled inductor, High step-up converter with inductor and switched capacitor, High Step-up converter with a coupled inductor and switched capacitor.

### 2.2.1. High Step-up Converters with Coupled Inductor

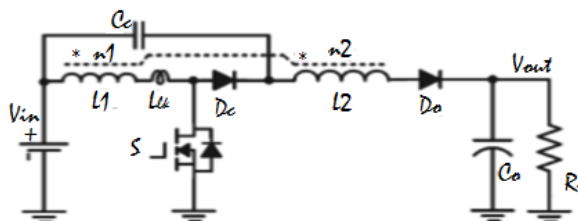


Fig.3. High step-up converter with coupled inductor

Fig.3. is a High step-up converter with coupled inductor is proposed in [5]. A coupled inductor is a device primarily used for energy storage during a power converter switching cycle; the power entering the coupled-inductor is not the same as the power leaving it in a given instant. Coupled inductor can serve as a transformer that is used to enlarge the voltage gain in non-isolated DC-DC converter [6]. Converter with coupled inductors can easily achieve high step-up voltage gain utilising low  $R_{DS-ON}$  switches at low power level. The coupled inductor based DC-DC converter has advantages over isolated transformer based dc-dc converter in minimising current stress, using lower rating component and simple winding structure. The leakage inductance energy can be absorbed by implementing a Clamp circuit (Active clamp circuit or passive clamp circuit). The clamp circuit is adapted to suppress the voltage spikes and to recycle the leakage energy.

### 2.2.2. High-Step-Up converters with Inductor and switched capacitor

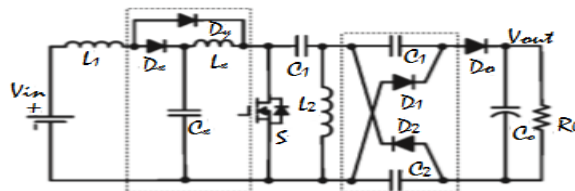
The switched-capacitor and boost converter can be integrated together to obtain a stepless voltage gain. A family of single switch dc/dc converters with high voltage gain is proposed in [7].

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

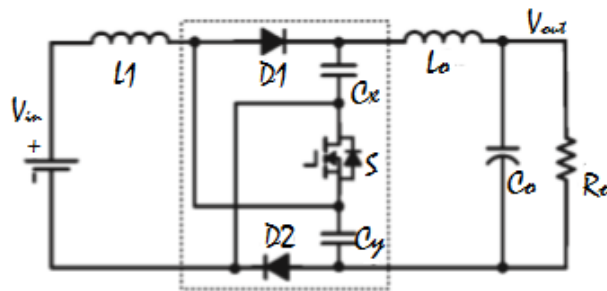
Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019



**Fig 4. High step up converter with inductor and switched capacitor**

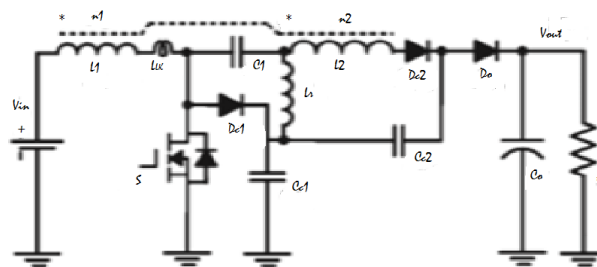
In fig .4.the first dashed block, which is composed of the diode  $D_x$  and  $D_y$ , the inductor  $L_x$ , and the capacitor  $C_x$ , is named as a boost multiplier cell, which can obtain a voltage conversion as the conventional boost converter. The second dashed block, which is composed of two diodes  $D_1$  and  $D_2$  and two capacitor  $C_1$  and  $C_2$ , is named as capacitor-diode multiplier, which can be in series to enlarge the voltage gain and to reduce the switch voltage stress.



**Fig 5. High step up converter with inductor and switched capacitor**

Another family of single switch high step-up dc/dc converter in fig.5.is proposed in [8]. The four terminal high step-up switch cells which are formed by two diodes, two capacitor, and a switch is shown in the dashed block. The voltage gain of the converter can be extended, and the switch voltage stress is reduced by the switching cell.

### 2.2.3. High-Step-Up converters with coupled Inductor and switched capacitor



**Fig. 6. Boost converter with coupled inductor and switched capacitor**

The concept of the coupled inductor and switched capacitor can be combined to derive high-step-up converter shown in fig6 is proposed in [9]. A wide range voltage conversion can be obtained by the coupled inductor and switched

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

capacitor. The output diode reverse recovery is alleviated by the leakage inductance of the coupled inductor. Without increasing the duty cycle of the switch by connecting an intermediate capacitor in series with the inductor the voltage gain of the converter can be increased [10]. The intermediate energy storage capacitor with coupled inductor charges in parallel and discharges in series with coupled inductor secondary.

### 2.3. General Solution for High-Step-Up Conversion

In this section, a general conceptual circuit is proposed to generate next generation DC-DC converter with high step-up and large current conversion [11]. The proposed general conceptual circuit is shown in fig 7.

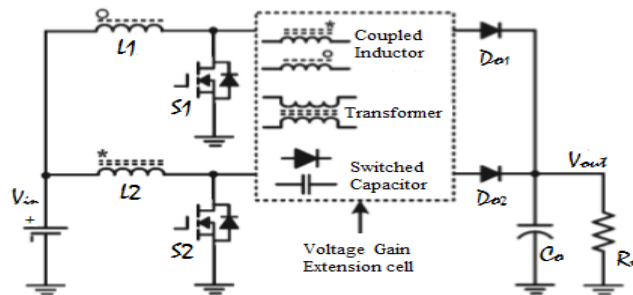


Fig 7. General conceptual circuit for high-step-up conversion.

A voltage gain extension cell is inserted between the switches and the output diode of the conventional interleaved boost converter. Due to the voltage gain extension cell, the extreme duty cycle is avoided, and the current ripples on the power switches are minimised to reduce the numbers of electrolytic capacitors. Consequently, low-voltage-rated MOSFETS are available to reduce the conduction losses and the converter cost.

### PWM control Technique (Pulse Width Modulation)

PWM represents the most commonly employed voltage control method. In this method, at fixed cycles, the amount of power corresponding to the power that needs to be output is switched on to extract it from the input. Consequently, the ratio between on and off, which is, the duty cycle, changes as a function of the required output electric power. PWM switching technique is a means to vary the output voltage in response to input and output voltage changes. Fig 8 shows the use PWM that controls the output to the associated power switch, which controls its on and off time (duty cycle). In operation, the regulator's filtered output voltage is fed back to the PWM controller to control the duty cycle. If the filtered output tends to change, the feedback applied to the PWM controller varies the duty cycle to maintain a constant output voltage. The filtered power switch output voltage is fed back to a circuit that controls the power switch on and off times so that the output voltage remains constant regardless of input voltage or load current changes.

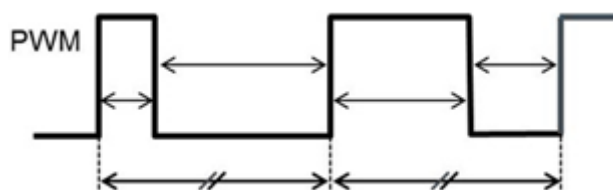


Fig 8. PWM waveform with fixed frequency.

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

An advantage of PWM control is that because the frequency is fixed, any switching noise that arises can be predicted, thus facilitating the filtering process. A drawback of the method is that also due to a constant frequency, the number of switching operations remains the same whether the load is high or low, and consequently, the self-consuming current does not change.

### III. PROPOSED SYSTEM

It consists of a front end high gain DC-DC converter a feedback network and a control unit as shown in fig.9. The converter is operated in continuous conduction mode design to step up a voltage level from 24V input to 380V output. In order to control the variation of the output voltage caused due to the fluctuation of the output load, the converter is controlled by using a voltage feedback control technique. In this technique, the output voltage is feedback through a network which is compared with a reference voltage and the differential error is used to produce the pulse width modulation system [PWM]. So any fluctuation in the output voltage due to the variation of the load will result in a change of duty cycle of PWM. In order to produce a result of a change in the set of duty cycle a microcontroller is used.

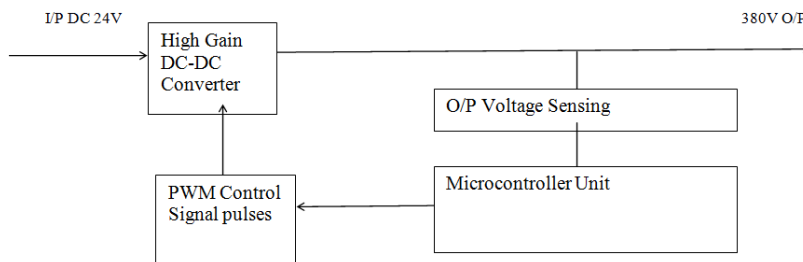


Fig9. General Block Diagram of Proposed System

#### High Gain DC-DC Converter Unit.

The converter shown in fig 10[12] is a high gain DC-DC converter. It consists of one passive clamp network, a coupled inductor (L1 and L2) and an intermediate capacitor apart from other components. The symbol 24v represents voltage applied to the circuit. S is the main switch of the proposed converter.

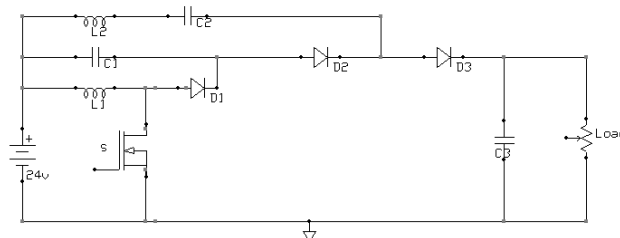


Fig 10.High gain DC-DC converter Unit.

The coupled inductors primary and the secondary inductors are denoted by L1 and L2. Passive clamp network across L1 is represented by C1 and D1. The capacitor C3 is the output capacitor while D3 is the output diode. The output voltage  $V_0$  is the average DC output voltage across the load. The feedback diode D2 and the intermediate energy storage capacitor, C2, are connected on the secondary.

# International Journal of Innovative Research in Science, Engineering and Technology

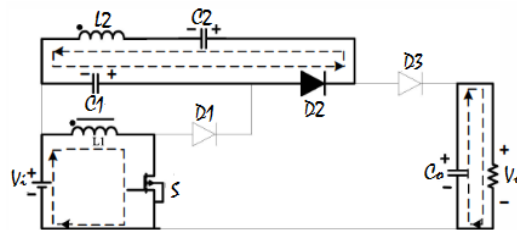
(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

## 2.1.a Different mode of operation (Current Flowing in the circuit)

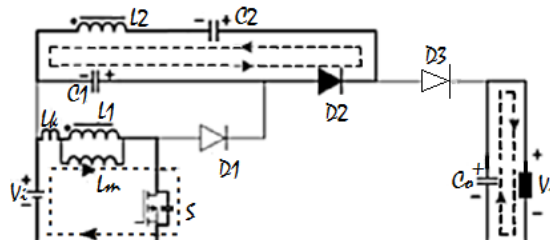
### Mode 1- [to-t1]



**Fig.11.a. Mode 1**

In this mode switch, S is turned on. The magnetizing current of the primary inductor increases linearly and the current flowing path is shown in Fig.11.a. The magnetizing current of the secondary coupled inductor L2 charges the capacitor C2 connected in series with it through the clamp capacitor C1 and forward diode D2. Diodes D1 and D3 are off in this mode. Diode D2 turned off when the secondary leakage inductor current becomes zero. At the end of this mode, primary inductor voltage (VLI) becomes equal to the dc input voltage (V). This mode ends when switch S is turned off.

### Mode 2-[t1-t2]



**Fig 11.b.Mode 2**

In this mode switch, S is turned off. Diode D1 is turned on and D3 is turned off. The operation for this mode is shown in Fig. 11.b. The leakage and magnetizing energy stored in the primary inductor are discharged to the clamp capacitor C1 through the forward diode D1. As inductor current cannot change its direction instantaneously, the current flowing through the secondary inductor L2 will continue to flow in the same direction until the secondary current becomes zero. This mode ends when the diode D2 is turned off.



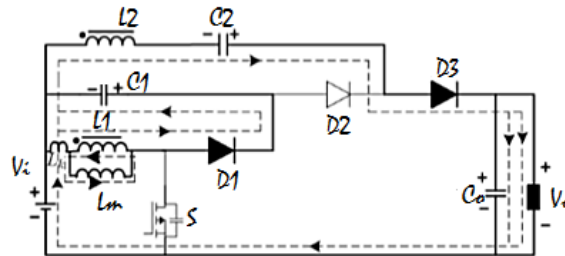
## International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

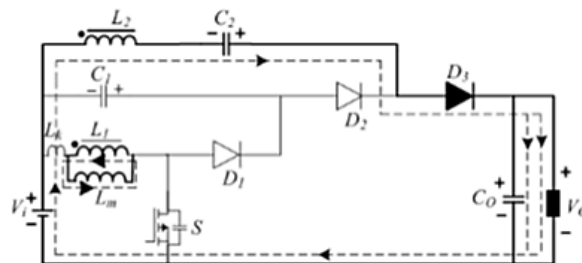
### Mode3 – [t2-t3]



**Fig 11.c.Mode 3**

In this mode switch, S and diode D2 are turned off. Diodes DI, D3 is turned on. The current flowing path is shown in Fig.11.c. The energy stored in the primary inductor discharged to the clamp capacitor C1. The energy stored in the secondary inductor L2 in series with dc source Vi and capacitor C2 transfer the energy to the load. This mode ends when the voltage across capacitor C1 becomes equal to  $V_{LI}$ .

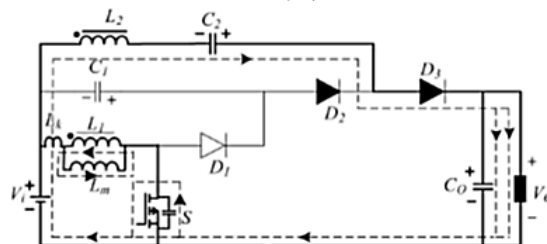
### Mode4 – [t3-t4]



**Fig 11.d.Mode 4**

In this mode switch, S is turned off. Diodes DI, D2 is turned off and D3 is turned on. The magnetizing energy stored in the secondary inductor in series with dc source and capacitor C2 transfer to the load is shown in Fig. 11.d. This mode ends with the turning on of the switch S.

### Mode5-[t4-t5]



**Fig 11.e.Mode 5**

Switch S turned on in this mode. Diodes DI and D2 are turned off and diode D3 is turned on. The primary inductor current will flow through the switch S as shown in Fig. 11.e. The secondary inductor current cannot change its direction instantaneously it will continue flow through the load until the current becomes zero. The primary side leakage current



# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

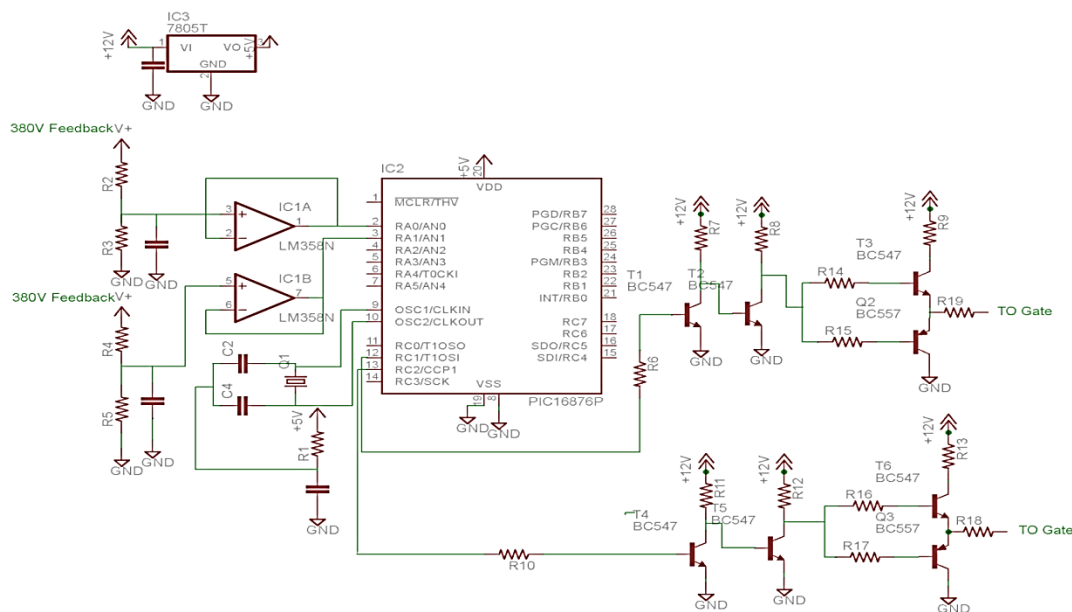
Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

of the coupled inductor is increased. This mode ends with secondary inductor current becomes zero and returns to mode 1.

## Feedback Unit Control Unit and PWM Signal

Figure 3.3 consist of circuit diagram of Microcontroller (uC) based PWM controller. For smooth selection of PWM frequency PIC16876P is selected as preferred microcontroller [13].



Note-Two separate channels are shown in the fig. Only channel 2nd is used.

**Fig 12. Designed Control Unit**

The Operating frequency is selected as 50 KHz and the internal timer register of uC is set accordingly. This controller requires a 5VDC source and is supplied by a series voltage regulator with filtering capacitors. The uC has 2 PWM channels and in order for testing with different PWM frequencies both channels were programmed and use one-at-a-time. The base operating frequency remains 50 KHz. The controller need to be fed with the sample of HV 380VDC, hence a unity gain buffer is utilized which provides good isolation between input 380VDC and output 0-5VDC uC side. Any changes in these voltage levels are sensed and internal program compensates for the change by adjusting its PWM duty cycle and is fed to the MOSFET switch, thus attaining regulation. Here 2 PWM channels are utilized; hence two NPN pull-up drivers are utilized to raise the voltage levels in-order to drive the MOSFET Gate. This MOSFET is connected in the HIGH gain DC-DC converter to gain voltage gains. Since the oscillator frequency of uC is very high, adaptation to any changes in output voltage is sensed and correction is done in very fast manner. This gives us smooth control over the DC-DC controlling function.

## FLOWCHART

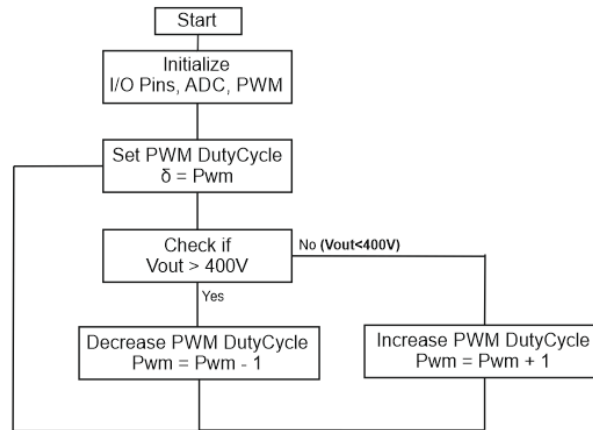
The flowchart below describes the operation of the microcontroller a default duty cycle is set initially for the controller to start its operation. Further, it continuously monitors the output voltage in keeping it constant by adjusting the duty cycle for varying output load.

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019



**Fig 13. Flowchart for over voltage protection**

## IV. ANALYSIS AND DESIGN

### Analysis

All the elements used in the converters are assumed to be ideal.

When Switch S is ON: The voltage across L1 is given by

$$VL1 (ON) = VI \quad (1)$$

The voltage across L2 is given by:

$$\begin{aligned} VL2 &= VC2 - VC1 \\ VL2 &= nVi \end{aligned} \quad (2)$$

When Switch S is OFF: The voltage across L1 is given by:

$$VL1 (OFF) = -VC1 \quad (3)$$

Switch Voltage – Voltage across the switch during the off period is given by:

$$VDS = Vi / (1-d) \quad (4)$$

The voltage across the clamp capacitor: The voltage across the clamp capacitor is nearly constant throughout the switching period.

$$VC1 = d / ((1-d)) Vi \quad (5)$$

Intermediate capacitor voltage VC2: The voltage across intermediate energy

Storage capacitor can be determined as follows:

$$VC2 = VC1 + VL2 \quad (6)$$

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

Reverse bias voltage across Diode (D1)

$$VD1 = VL1 (ON) + VC1 \tag{7}$$

Voltage across diode (D2) is:

$$VD2 = VL2 + VC2 - VC1 \tag{8}$$

Voltage across diode (D3):

$$VD3 = VL2 - VC2 - Vi +Vo \tag{9}$$

**The System Parameter is as follows**

This section covers the detail specification, waveforms and results of the hardware circuit designed and tested in the laboratory.

**TABLE 1**  
**SPECIFICATIONS OF THE LABORATORY PROTOTYPE CONVERTER**

Rated Power	150 W
Input DC voltage	24 V
Output Voltage	370-380 V
Turns ratio of the coupled Inductor (n)	4
Switching Frequency (fs)	50Khz
Duty Cycle	PWM Controlled

Table1 contain the specification of the hardware implemented in the lab. The specification was based on the need and application of the project. The frequency was set to 50Khz. The rated power of the unit is 150W.

**TABLE 2**  
**LIST OF COMPONENTS**

Mosfet	IRF 3710 (100V/57A, $R_{DS(On)}=23m\Omega$ )
Diode D <sub>1</sub>	UF 5408 (trr = 260 ns)
Diode D <sub>2</sub>	UF 5408 (trr = 260 ns)
Diode D <sub>3</sub>	UF 5408 (trr = 260 ns)
C <sub>0</sub>	400V/180uf
C <sub>2</sub>	250V/47uf
C <sub>1</sub>	63V/1uf
Coupled Inductor	Cosmo ferrite core

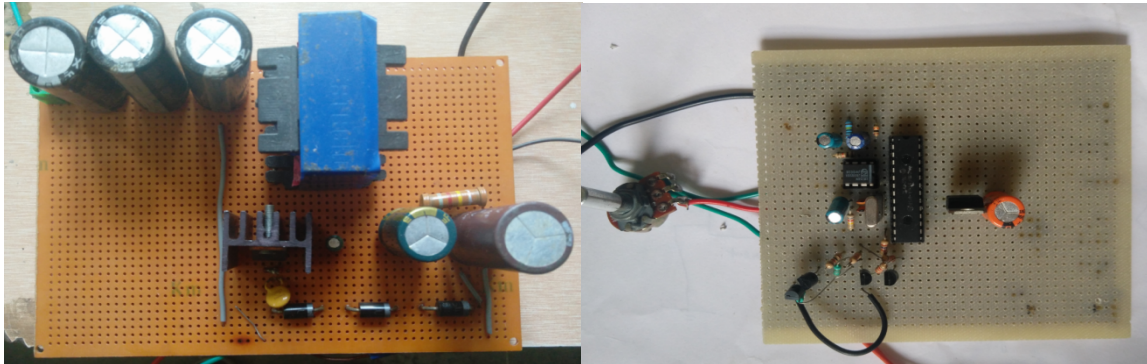
Table 2 contains the list of components for the converter implemented in the lab. The values are calculated and equivalent components were selected.

## International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019



**Fig 14.a. Hardware Unit of High Gain DC - DC Converter.b. Proposed Control Unit**

Fig 14 shows the implemented hardware unit consisting of a high gain high efficiency DC-DC converter and a PWM control unit using PIC16876P. A variable load was connected across the output of DC-DC converter in order to vary the output load over the range of full load to half load and measure the output DC link voltage. Result is provided in table 3.

### IV.RESULT AND DISCUSSION

#### Power Calculations –

Input voltage = 24V.

Input Current = 6.4 Amps @actual current drawn by the circuit.

Input Power =  $24 \times 6.6 = 153.6$  W.

Output voltage = 380V.

Output current = 380mA.

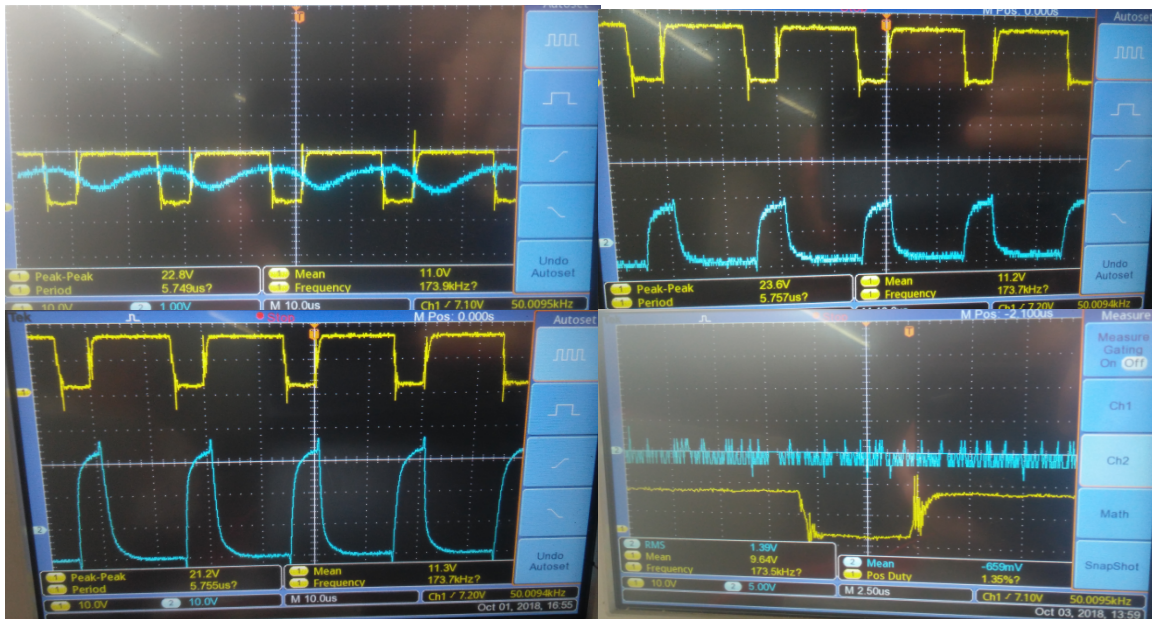
Output Power =  $380 \times 0.38 = 144.4$  Watts

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019



**Fig 15a. Inductor Current and Switch voltage waveform . b. Switch Voltage and Diode D1 Voltage waveform .c. Switch voltage and Diode D2 voltage waveform .d. Capacitor AC Ripple waveform**

Fig 4.3 shows various experimental results waveform across various components of the converter under full load condition.

**TABLE 3**

Experimental Result of input and output parameter in accordance to the variation of load with PWM controlled technique.

I/P voltage(V)	I/P current (a)	O/P voltage (V)	O/P current(mA)
24	6.4	380	380
24	5.5	380	340
24	5.2	379	320
24	4.2	378	260
24	3.5	375	220
24	3.12	375	190

Table 3 contain the experimental results of input and output voltage and current. With the help of the voltage feedback control technique the output voltage is held constant over a wide range of output load variation from full load to half load. This method is cost efficient and is ease to implement.

## V. CONCLUSION

In this thesis, the converter output voltage was regulated at around 380V DC by designing a hardware prototype in the lab. By varying the load from full load to half load and change in the output current along with the output voltage were noted. A steady output voltage is achieved with this prototype. The regulation is achieved using voltage feedback control technique using a PIC16876P microcontroller. The system was operated at 50 KHz cycle and where the regulation from full load to half load is achieved with an error of +/- 5 Volt and having the efficiency of 94%

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 8, Issue 2, February 2019

at full load. The results are tested in lab using variable load. With the help of PWM technique we were able in achieving voltage regulation and to protect the output filter capacitor from overvoltage.

## REFERENCES

- [1] J. Selvaraj and N. A. Rahim, "Multilevel inverter for grid-connected PV system employing digital PI controller," *IEEE Trans. Ind. Electron.*, vol. 56, no. 1, pp. 149–158, Jan. 2009.
- [2] O. Alonso, P. Sanchis, E. Gubia, and L. Marroyo, "Cascaded H-bridge multilevel converter for grid connected photovoltaic generators with independent maximum power point tracking of each solar array," in *Proc. IEEE PESC*, 2003, pp. 731–735.
- [3] V. Scarpa, S. Buso, and G. Spiazzi, "Low-complexity MPPT technique exploiting the PV module MPP locus characterization," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1531–1538, May 2009.
- [3] Hsieh, Y.P.; Chen, J.F.; Liang, T.J.; Yang, L.S. Novel high step-up DC-DC converter for distributed generation system. *IEEE Trans. Ind. Electron.* 2013, 60, 1473–1482
- [4] T. Shimizu, O. Hashimoto, and G. Kimura, "A novel high-performance utility-interactive photovoltaic inverter system," *IEEE Trans. Power Electron.*, vol. 18, no. 2, pp. 704–711, Mar. 2003.
- [5] Q. Zhao and F.C. Lee, "High – Efficiency, high step-up dc-dc converters," *IEEE Trans. Power Electron.*, vol... 18, no. 1, pp. 65-73, Jan 2003
- [6] Arthur F. Witulski, "Introduction to Modeling of Transformers and Coupled Inductors" *IEEE Trans. Power Electron.*, vol. 10, no. 3, May 1995.
- [7] E. H. Ismail, M. A. Al-Saffar, A. J. Sabzali, and A. A. Fardoun, "A family of single-switch PWM converters with high step-up conversion ratio," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 55, no. 4, pp. 1159–1171, May 2008.
- [8] E. H. Ismail, M. A. Al-Saffar, and A. J. Sabzali, "High conversion ratio dc–dc converters with reduced switch stress," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 55, no. 7, pp. 2139–2151, Aug. 2008
- [9] R. J. Wai and R. Y. Duan, "High-efficiency bidirectional converter for power sources with great voltage diversity," *IEEE Trans. Power Electron.*, vol. 22, no. 5, pp. 1986–1996, Sep. 2007.
- [10] R. J. Wai, W. H. Wang, and C. Y. Lin, "High-performance stand-alone photovoltaic generation system," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 240–250, Jan. 2008.
- [11] W. Li and X. He, "Review of non-isolated high-step-up DC/DC converters in photovoltaic grid-connected applications," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1239–1250, Apr. 2011.
- [12] M. Das and V. Agarwal, "Design and Analysis of a high Efficiency DC-DC converter with soft switching capability for Renewable Energy Applications Requiring High Voltage Gain" in *proc. IEEE Transactions on Industrial Electronics*, pp. 2936 – 2944, 07<sup>th</sup> Jan 2016.
- [13] Microchip, "28/40-Pin 8-Bit CMOS FLASH Microcontrollers," PIC16F87X datasheet, Nov. 2001.