Imperial Journal of Interdisciplinary Research (IJIR)
Vol-2, Issue-11, 2016
ISSN: 2454-1362, http://www.onlinejournal.in

Design of a Super Lift Based Boost Converter Using MPPT Technique for Powering Railway Sockets

Amit Rashinkar[1] & Dr. Usha P[2]
[1]IV sem, M.Tech, Power electronics, EEE Dept. Dayananda Sagar College of Engineering
[2]Professor, EEE Dept. Dayananda Sagar College of Engineering

***Abstract**: Conventional boost converters require their switches to be operated at high duty ratio or by the use of large circulating energy resulting in high voltage strain across it. A modified & efficient boost converter is proposed that employs (coupled inductor & super lift) techniques which provides large voltage boost without operating switch at much higher duty ratio. Super lift stage provides moderate voltage gain by absorbing energy of leakage inductor. Coupled inductor used provides large voltage boost. It also reduces the (off state) voltage appearing across the main switch. This converter as is very efficient can be used with solar energy and MPPT method to supply power to sockets installed in Indian Railways that operate at 110V DC. The results were verified both in simulation (MATLAB) as well as with the hardware prototype. The hardware prototype was verified with smaller wattage solar panel.*

1. Introduction

In some applications such as UPS, telecommunication systems, etc. the output voltage required is usually very high. The converter used should be highly efficient, should have low current ripple and low EMI. Therefore a highly efficient DC-DC converter satisfying these requirements should be designed. A conventional boost converter operates at high duty ratio to achieve a large output voltage. Due to this, it produces large current ripples, more conduction losses in the switch and hence they cannot be used for such purposes.

Step up converters (DC-DC) are categorized into two main types: isolated converters & non-isolated converters. In isolated converters, the transformers turns ratio is adjusted to achieve high voltage gain. The switch in these converters is subjected to high voltage stress. It also produces voltage spikes which can be reduced by using snubbers. In non-isolated converters some techniques such as voltage doubling, switched capacitor, voltage lift etc. are used. But conduction losses in main switch is still of a significant value and also results in high transient currents.

A modified boost converter proposed in paper can overcome these difficulties. This converter provides large DC voltage gain without operating switch at higher duty ratio. This reduces the losses in the power devices of the circuit which improves the efficiency. Further a switch with low on-state resistance can be used which also reduces the losses when the switches are conducting. Soft switching of the diodes also prevent their reverse recovery difficulty & hence these converters are best suited for high voltage gain purposes.

This paper proposes a super lift based boost converter with MPPT method for powering sockets installed in Indian Railways that are used for charging mobile phones. These sockets are rated for 110V DC which is provided by the boost converter proposed in paper. Further, with solar panels mounted on railway coaches, the input can be provided from solar panels. During times when solar energy is not available, it can be used to charge a battery which provides the continuity of supply to the system. A normal irradiance of 1200W/m^2 applied to the converter provides a constant output voltage of 110V DC at nearly 1A. MPPT technique improves the efficiency of solar panels by operating them at max. power point. The simulation has been performed in Matlab and the results obtained are satisfactory.

The hardware prototype has been tested with a lower wattage panel (30W) which nearly generates input current of 1.8A to the converter circuit that provides an output voltage of 50V. The hardware results also match with simulated results when performed at same values of input parameter (reducing irradiance in simulation provides the same output voltage).

2. Proposed Boost Converter

A. Working Principle

The circuit schematic of converter is shown in fig 1. A modified boost converter with both (coupled inductor & super lift) techniques is shown in the fig. The converter employs a power switch (S), 4 diodes, 4 capacitors & coupled inductor.

Coupled inductor consists of leakage inductance L_k and magnetizing inductance L_m. The combination

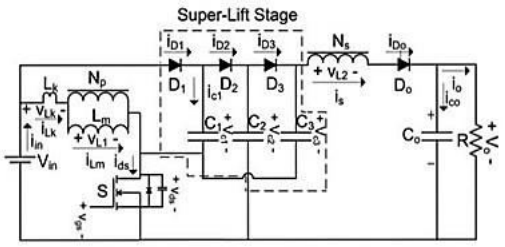


Figure 1: Circuit diagram of the converter

of three diodes and three capacitors shown in fig 1 in dotted lines forms the super lift part. Main switch (S) used in the circuit has a voltage strain V_{ds} equal to the sum of V_{c1} & V_{c2}. The capacitors C_1 & C_2 are in series with opposite polarity and hence their voltage is difference between V_{c1} & V_{c2}. This is the voltage appearing across switch and hence voltage strain across switch reduces. Also, conduction losses can be lowered by using a switch with low on state resistance R_{ds} (on). Typically a MOSFET is preferred as it has low R_{ds} (on). When the main switch is turned on, the energy absorbed by C_2 is transferred to C_3. V_{in}, voltage across coupled inductor & V_{c3} combined produce an output voltage V_{out}.

For analysis purposes, the capacitors are considered to be of large value so that voltage across them remains constant. The diodes are considered as ideal devices. Here, n= N_s/N_p and k=L_m/ (L_m+L_k) are the transformation ratio & coupling factor of coupled inductor.

The steady state analysis of the converter is analyzed for different modes and equations derived from them gives the voltage gain as:

$$M_{CCM} = \frac{3+D(kn-1)}{1-D}$$
(1)

The duty ratio of the circuit is:

$$D_{C_1} = \frac{t_C}{T_S} = L_k \frac{i_{opeak}-i_{ipeak}}{V_{L_k}^{III}} \quad (2)$$

The voltage strain across 'S' is:

$$V_{DS} = V_{C_2} - V_{C_1} = \frac{V_0+V_{in}(kn-1)}{kn+2} \quad (3)$$

The coupling factor 'k' has minor effect on voltage gain. By inputting k=1 in (1), we get:

$$M_{CCM} = \frac{3+D(kn-1)}{1-D} \quad (4)$$

3. PV system Modelling and MPPT unit

The proposed scheme is initially simulated in Matlab to verify system's operation & results.

A. PV system for the proposed scheme

The modelling of PV system is carried out for "Kyocera 135GX-LP" based on theoretical calculations of the PV cell in Matlab environment. The solar array model is shown in fig 2.

This solar array could output power greater than 100W. The V_{mp} & I_{mp} for this panel is 17.7V & 7.6A while V_{oc} & I_{sc} are 22V & 8.4A. By using these values, the maximum power we get is:

$$P_{max} = V_{mp} \times I_{mp}$$
(5)

which gives maximum power of 134.5W under solar irradiance of 1000W/m^2. This is the same value specified in the datasheet of the "Kyocera *135GX-LP"*

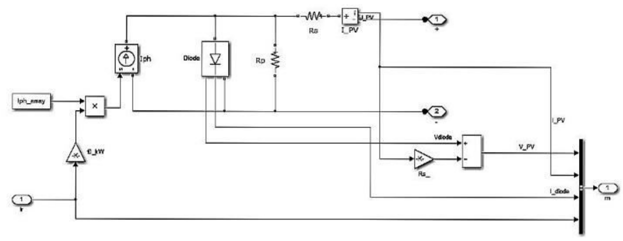


Figure 2: Kyocera 135GX-LP panel's solar array model

By varying the irradiance level, we can extract V v/s I and P v/s V graph to find MPP of solar array shown in fig 3.

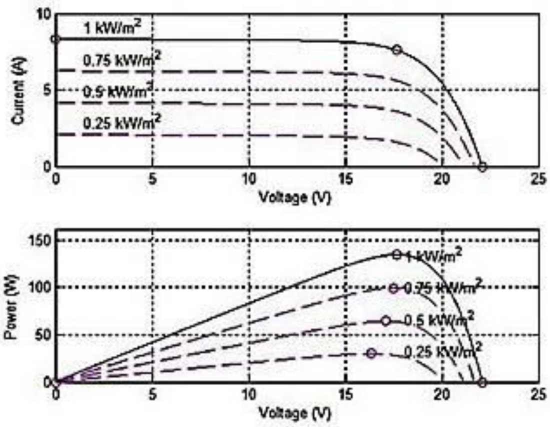


Figure 3: P v/s V and I v/s V plot for the solar array modelled

The diode inside the solar array model is modelled by the equation

$$I_d = I_{sat}(e^{\frac{qV_d}{kT}} - 1) \quad (6)$$

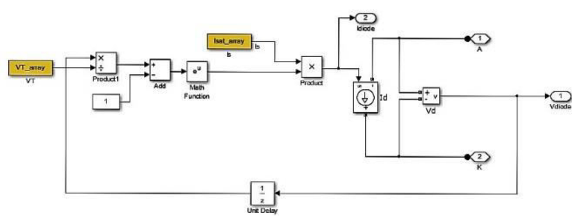


Figure 4: The diode model used in the solar array

B. MPPT unit

The efficiency of solar panels is very low (typically 20%-25%).As solar cells are inefficient, it becomes essential to improve its efficiency in order to extract more power from them for implementation in practical applications. Hence the technique MPPT is used for this purpose.

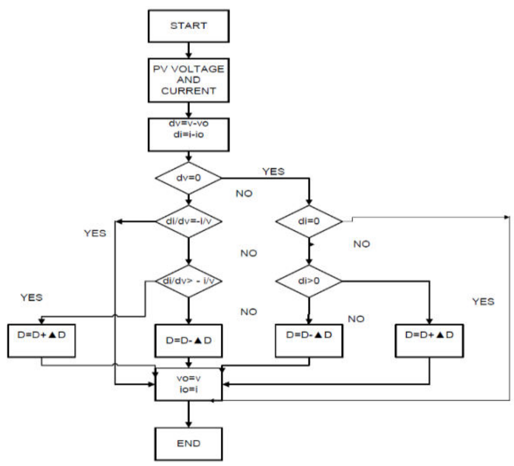
MPPT technique automatically finds V_{mp} & I_{mp} for a particular solar panel to operate so as to deliver maximum power to load at given irradiance level & temperature. PV modules deliver max power by adjusting the electrical operating point of the modules with the help of this technique. Each solar cell has a point at which voltage & current output results in maximum power extraction from the cell and MPPT adjusts itself to that point. The duty ratio of the boost converter are adjusted in such a way that load and source impedance are matched to obtain maximum power. There are various MPPT techniques employed: P&O, Incremental conductance & constant duty cycle.

The INC algorithm is implemented in this paper. To ensure maximum power throughout the time, MPPT algorithm controls duty cycle or operating voltage of PV system. The INC algorithm is complex & robust in nature compared to its counterpart. The central idea used here is that the incremental conductance is compared with instantaneous conductance based on which the duty cycle is adjusted accordingly. The incremental conductance $\mathbf{dI/dV}$ is continuously compared with $\mathbf{I/V}$. When $\mathbf{dI/dV = -I/V}$, the MPP is achieved. Comparing incremental conductance with actual conductance of PV array, we can determine MPP point as to which side it is located given as:

$$\mathbf{dP/dV = 0, indicates\ point\ at\ MPP}$$

$$\mathbf{dP/dV > 0, indicates\ point\ at\ left\ of\ MPP}$$

$$\mathbf{dP/dV < 0, indicates\ point\ at\ right\ of\ MPP}$$



The flow chart for INC algorithm is shown in fig 5.

Figure 5: Flowchart of INC algorithm

4. Complete Integrated unit

The system integrated with all of the components is simulated in Matlab and shown in fig 6.

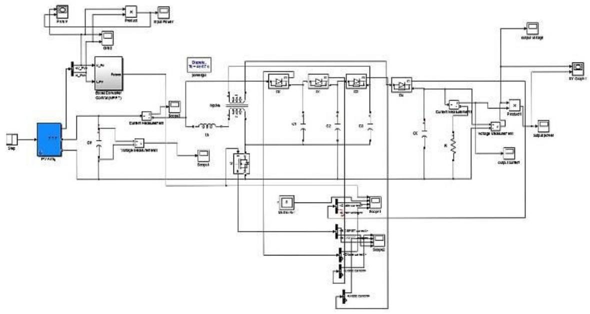


Figure 6: Integrated system's simulated circuit

Solar panel receives the incident sun's energy which is converted to direct current electricity that is applied to boost converter. The input capacitor C_{in} is used to store charge received from PV array which will be used to deliver power to the load for specified duration. It acts as a constant voltage source to the boost converter. This is generally an electrolytic capacitor that acts as an energy reservoir. The DC-DC boost converter provides low current & higher voltage at its output.

The proposed converter's efficiency is above 95%, therefore the complete system equipped with PV array and MPPT is quite attractive and efficient.

The DC-DC converter regulates the current or voltage at the PV output. The pulses to the power switch are calculated based on the MPPT algorithm. The MPPT when operated at proper conditions deliver highest power to load with minimum losses. The factors such as MPP tracking error, boost converter efficiency, solar cell conversion efficiency results in small amount of losses in the MPPT system. Also when there is variation in irradiance, the MPP adjusts the panels to operate at new set point and at this point there is small amount of tracking error. In physical world, it is difficult to measure this error. However in simulation as we control the irradiance in controlled manner, it is easy to measure. Therefore, the power output at load will be lesser than maximum power obtained at input of solar panels. This loss is generally attributed to converter loss that takes place in power switch and other components used in circuit.

5. Simulation Results

Proposed DC-DC converter is simulated first in open loop mode to verify the theoretical waveforms with simulated one & is then integrated with PV panel and MPPT system and is simulated in Matlab/Simulink to verify the results of complete integrated system.

Specifications of the converter listed in table 1 is built in Matlab for simulation investigation. This table gives the values for various components used in converter.

Table 1: Component values used for simulation model

Parameter	Symbol	Value
Input capacitor , mf	C_{in}	1
Switching freq , kHz	f_s	25
Leakage inductance, μH	L_{L_k}	0.25
Magnetizing inductance, μH	L_m	30
Turns ratio	$N_s: N_p$	1: 7
Output cap, μF	C_0	30
Capacitors, μF	C_1, C_2, C_3	10

The irradiance has been assumed to be constant at 1000W/m^2 at a standard temperature of 25ºC.The converter is operated at duty cycle of 75%.The PV modelling has been executed for 'Kyocera 135GX-LP" system whose parameters are given in table 2.

Table 2: Kyocera 135GX-LP parameter settings

Module parameters	Value
Maximum power(W)	135.004
Irradiance (W/m2)	1000
Temperature (ºC)	25
Open circuit voltage (V)	22.099
Short circuit current (A)	8.3
Series resistance (Ω)	0.21
Parallel resistance (Ω)	120
Diode quality factor	1.36
Open circuit voltage temp. coefficient (V/ºC)	$-8.0 \times e^{-003}$
***Short circuit current temp* coefficient (A/ºC)**	$5.02 \times e^{-003}$
Electron charge, coulombs(q)	1.6×10^{-19}
Boltzmann's constant (k)	1.38×10^{-23}

The maximum voltage & current of the current PV panel is 17.7V and 7.6A. The various simulation results with MPPT & without MPPT system are shown in plots below.

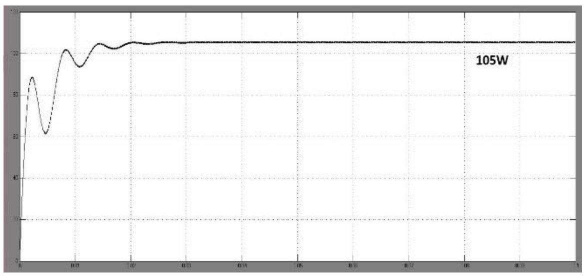


Figure 7: Input power v/s time plot without MPPT

The plot of input power of PV array is shown in fig 7. From the plot, it is seen that the input power has a value of nearly 105W. This value obtained is without MPPT which is lesser than the maximum value given in table 2.

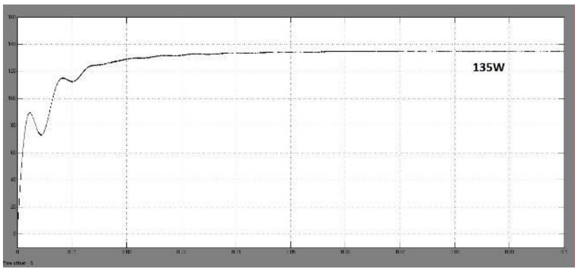


Figure 8: Input power v/s time plot with MPPT

The plot of fig 8 shows the input power of PV array with MPPT system. The value of power obtained is nearly 135W which equals the value of maximum power given in table which validates MPPT operation.
The validation of MPPT can be verified from the graph obtained in Matlab shown in fig 9 which shows the plot of power versus voltage of a PV panel. The PV system used is 'Kyocera 135GX-LP' which has a peak power of 135W at 17.7V as obtained in graph. Beyond this point the slope of the curve decreases.

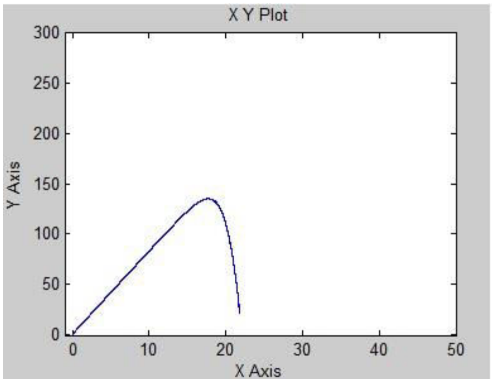


Figure 9: X-Y plot of PV array in Matlab

The proposed system when operated at irradiance of 1200W/m^2 provides an output voltage of 110V DC. The system is capable of providing this value with the MPPT system in operation. Without MPPT, the value would be smaller as already seen from the plot obtained without MPPT above.

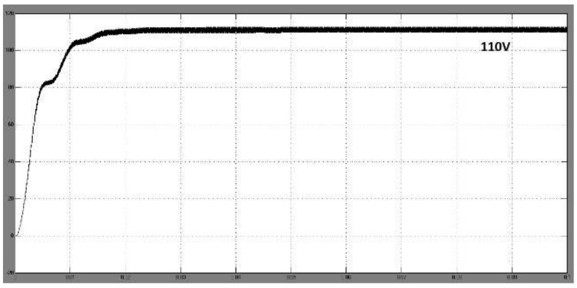


Figure 10: Output voltage plot at 1200W/m2

The above plot (fig 10) shows the output voltage versus time plot for the system with MPPT algorithm. The value obtained is nearly a constant value of 110V DC which can be supplied to the load.

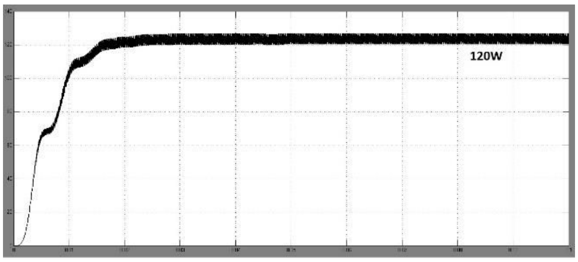


Figure 11: Output power plot at 1200W/m2

The plot of output power versus time is shown for irradiance of 1200W/m^2 which provides an output power of nearly 120W with MPPT system in operation. The output current obtained is nearly 1.1A that is sufficient to power the socket.

6. Experimental Results of the Hardware

The hardware prototype of the complete setup is depicted in fig 12. Supply to the power circuit is delivered by 30W solar panel (not shown in fig) that provides an input voltage of 12V & current of nearly 1.8A and an isolated power supply of 5V powers the microcontroller circuit. The isolation is provided by optoisolator which isolates the power & converter circuit. A MOSFET driver (IR2110) is used to supply the required value of gate voltage to power switch. The 12V source is reduced to 5V source with the help of potential divider arrangement. Further a 5V regulator and voltage divider arrangement powers the microcontroller board. The microcontroller used is the Atmega 328 & a pseudo code for MPPT incremental conductance algorithm is written & executed. The voltage is measured at the output resistor of value 3KΩ. The discrete components used for the converter circuit & its values are as shown in table 3.

The experimental test was carried with a 30W panel on a cloudy day. The output voltage when measured with a mutlimeter across load resistor indicated 50V. The duty ratio was set at 75% & frequency is set at 32 kHz. The voltage obtained would be higher with higher wattage of panel and if the test would have been conducted on a bright sunny day. Due to non-availability of higher rating of solar panel & environmental conditions, the output voltage obtained was nearly half of the expected results. The simulation circuit is operated at higher wattage of solar panel. However the same results could be obtained in simulation if irradiance is reduced which verifies the hardware setup experimental results.

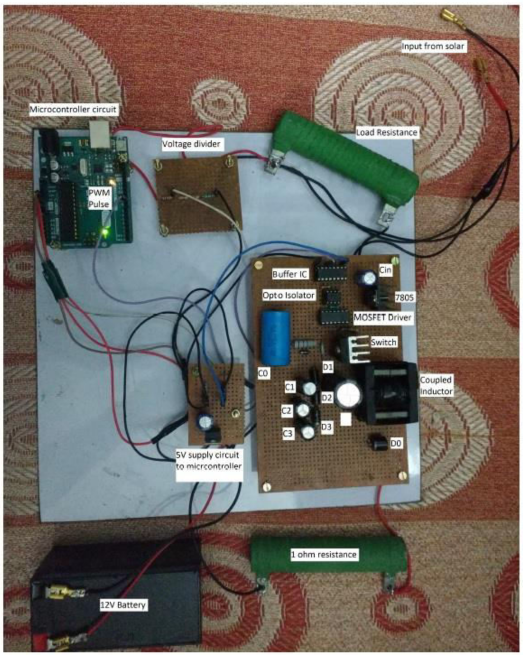


Figure 12: Hardware setup of the system

Table 3: Specifications of components in experimental investigation

Parameter	Symbol	Value
Input DC voltage(Solar), V	V_{in}	12
Output DC voltage, V	V_{out}	50
Solar Power Input, W	W_{in}	30
Solar input current, A	I_{in}	2
Switching Frequency,kHz	f_s	32
MOSFET	S	$IRFP450$
Regulator IC	$--$	$UA7805C$
Output diode	D_0	$UF4007$
Diodes	$D_1/D_2/D_3$	$1N5819$
Magnetic core	$--$	$ETD-39$
Leakage Inductance, μH	L_{L_k}	0.25
Magnetizing Inductance, μH	L_m	30
Turns Ratio	$N_s : N_p$	$1:7$
Output Capacitor, μF	C_0	30
Capacitors, μF	$C_1/C_2/C_3$	10
Buffer IC	$--$	$CD4050BE$
MOSFET Driver	$--$	$IR2110$
Opto isolator	$--$	$6N137$

Duty cycle waveform obtained on CRO is depicted in fig 13. The duty cycle measured on CRO yields value of 75%.

The output voltage waveform obtained is approximately 50V shown in fig 14 below. The output voltage is a constant value of 50V as seen in the CRO plot.

The waveform across V_{ds} is shown in fig 15 below which shows that voltage obtained is nearly 13V at the instant when main switch 'S' is off.

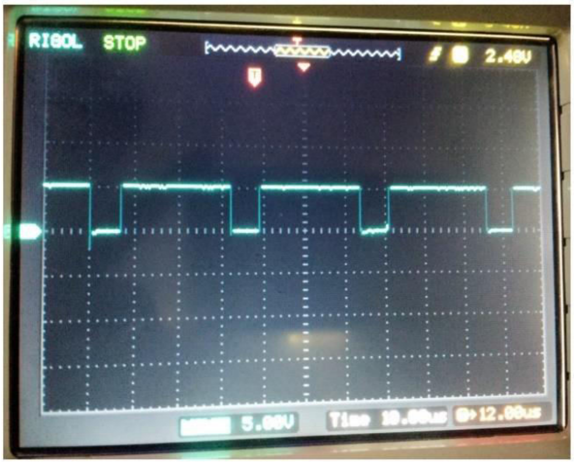


Figure 13: Plot of duty ratio obtained across CRO

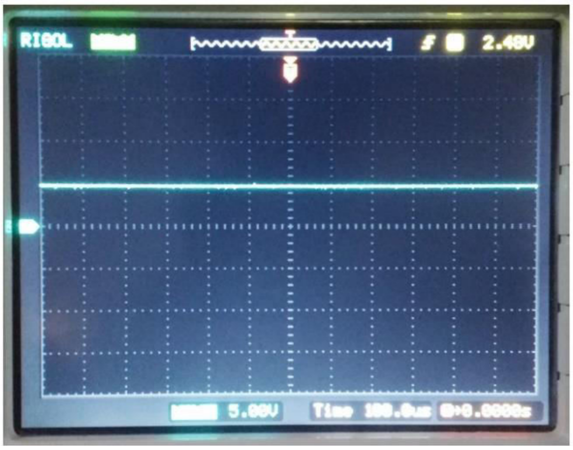


Figure 14: Output voltage of the system

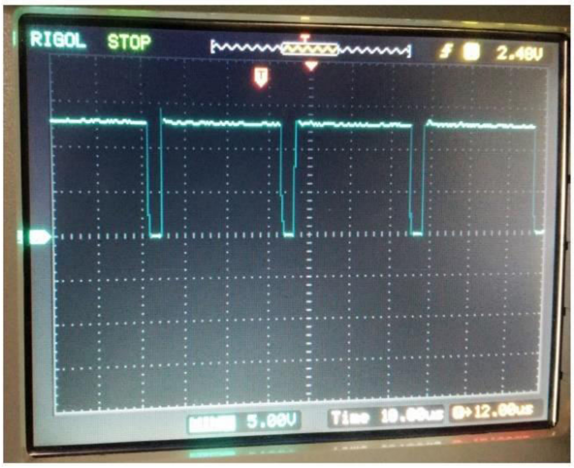


Figure 15: Off state voltage waveform (Vds) across the switch

7. Conclusion

The DC-DC boost converter used in this paper has large voltage boost and is highly efficient by employing both coupled inductor and super lift technique. Super lift stage decreases the voltage (off state) of main switch to lower value resulting in reduced peak voltage during turn off of coupled inductor's leakage inductance and facilitates the reverse recovery of the output diode. The DC-DC converter is implemented with PV system and MPPT and results have been simulated in Matlab/Simulink to confirm its operation. Also the hardware prototype of the system has been carried out with a lower wattage panel & the results obtained were quite satisfactory & had close agreement with the simulated results.

This proposed system can power a single socket provided in railway coaches through solar energy provided irradiance is maintained at its rated value. However this system can be implemented at larger scale by providing more array of solar panels to meet the required input power and battery system to ensure continuity of supply. Hence this system has a good potential and results in energy savings.

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