Soft Switching DC-DC Converter Using PI Controller for Low and Medium Power Applications

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Abstract. In this paper, The DC-DC Converter (DCC) has gained popularity with an increase of utilization of renewable energy sources over conventional energy sources. It is easy to operate Hard Switching DC–DC Converter (HSDCC) with rising power losses and deteriorating efficiency than with Soft Switching DC-to-DC Converter (SSDCC). The latter is employed along with PI Controller to minimize the switching losses and increase the efficiency. Parameters of DCC are calculated then tested for maximum consistency through root locus and bode plots before implementing simulation work in MATLAB environment. Comparisons are made for both HSDCC and SSDCC considering the boost operation from 24V to 48 V with a switching frequency of 25 kHz and 500W.

Keywords: DC to DC Converter · MOSFET · HSDCC · SSDCC · PI Controller · Switching losses

1 Introduction

In present-day years, renewable energy sources (RES) have offered a high advance, convertible to never-ending resources with the lowermost eco-friendly effects [1]. Moreover, in everyday life, the expansion of RES is built fundamentally on the applications of power converters [2]. Nevertheless, the converters provided with RES, primarily the sources from photovoltaic are familiar by their significantly little yield [3]. Consequently, this type of claim desires the following design conditions: decrease of electromagnetic interface (EMI), minimization of losses, and balance of junction temperature. All these conditions offer enhanced efficiency of the converters. To report these issues mentioned above, soft-switching practices are encouraged as an alternative of hard-switching techniques [4].

The boost converter is emphasized in numerous studies so far for different applications which permit decent controllability, and a simple and low-cost design to device [5]. The traditional converter which is frequently used in a switch working approach leads

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to significant losses from switching action [6]. Furthermore, higher switching frequency leads to increase in switching losses along with the EMI [7]. But still, traditional converters are an acceptable option for enhancing the reliability, efficiency, cost and power density for fixed viable claims [8].

The applications used in this paper are about how the DC-to-DC converter is employed in our day-to-day lifestyle. Some of the applications are DC Home Appliances, Electric vehicles, Fuel cell stacks, Photo voltaic arrays, Battery, and Satellite. All these are used in many ways where a DC-DC appliance containing a boost converter on the electronics board helps to derive an appropriate low-current high-voltage source to power the display [9]. The DC-to-DC converter in the Electric vehicle power supply shows that at least one DC-to-DC converter is essential to interface the Fuel Cell (FC), Battery, or the Super capacitors module to the DC link. In the FC stack, the barriers to the extensive use of fuel cells are their sluggish response to unexpected load changes and higher fixing costs. In this way, not only these applications but also many appliances can be worked with the help of the dc-dc converter.

1.1 Problem Identification and Solutions

From the literature work, the following problems are identified along with solutions incorporated with them. Unstable output voltages, higher switching and conduction losses [9]; Lower efficiency, weakening performance [8]; Uninterrupted operation under faulty semiconductor switches [4]. Switching losses happen when the device is moving from the blocking state to the conducting state and vice-versa [10]. This interval is considered by a substantial voltage across the switch and current through it. Switching losses occur when the power switch or rectifier is shifting between the ON state to the OFF state and vice versa [10]. These are dependent on switching frequency as there are more changeovers happen per second in higher frequencies which leads to more switching. As MOSFET has a finite switching time, the switching losses happens from dynamic current and voltage, the MOSFET must be in a position to handle ON and OFF time intervals [10]. With increase in switching frequency, quicker rise or fall time can be achieved, so that lesser the switching loss during the changeover time cab be obtained. That is lower switching losses can be obtained by considering the compromise between both the switching changeover time and the switching frequency [11]. The solutions with respect to various problems mentioned are an auxiliary converter in addition to a boost converter [4].

Full-Bridge PSPWM converter with a resonant circuit [6]. These of Use of Snubber in order to achieve low switching Losses and to improve the efficiency of the boost converter/performance of boost converter [8]. Full bridge PSPWM converter with resonant circuit [9]; And also Cascade of boost converter topology with reduced conduction Losses [10]. Cascade of boost converter topology with reduced conduction losses [11].

This paper presents an introduction to the topic of a DC-DC Boost Converter with low switching losses for low and medium-power applications. The objectives of this work are to design a DCC and DCC with a snubber circuit along with its stability analysis; DCC with PI controller; DCC with a snubber circuit using PI controller. DCC is termed as a Hard Switching Circuit and DCC with snubber is named as a Switching Circuit.

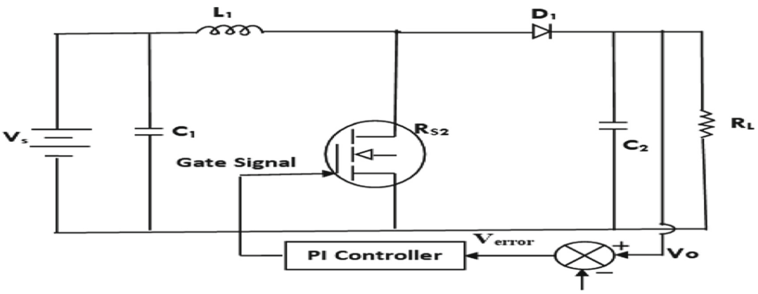

Fig. 1. Hard Switching Circuit with PI Controller

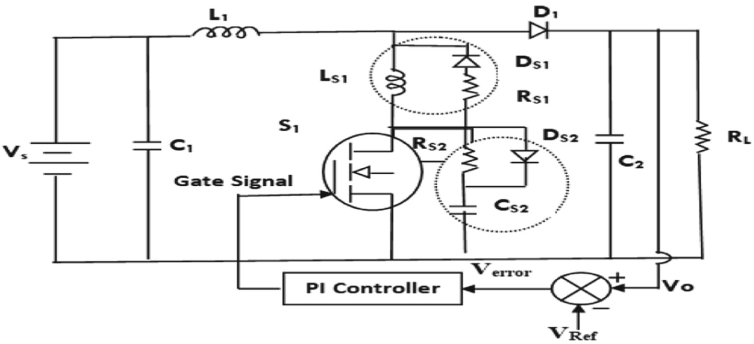

Fig. 2. Soft Switching Circuit with PI Controller

2 DC-DC Converter with Hard Switching and Soft Switching Circuits

The MOSFET employed in DCC to obtain the desired output voltage. DCC with hard switching and soft switching circuits using PI Controller are represented in Figs. 1 and 2 respectively. The stability analysis using bode plot and root locus are also plotted here before designing parameters of a boost converter.

3 Design of Proposed HSDCC and SSDCC

By considering a duty cycle of 0.5, with a supply voltage Vs, 24V; switching frequency fs, 25 kHz; the L and C are obtained for HSDCC is given in Table 1 using the Eqs. 2 and 3 separately. Where as the relation between duty cycle and voltages is given in Eq. 1.

$$D = 1 - \frac{V_s}{V_O} \tag{1}$$

$$L_{min} = \frac{V_s D}{f_s \Delta I} \tag{2}$$

$$C_{max} = \frac{I_O D}{f_s \Delta V} \tag{3}$$

When MOSFET is subjected to forward-biased, it can be made ON by providing a positive voltage between source and gate. But there is a stay time or transition to move from a forward blocking state to conduction state. This transition time is sectioned into 3 intervals delay time (t_d); rise time t_r; and ON time t_{ON} depicted in Fig. 3.

With a switching frequency fs, 25 kHz from MOSFET's switching characteristics shown in Fig. 3, the following time values are obtained:

t_r = Rise Time = 30μ sec; t_f = Fall Time = 20μ sec; V_{in} = input voltage= 24V; t_{on} = Turn on Time = 200μ sec.

Using these time values, Inductance (Ls1), Capacitance (CS2) and Snubber Resistance (Rs1,2) are obtained for snubber circuit using the following Eqs. 4, 5 and 6.

$$\text{Snubber inductance } (L_{s1}) \geq \frac{V_{in} t_r^{\circ}}{I_{in}} \tag{4}$$

$$\text{Snubber capacitance } (C_{s2}) \leq \frac{I_{L^{\circ}} t_{r^{\circ}}}{V_{in}} \tag{5}$$

$$\text{Snubber resistance } \left(R_{s1,2}\right) \leq \frac{ton^{\circ}}{V_{in}} \tag{6}$$

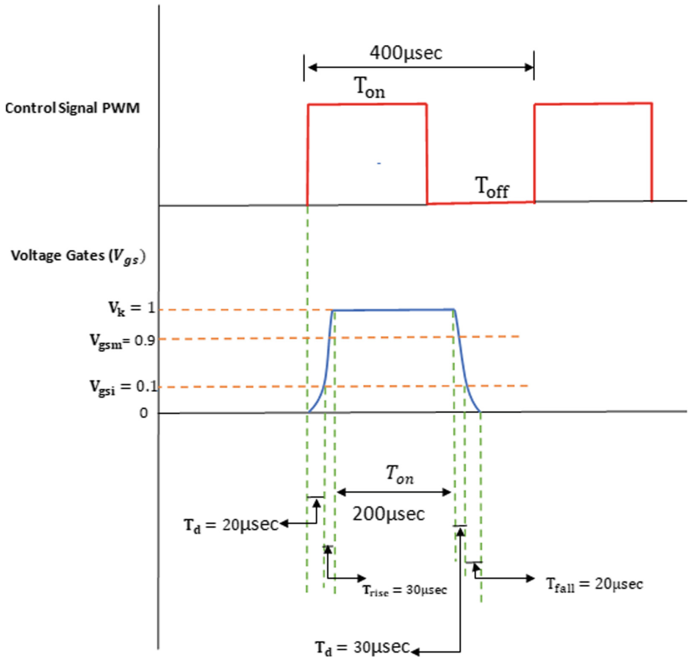

Fig. 3. MOSFET's switching characteristics

4 Stability Analysis

The stability study of boost converter is found to verify the derived L and C values which are not stable. To find the stability of the boost converter we have found out the transfer function and found its root locus and bode plot. First the transfer function is found for hard switching circuit later root locus and bode plots are plotted to obtained the stability analysis. When MOSFET is OFF and ON the transfer, function is found from the Eqs. 7 and 8 using the Figs. 4 and 5 respectively.

$$\text{Transfer function}, \frac{V_o(s)}{V_{in}(s)} = -\left[\frac{1}{s^2LC + \frac{sL}{R_o} + 1}\right] \tag{7}$$

$$\text{Transfer function}, \frac{V_o(s)}{V_{in}(s)} = \frac{LC}{s^2} \tag{8}$$

From the Fig. 6 it is observed that the obtained poles lies on left side of the plane with 0.509 & 0.512 respectively as damping factors. The **OVERSHOOT** is 15.6% & 15.4% Volts in Output Voltage Response. Hence, it is **UNDER DAMPED SYTEM** & its transfer function is **STABLE** for derived L & C values.

From the Fig. 7, it is observed that the obtained pole lies on imaginary axis with 1 as damping factor. The **OVERSHOOT** is 0% Volts in Output Voltage Response. Hence, it is **CRITICALLY DAMPED SYSTEM** & its transfer function is **MARGINALLY STABLE** for derived L & C values.

The results from Fig. 8 obtained are ωpc = ∞; ωgc = 0 rad/sec; phase margin is ∞ and gain margin is 217dB. It shows that the system is stable as ωpc > ωgc;

The results from Fig. 9 obtained are ωpc = 0.00196 rad/sec; ωgc = 0.00196 rad/sec; It shows that the system is marginally stable as ωpc = ωgc; Based on the design and

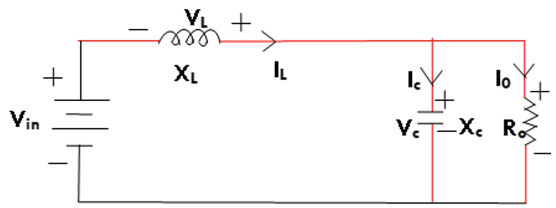

Fig. 4. Circuit Diagram when MOSFET is OFF

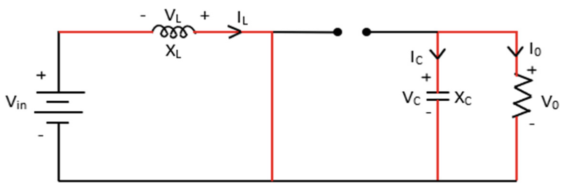

Fig. 5. Circuit Diagram when MOSFET is OFF

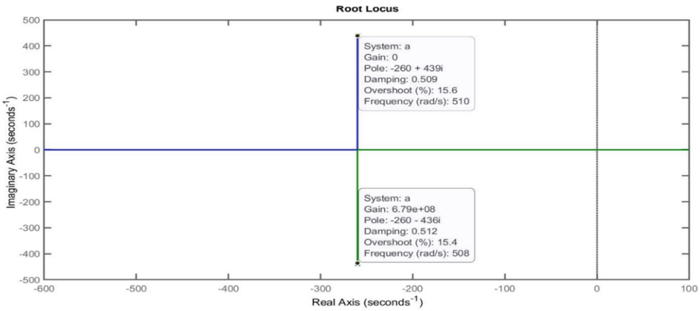

Fig. 6. Root Locus Plot When MOSFET is OFF

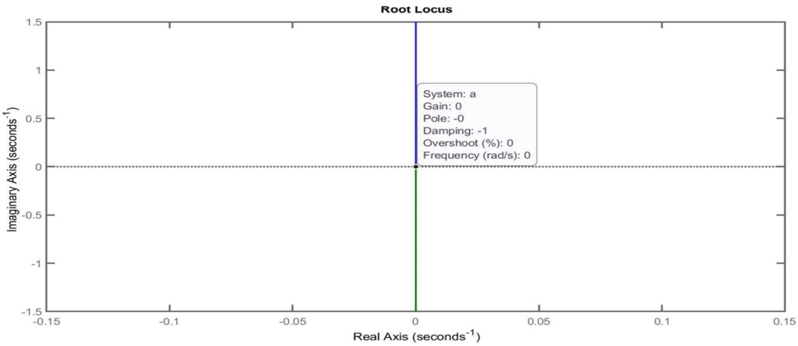

Fig. 7. Root Locus Plot When MOSFET is ON

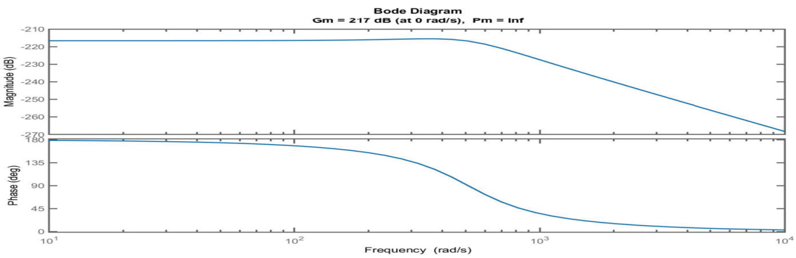

Fig. 8. Bode Plot When MOSFET is OFF

stability analysis, the design values along with specifications are used in this work are given in Table 1.

5 Result and Analysis

The following are the different possible cases of a DC-DC converter for low and medium applications.

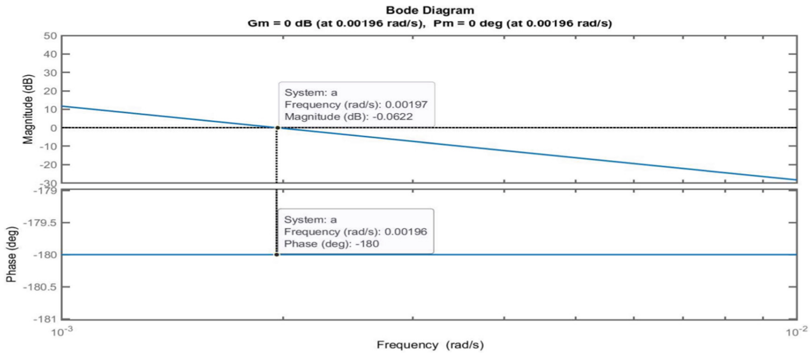

Fig. 9. Bode Plot When MOSFET is ON

Table 1. Specifications of DC-DC Boost Converter

Parameter	Value
Supply Voltage (**V_s**)	24 V
Switching Frequency (f_s)	25 kHz
Output Voltage **(Vo)**	48 V
Load Current **(Io)**	10 A
Ripple Current (**ΔI**)	5%
Ripple Voltage (**ΔV**)	5%
Inductance **(L)**	9.6 mH
Capacitance **(C)**	400 µF
Inductance (**L_{S1}**)	36 µH
Capacitance (**C_{S2}**)	8.33 µF
Snubber Resistance (**$Rs_{1,2}$**)	0.75 Ω

5.1 Hard Switching Circuit (Without Snubbers)

The hard switching circuit without Snubber is analyzed with stability aspects using soft locus and bode graphs and Figs. 6, 7, 8, 9 is found that the designed values are satisfactory for a DC-DC Converter. The various plots are plotted like output voltage; output current; switching current and voltage; switch power loss and are given in Figs. 10, 11, 12, 13 respectively. It is found that the switch power loss is 7.6mW.The output voltage obtained is 45.15 V.

5.2 Soft Switching Circuit (with Snubbers)

Snubber circuit is designed along with DC-DC converter. The respective plots are plotted for output voltage; output current; switch current and voltage; switch power loss and

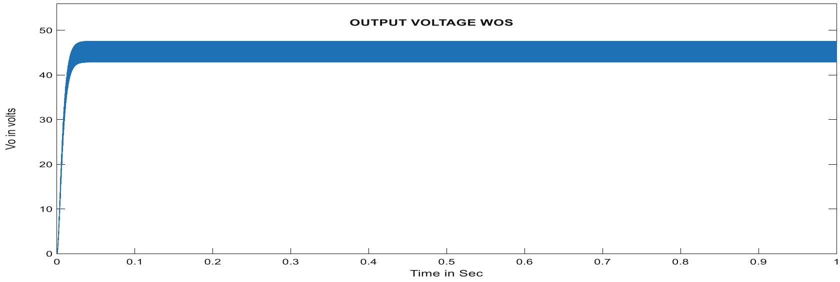

Fig. 10. Hard switching circuit (without snubbers) Output Voltage

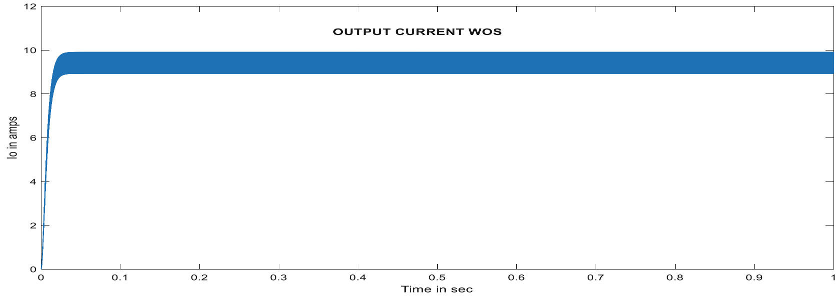

Fig. 11. Hard switching circuit (without snubbers) Output current

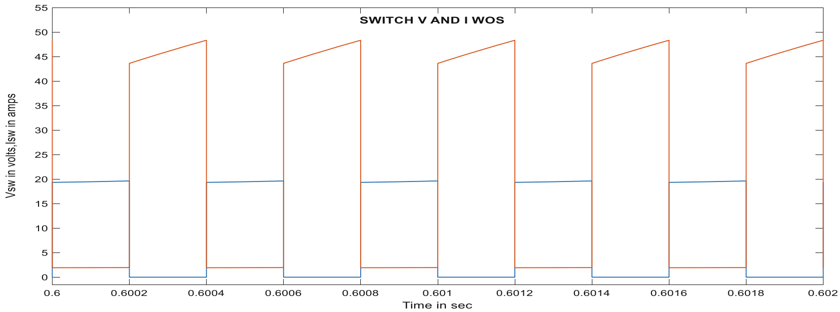

Fig. 12. Hard switching circuit (without snubbers) Switch Current and Switch Voltage

are shown in Figs. 14, 15, 16, 17 respectively. The output voltage obtained is 47V and switch power loss is 4.47 mwatts.

5.3 Hard Switching Circuit Using PI Controller

In this case, closed loop control of Hard Switching circuit is analyzed. The different plots are given in Figs. 18, 19, 20, 21 for output voltage; output current; switch current and voltage; Switch power loss respectively. The output voltage obtained as 48V and switch power loss is 10.216 mW.

Fig. 13. Hard switching circuit (without snubbers) Switch Loss

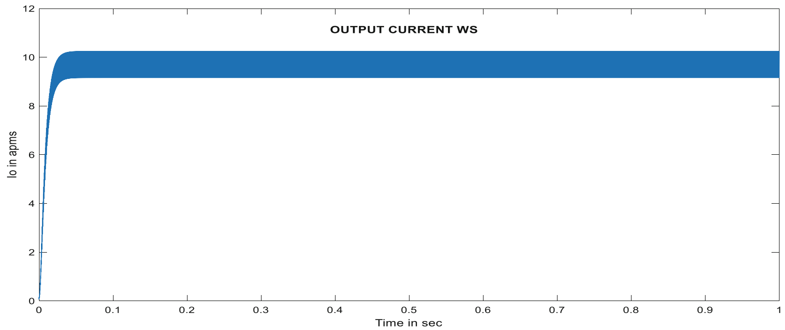

Fig. 14. Soft switching circuit (with snubbers) Output Current

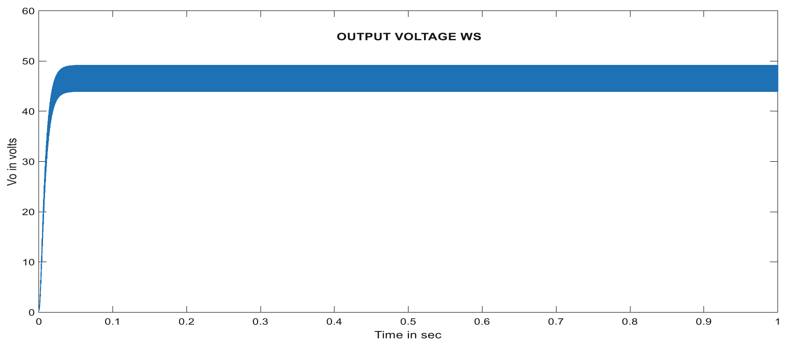

Fig. 15. Soft switching circuit (with snubbers) Output Voltage

5.4 Soft Switching Circuit Using PI Controller

DC-DC converter associated with Snubber circuit along with PI controller is designed. The results are plotted for a output voltage; output current; switch current and voltage; Switch power loss in Figs. 22, 23, 24, 25 respectively. The Output voltage is 48V, Switch power loss is 11.04 mW.

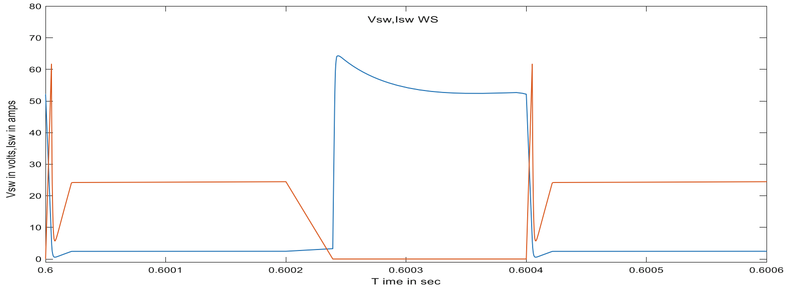

Fig. 16. Soft switching circuit (with snubbers) Switch Current and Switch Voltage

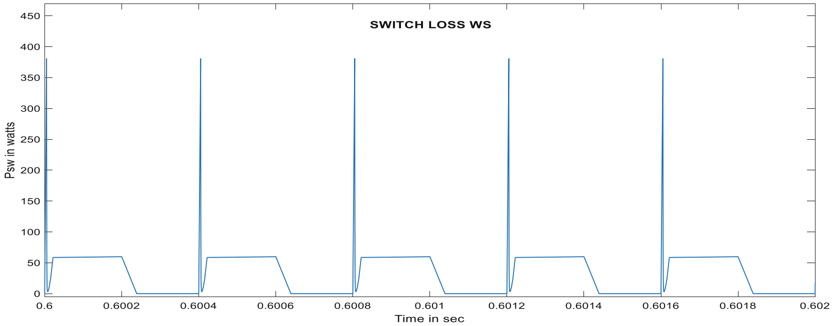

Fig. 17. Soft switching circuit (with snubbers) Switch Loss

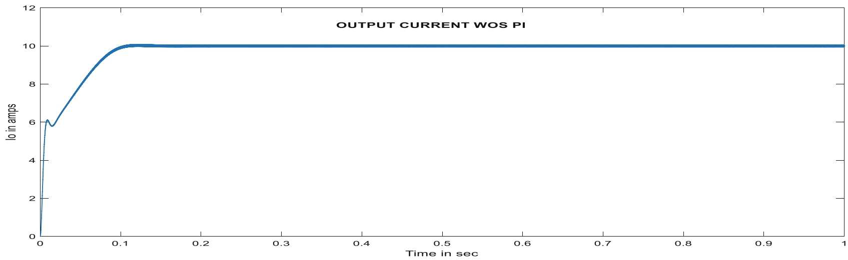

Fig. 18. Hard switching circuit (without snubbers) Output current with PI Controller

All these cases are tabulated in Table 2 for better understanding. The efficiency and percentage of ripple current in Io, Vo are found less whereas gain is more.

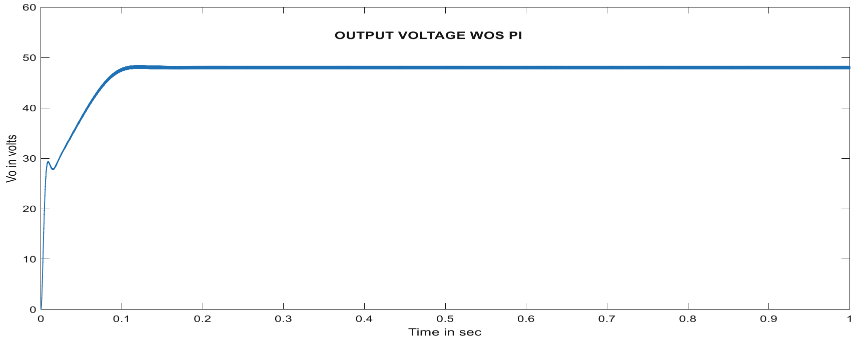

Fig. 19. Hard switching circuit (without snubbers) Output Voltage with PI Controller

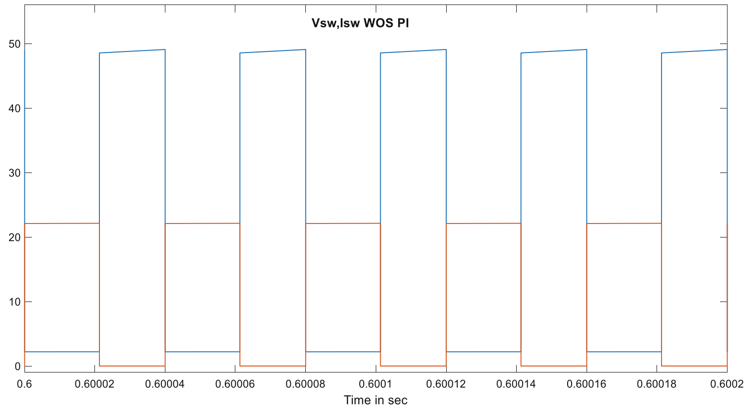

Fig. 20. Hard switching circuit (without snubbers) Switch Current and Switch Voltage with PI Controller

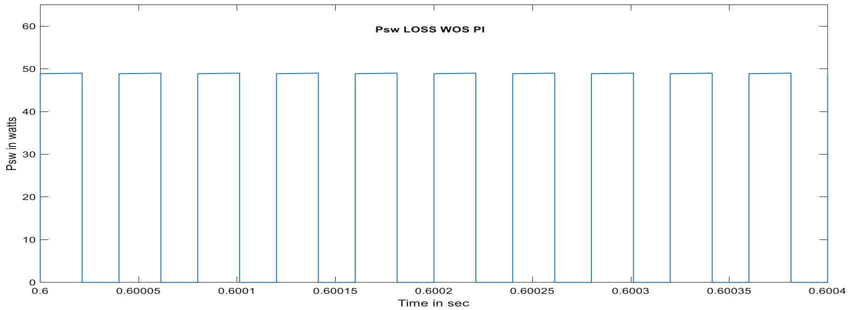

Fig. 21. Hard switching circuit (without snubbers) Switch Loss with PI Controller

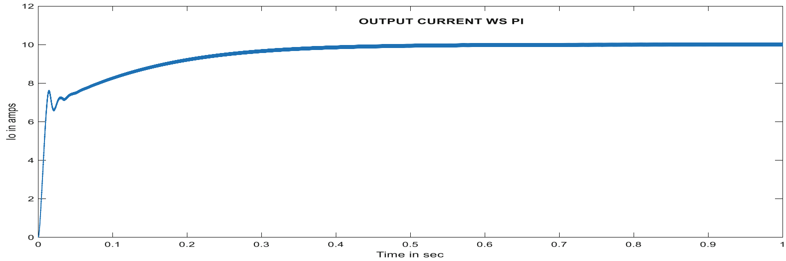

Fig. 22. Soft switching circuit (with snubbers) Output current with PI Controller

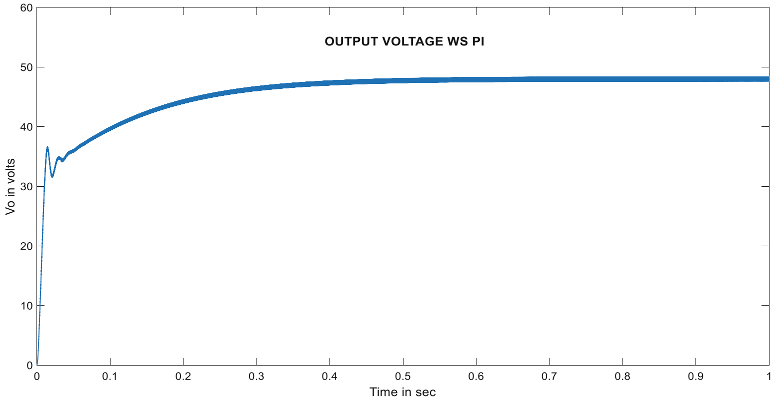

Fig. 23. Soft switching circuit (with snubbers) Output Voltage with PI Controller

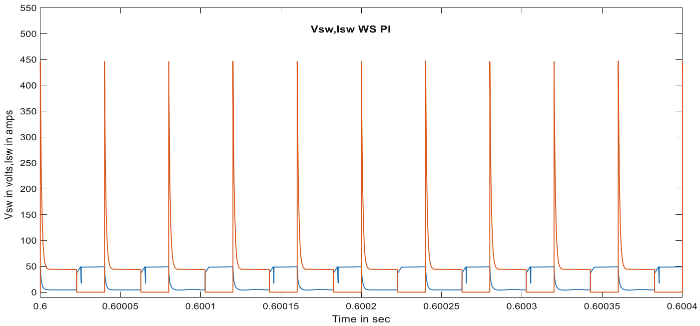

Fig. 24. Soft switching circuit (with snubbers) Switch Current and Switch Voltage with PI Controller

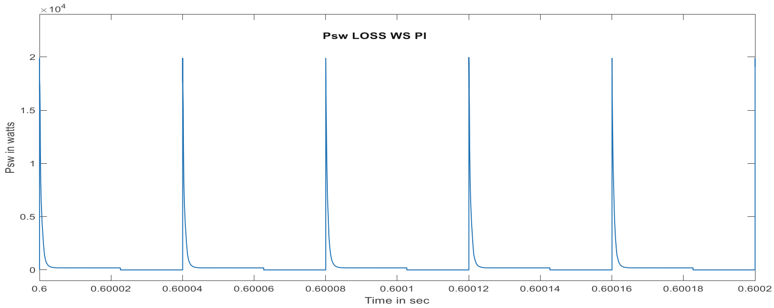

Fig. 25. Soft switching circuit (with snubbers) Switch Loss with PI Controller

Table 2. Comparison Table for all 4 cases

Parameter with Unit	Without Snubber	With Snubber	Without Snubber & PI Controller	With Snubber & PI Controller
Vin **(V)**	24	24	24	24
Iin **(A)**	19.16	23.9	21.7	23.4
Vo **(V)**	45.15	47	48	48
Io **(A)**	9.43	9.44	9.95	9.98
Pin **(KW)**	0.46	0.57	0.52	0.56
Po **(KW)**	0.43	0.44	0.48	0.48
Psw **(mW)**	7.6	4.47	10.21	11.04
Gain **(dB)**	5.49	5.84	6.02	6.02
Vo ripple **(%)**	10.41	8.9	1.35	1.25
Io ripple **(%)**	10.08	9.5	1.90	1.6

6 Conclusion

The proposed HSCDC and SSCDC along with PI controller is implemented in MATLAB environment. Low switching losses has achieved under soft switching circuit which is desired and reduced using SSDC from 7.6 mW to 4.4.7 mW. It is also observed that the ripples in both output currents and output voltages using Snubber and PI controller have reduced from 10% to 1.6%. Gain in both open and closed loop operation with Snubber & PI controller is improved from 5.49 dB to 6 dB. Desired output power, output voltage and output current with PI controller is obtained. It is suggested in future the proposal circuit can be implemented with multi input such as solar, wind, fuel cell for multi output application such as grid, energy storage system loads etc.

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