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Static and Dynamic Performances of PWMBased SMCBB Converter:Experimental Investigation

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Abstract:*In this paper an experimental prototype pulse width modulated (PWM) sliding mode controller (SMC)was applied to a DC/ DC buck-boost (BB) converter. The implementationprocedure is given in detail. Both the static and dynamic performances of the experimental system are tested in the Lab.Agood voltage regulation is obtained and the control scheme seems to be suitable for the DC/DC conversion applications.The behavior of the converter was also shown experimentally when it was operated without the mentioned controller; just to distinguish the effect of the controller. The main drawback of the prototype is the process of sensing the capacitor current which hasa quite high frequency and small value.*

Index Terms—*PWM, Buck-boost DC/DC converter, SMC*

I. Introduction

DC to DC Buck-boost converters need to be controlled by an appropriate method and act on the main switch (MOSFET), to obtain regulated output voltage at different levels, more than, less than or equal to the input source voltage. There are many applications for the BB type converters, like systems powered by bank of batteries, where the input DC voltage can vary starting from full charged value and step by step decreasing as the battery is exhausted. When the battery is full charged, its voltage may be higher than the proposed value; in this case the buck mode of operation would be effective in keeping the supply voltage almost steady. While when the input battery voltage falls below a certain accepted level, at this condition the boost mode of operation of the converter will do the job accurately.

When using the traditional PID or PI type controllers it is found that the main problem will be thelossofstability because of the existence of system uncertainties. Also it causes problems when large loadare subjected suddenly to the system.

Due to the ON/OFF characteristics of the converter's main switch, sliding mode (SM) controllers can be considered as a proper and natural control strategy, also, these types of controllers are famous for their robustness and stable behavior.

In this paper, the approach of BB converters and their SMC principles are discussed and an experimental prototype is implemented of the proposed PWM-based SM BB converter. The static and dynamic performances of the implemented experimental system are investigated and recorded.

II. Principle of SM Control

The SMCdesigned for a system which main requirement is to be insensitive to when parameters are varying variations and with a load which is varying time to time. It is very important to take care during the choice of the state variables of the system which will certainly affect the performance of control process and decide the complexity,and how much it will be, when the whole control system is implemented.Thecomplete detail of this kind of controller is summarized in references [1] and [2].

The realization of the approach is considered by fast switching control law by which the path of thesliding surface is predetermined and stayed in that surface thereafter and before it reaches the switching surface, it passes through a control which is directing to the surface and this control is called reaching mode. When reaching the sliding surface the process is called sliding mode (SM), in which the system remains insensitive to parameters variations and load or supply voltage disturbances.

In SMC method it is required only to drive the error signal to a switching surface, then the system is said to be in SM and it will be robust against both, uncertainties caused in modeling phase and disturbances caused by the supply voltage or the load.

Suppose that a linear time invariant system is represented by.

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (1)$$

which can be rewritten as

$\dot{x}(t) = f(x, t, u)$ (2)

where

x is the state vector

u is the control input signal

f is function vector
For a sliding surface *S*(*x*)= 0, then

$$f = (x,t,u) = \begin{cases} f^{+}(x,t,u^{+}) if S > 0 \\ f^{-}(x,t,u^{-}) if S < 0 \end{cases} \quad (3)$$

If the point which is assumed to be the representative of the system moves on the sliding surface *S*(*x*) = 0, then it is said that the system is in the sliding mode and the sliding surface is the switching function because the control process depends on its sign on both sides of the surface called manifold *S*(*x*) = 0, in which the control method was developed fordrivingpurposes.With a motion in subspace S

$$\dot{\mathrm{S}} = \mathrm{CAx} + \mathrm{CBu} \quad (4)$$

The solution of $\dot{S} = 0$is assumed to be the equivalent control (u_{eq}) which is represented by the following equation.

$$u_{eq} = -(CB)^{-1}(CAx) \quad (5)$$

It is proved that, for the SM controller to achieve finite time convergence to the sliding surface the following condition should be fulfilled [3]:

$$u = \begin{cases} 1 & for S > 0 \\ 0 & for S < 0 \end{cases} \quad (6)$$

III. Modeling ofthe SM Base Controller forthe Buck-Boost Converter

The state-space representation of the converter model in terms of its voltages and currents is shown below [4]

$$\boldsymbol{x} = \begin{bmatrix} x_1 = V_{Ref} - \beta V_o \\ x_2 = \frac{\beta V_o}{RC} + \int \frac{\beta V_o \bar{u}}{LC} dt \\ x_3 = \int x_1 dt \end{bmatrix} \quad (7)$$

Where
xis the control variable.
x₁is thevoltage error.
$\boldsymbol{x_2}$ is the rate of change of voltage error or thevoltage error dynamics.
$\boldsymbol{x_3}$ is the integralof voltage error.
L is the inductance of the power stage of the converter
C is the capacitance, of the power stage of the converter
*R*is the converter load resistance.
$V_{Ref}$is the reference voltage.
$V_i$is the input voltage
V_o is the output voltage
and*ß* denotes to the feedback network ratio.

The state-space matrix parametersrepresentation of SMCBB converter operating in continuous current mode (CCM), are

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{1}{RC} & 0 \\ 1 & 0 & 0 \end{bmatrix}, \quad (8)$$

$$\boldsymbol{B} = \begin{bmatrix} 0 \\ \frac{\beta V_o}{LC} \\ 0 \end{bmatrix}, \quad (9)$$

$$\boldsymbol{D} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad (10)$$

Taking the time differentiation of (7), state-space formation for the controller design of the buck-boost controller is given by

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{1}{RC} & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\beta V_o}{LC} \\ 0 \end{bmatrix} \bar{u} (11)$$

Where $\bar{u} = 1 - u$ and u = 0 or 1 is the switching state of power switch (MOSFET).
Using equations (8, 9, 10 and 11) it can be shown that the control voltage equation will be as follows

$$v_c = -k_{p1} i_C + k_{p2}\left(V_{ref} - \beta V_o\right) + \beta V_O \quad (12)$$

where
$v_C$is the control voltage
kp$_1$and kp$_2$ are the sliding model controller gains

IV. Dc/Dc Bb Converter Topology

The traditional type of DC/DC BB converter is shown in Fig. 1.

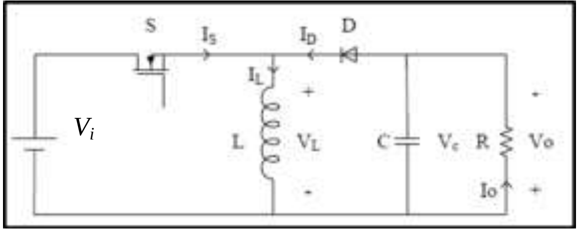
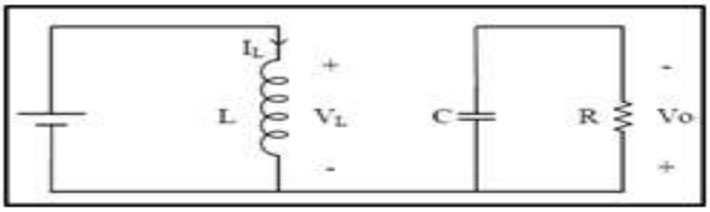


Fig. 1 General schematic diagram of a DC/DC BB converter

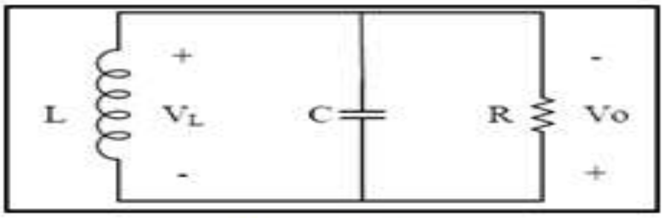
When the main switch of the circuit isclosed, current builds up through the inductor. When the switch now is opened, the current supplied by the inductor through the diode*D* to the load. The polarity of the output voltage is negative [5]

For mathematical analyzing purposes the buck-boost converter is considered as a variable structure system consisting of two continuous nonlinear subsystems, described by a finite number of first order ODE coupled together. The magnitude of the output voltageV_o may be more than or less than compared with the magnitude of the input voltageV_i and of opposite polarity, according to the arrangement of the components used in implementing the circuit, as shown in Fig. 1.

The basic operation principle of the DC/DCBB converter is shown in Fig. 2.



(a) ON-State



(b) OFF-State

Fig. 2 The two operating states ofthe BB converter:
(a) When the main switch is turned ON
(b) When the main switch is turned OFF

(a) ON-State

For the ON-state, i.e. the switch in the circuit of Fig.1 is ON; the input voltage is directly connected to the terminals of the inductor (L) as shown in Fig.2a. This results in saving energy in (L), according to$\frac{1}{2} L i_L^2 Jouls$.

In this stage, the capacitor transmits energy according to $\frac{1}{2}Cv_C Jouls$to the output load, where i_L is the instantaneous current passing through the DC supply and the main inductance (L) of the circuit in the ON-state. While $v_C$is the voltage across the capacitance (*C*) in the ON-state. *L* and *C* are the main inductance and capacitance of the converter circuit respectively [6].

$$L\frac{di_{LON}}{dt} = V_i \dots (13)$$

At the end of the ON-state

$$\Delta i_{LON} = \int_0^{DT} di_{LON} = \int_0^{DT} \frac{V_i}{L} dt = V_i \frac{DT}{L} \dots (14)$$

Where*D* is the duty cycle

(b) OFF-State

In the OFF-state i.e. the switch in the circuit of Fig.1 is now OFF, the inductor is directly connected to the output load resistance and the main capacitor as shown in Fig.2b, and the energy is transferred from *L* to *C* and *R*. If we assume zero voltage drop across the diode, and a capacitor voltage is assumed to remain constant because of its large value, then

$$\frac{di_{LOFF}}{dt} = -\frac{V_o}{L} \dots (15)$$

So the variation of i_L in the OFF-state is given by [7].

$$\Delta i_{LOFF} = \int_0^{(1-D)T} di_L = \int_0^{(1-D)T} \frac{V_o dt}{L} = \frac{V_o}{L}(1-D)T \qquad \dots (16)$$

in continuous mode the current through the inductor *L* is assumed not to fall to zero during a commutation cycle. The value of i_{LOFF} at the end of the OFF- state must be equal to the value of i_{LON} at the beginning of the ON-state, and

$$\Delta i_{LON} + \Delta i_{LOFF} = 0 \qquad \dots (17)$$

Substituting the values given by eqs. (14) and (16) in equation eq. (17)yields,

$$\Delta i_{LON} + \Delta i_{LOFF} = \frac{V_i DT}{L} + \frac{V_O(1-D)T}{L} = 0 \quad \dots (18)$$

so,

$$\frac{V_O}{V_i} = \frac{D}{D-1} \dots (19)$$

or

$$D = \frac{V_O}{V_O - V_i} \dots (20)$$

By adjusting the duty cycle *D*of the MOSFET, converter output voltage $V_o$can vary linearly from between the values of 0 to (+ / -) ∞ (assuming an ideal converter).

V. Experimental Prototype

In this work the controller is implemented as shown in Fig.3. In the experimental circuit only three analog gain amplifiers and a summer (LM318) are used to implement this signal just to fulfil the control equation given in (12).Theparameters of these circuitries can be easily calculated usingknown values of *ß* , *R*, *L*, and *C*, (Calculation of the parameters of the experimental circuit is out of the scope of this work) and are shown in Table 1.

The formulation of the ramp voltage signals V_{ramp} for DC to DC buck-boost converter depends on the instantaneous output voltages as shown below

$$V_{ramp} = \beta V_o \dots (21)$$

Using 555 pulse generator output signalwith the logic AND IC chip (CD4081) the maximum duty cycle of the controller is clamped and a duty cycle of 100% is never reached, and this is called *Duty Cycle Protection*. The control and ramp signal circuitries with the pulse-width modulator (LM311) forms the basicarchitecture of the PWM-based SM controller [8].

Table 1

Description	Parameter	Nominal value
Input voltage	V_i	24 volt
Capacitance	C	220 µF
Capacitor ESR	r_C	36 mΩ
Inductance	L	200 µH
Inductor resistance	r_L	0.12 Ω
Switching frequency	f	200KHz
Minimum load resistance (buck)	$R_{L(Min.)}$	14 Ω
Minimum load resistance (boost)	$R_{L(Max.)}$	140 Ω
Desired output voltage (buck)	V_{od}	12 volt
Desired output voltage (boost)	V_{od}	48 volt

VI. Experimental Results

The experimental prototype of the controller is verified through many tests for the steady-state and dynamic conditions in the laboratory. The open-loop condition is performed just to compare its results with the closed-loop condition.

Figure 4 shows the voltage across main inductance for open-loop boost mode operation with a duty ratio =55%. In Fig.5 the current passing through the main capacitor is shown also for open-loop, boost mode operation with a duty ratio =55%.

In Fig.6 two-step changes in supply voltage, 24 to 20 volt then from 20 to 24 volt are carried in open-loop buck mode operation condition with duty ratio =33%. The open-loop boost mode operation for aduty ratio = 55%, is shown in Fig.7 with two-step changes in supply voltage, 24 to 28 volt then from 28 to 24 volt. The load change effects also are investigated in open-loop condition for both buck and boost modes for 33% and 55% duty cycles respectively and the results are shown in Figs. 8 and 9 respectively.

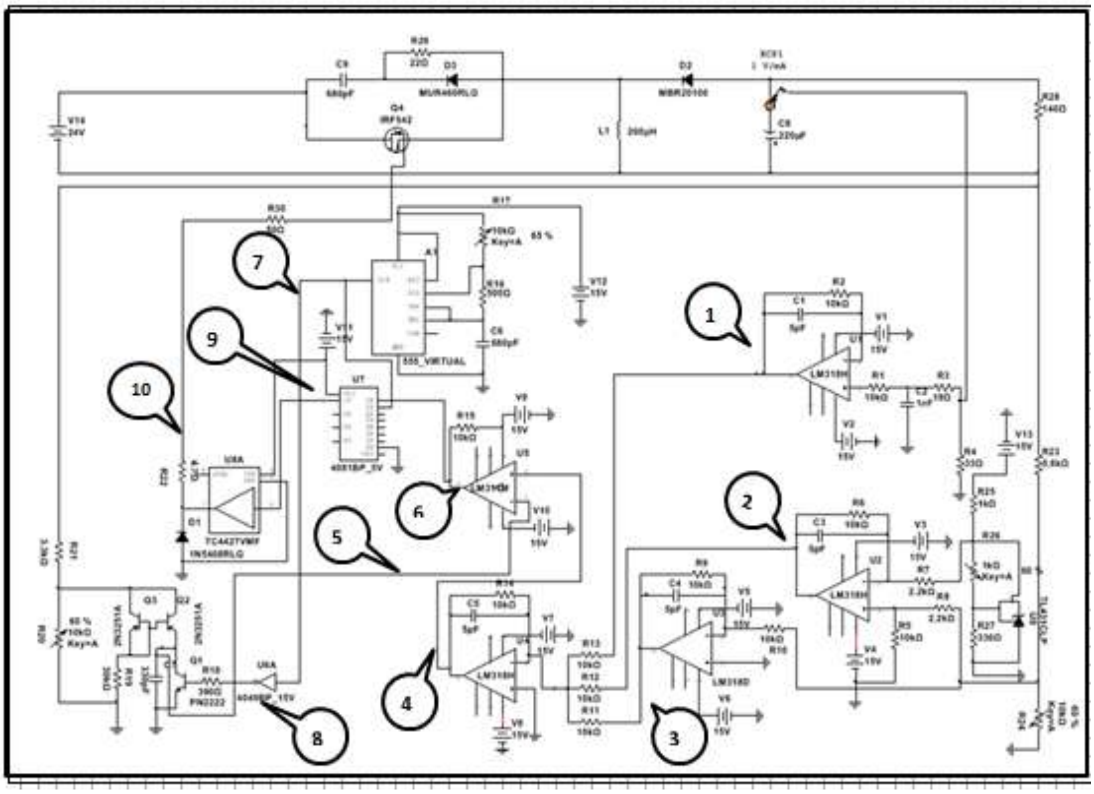


Fig.3 Complete schematic diagram of the circuit used in the Lab. (Power and Control Circuits)

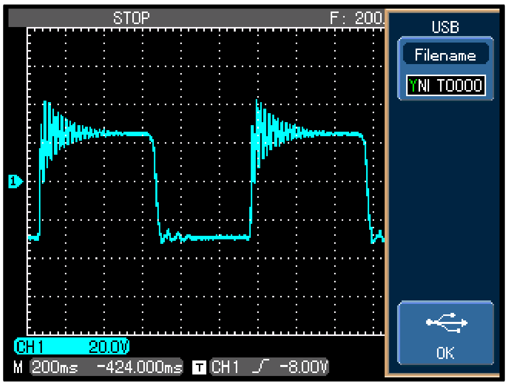


Fig. 4 Open-Loop Operation, Voltage across inductance, Input Voltage =24 volt, Boost Mode Operation, Duty ratio =55%

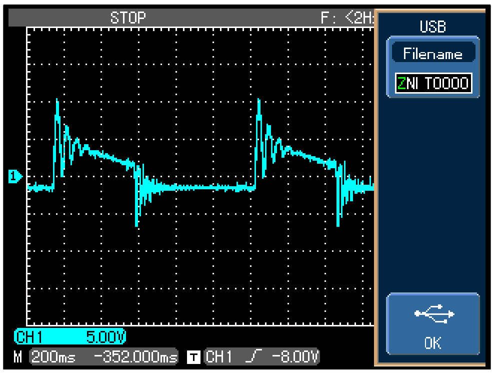


Fig. 5 Open-Loop Operation,Current in the Main Capacitor , Input Voltage =24 volt, Boost Mode Operation, Duty ratio =55%

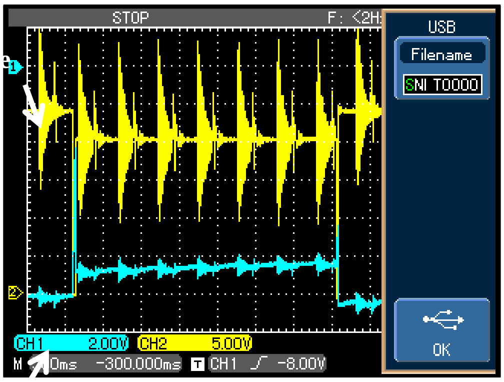


Fig. 6 Open-Loop Operation, Buck Mode, Duty ratio =33%, Two Step changes in supply voltage, 24 to 20 volt then from 20 to 24 volt

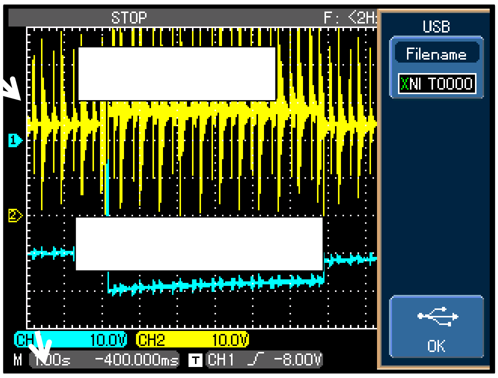


Fig.7 Open-Loop Operation, Boost Mode, Duty ratio = 55%, Two Step changes in supply voltage, 24 to 28 volt then from 28 to 24 volt

The experimental waveforms of the control circuit test points given in Fig. (3) are shown in the following figures for closed-loop, buck mode operation, V_{in}=24V, V_{od}=-12V, D=33%.

Fig.8 Open –Loop Operation, Buck Mode-Duty ratio = 33%, Input Voltage =24 volt. Output voltage profile for load resistance step changes.

Fig.9 Open –Loop Operation, Boost Mode-Duty ratio =55 %, Input Voltage =24 volt, Output voltage profile for load resistance step changes.

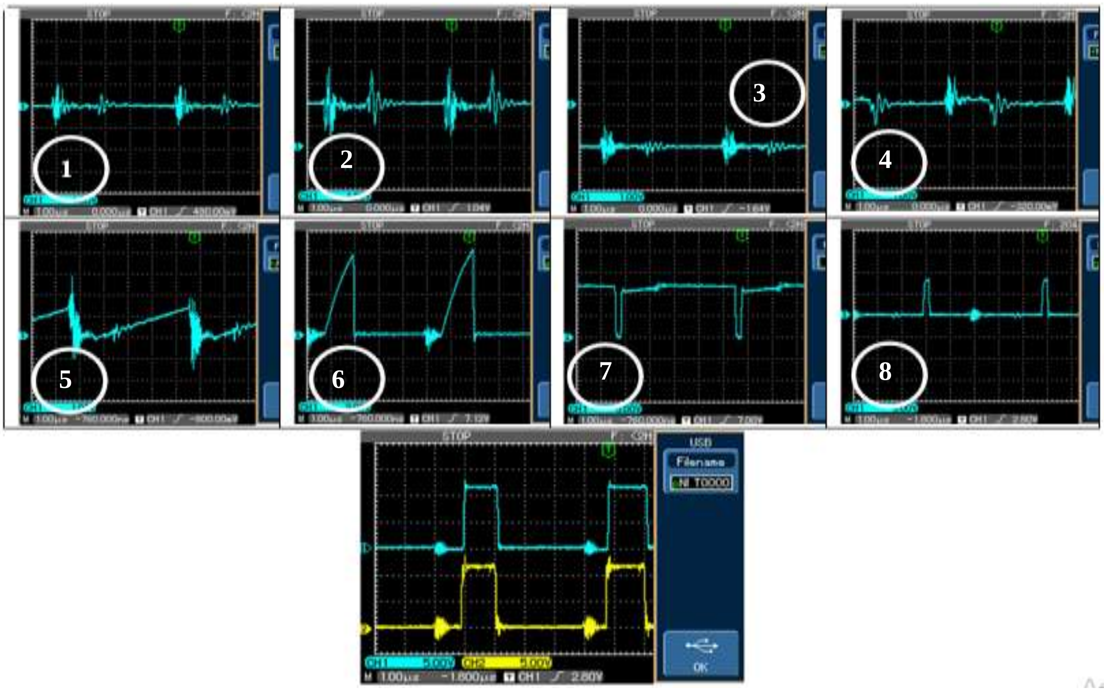


Fig.10 Experimental waveforms of the test points for closed-loop, buck mode operation,V_{in}=24V, V_{od}=-12V, D=33%.

The implemented circuit was testedin the Lab. with the closed loop controller both for buck and boost mode of operations. For buck mode operation the desired output voltage is seted to be 12 volt while the input was 24 volt. A step change of the load from 140 to 14 Ω shows a good regulated performance of the controller as shown in Fig.(11). Also a small step change in the supply voltage (24 to 20 volt) is done to investigate the robustness of the system as shown in Fig.(12). The same is investigated for a small increase in the input voltage (24 to 28volt) as shown in Fig. (13). While the starting of the converter is shown in Fig. (14).

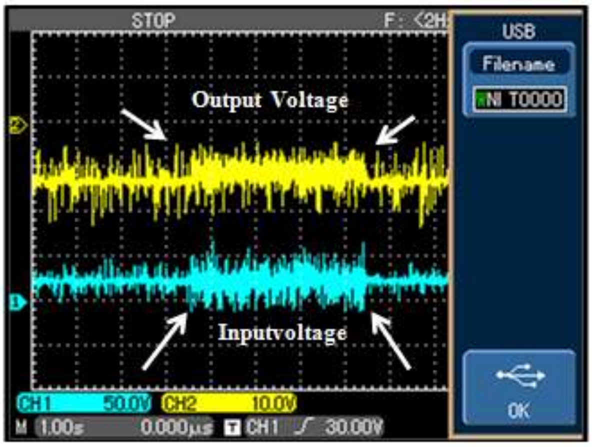


Fig. 11 Input &output voltage profiles with step change in load resistance140 Ω to 14Ω then to 140Ω, V_{in}=24V, V_{od}= -12V, D=33%

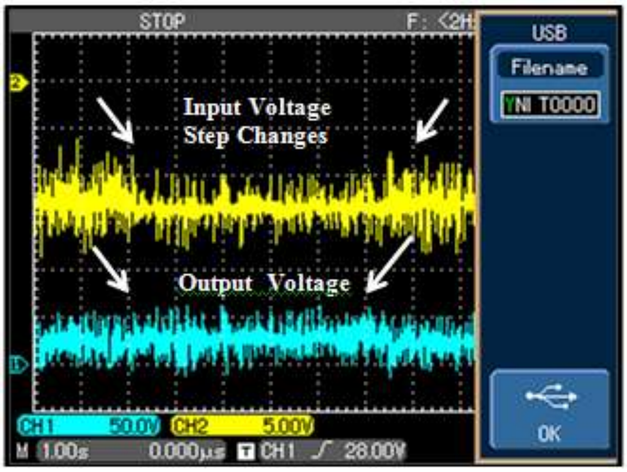


Fig. 12 input &output voltage profiles with step change in input voltage24V to 20Vthen to 24V V_{od}= -12V, D=33%R= 140Ω

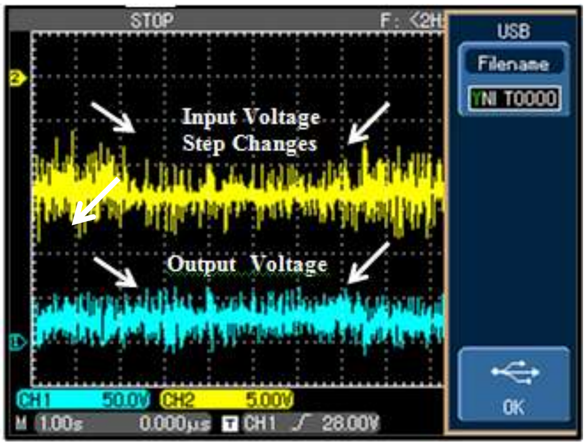


Fig. 13 Input &output voltage profiles with step change in input voltage24V to 28V then to 24V V_{od}= -12V, D=33%, R= 140Ω

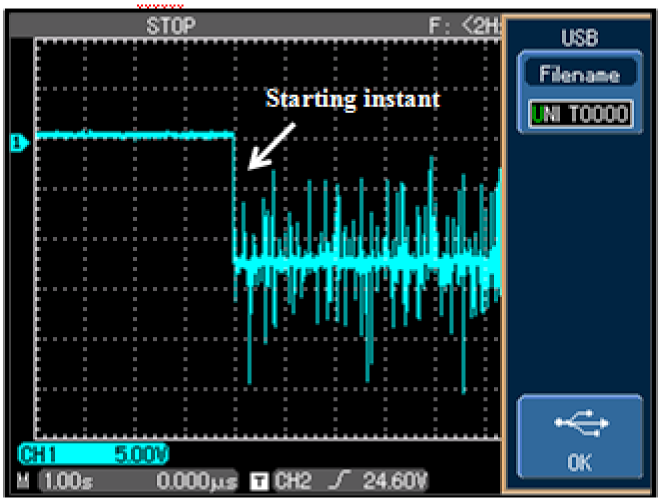


Fig. 14 Starting forbuck mode operation, V_{in}=24V, V_{od}= -12V, R=140Ω, D= 33%, V_{ref}=1.6V

For boost mode of operation the starting transient is shown in Fig. (15)for which the desired output voltage is set to be 36 volt. A step change in the output load resistance is applied to the experimental set and the output voltage profile during this change is shown in Fig. (16).

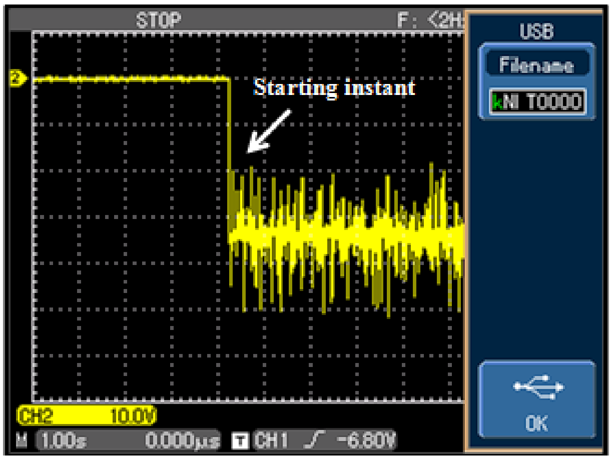


Fig. 15 Starting for boost mode operation,V_{in}=24V, V_{od}= -36V, R_L=140Ω, D= 60%, V_{ref}=4.2V

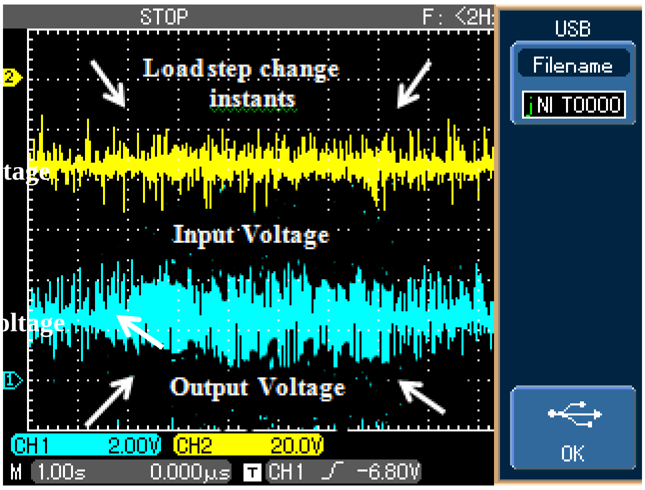


Fig. 16 Input & output voltage profiles with step change in load resistance140Ω to 50Ω then to 140Ω, V_{in}=24V, V_{od}= -36V, D=60%

The whole experimental setup of the PWM SMC BB converter is shown in Fig. (17).

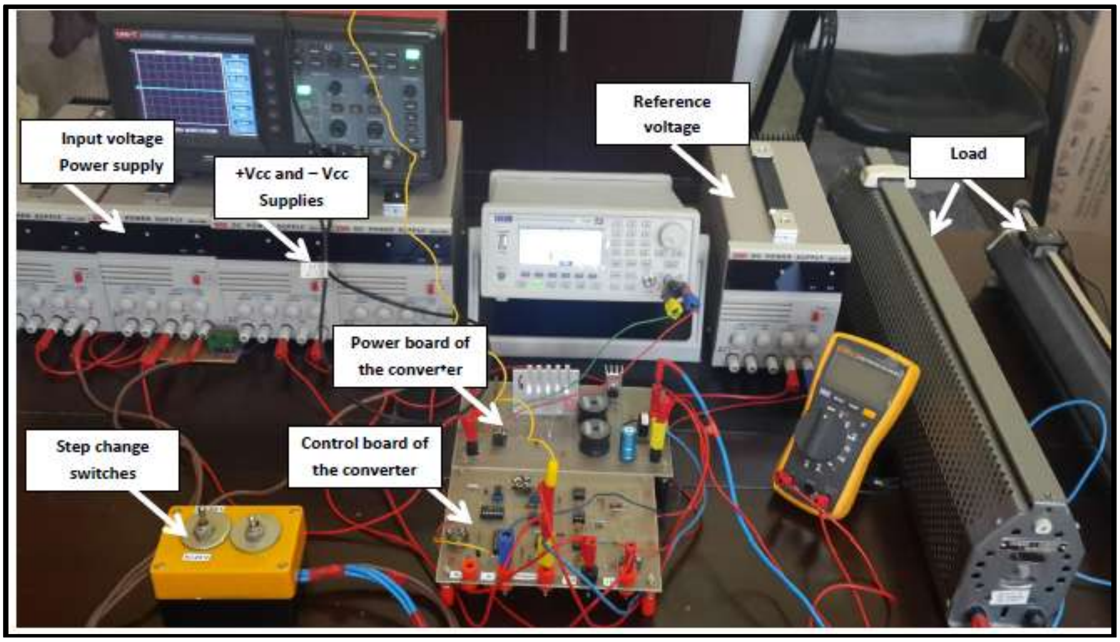


Fig. 17 Experimental setup of PWM-based SMVC BB converter.

VII..Conclusions

In this research work an experimental prototype is implemented for the sliding mode based DC to DC buck-boost converter and tested carefully in the lab. to fulfil the robustness of such kind of controlling systems. By the way the voltage signals in different points of the controller circuit are also checked and step changes are performed to input voltages and the output load resistances. The closed-loop output voltage profile during the step change instants and its steady-state performance showed a very good performance comparing to the open-loop step change case.

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