Implementation Of DC-DC Buck Converter With Switched Mode Control Technique For Enhancement of Efficiency of Solar Cell

Srikant Misra, Sujit Kumar Patro, Debasis Mahapatra, Partha Sarathi Mansingh

Abstract - The solar arrays are dependent power sources with nonlinear voltage-current characteristics under different environmental conditions (temperature & insulation). From this point of view, the DC/DC converter is particularly suitable for the application of the switching mode control in photovoltaic application, because of its controllable states. The switched-mode dc-dc converters are some of the most widely used power electronics circuits for its high conversion efficiency and flexible output voltage. This leads to the requirement of more advanced control methods to meet the real demand. Many control methods are developed for the control of dc-dc converters. Conventionally, the dc-dc converters have been controlled by linear voltage mode and current mode control methods. These controllers offer advantages such as fixed switching frequencies and zero steady-state error and give a better small-signal performance at the designed operating point. But under large parameter and load variation, their performance degrades. Switched mode (SM) control techniques are well suited to dc-dc converters as they are inherently variable structure systems. These controllers are robust concerning converter parameter variations, load and line disturbances. SM controlled converters generally suffer from switching frequency variation when the input voltage and output load are varied. The main objective of this research work is to study different control methods implemented in dc-dc converter namely (linear controllers, current programmed control, and switched mode (SM) control). A comparison of the effects of the PWM controllers and the SM control on the dc-dc buck converter response in steady state, under line variations, load variations is performed. Simulations are performed in Matlab/Simulink software. The simulation results are presented for a step change in reference voltage and input voltage as well as step load variations. The simulations results of proposed method are compared with the conventional PID controller and PWM controller. The results show the good performance of the proposed switched mode controller. In this paper, a new switched mode controller is proposed as the indirect control method and compared to a simple direct control method in order to control a buck converter in photovoltaic applications.

Keywords- Switched mode control, PID controller, PWM controller, PCM Control , Dc-dc buck converter, variable structure system.

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1. INTRODUCTION:

The new generation power systems require highly efficient, high-quality, small, lightweight, reliable, power supplies. The switched mode dc-dc converters are some of the simplest power electronic circuits which convert one level of electrical voltage into another level by switching action[1].

These converters have received an increasing deal of interest in many areas. This is due to their wide applications like power supplies for personal computers, office equipments, appliance control, telecommunication equipments, DC motor drives, automotive, aircraft, etc. The analysis, control and stabilization of switching converters are the main factors that need to be considered. Many control methods are used for control of switch mode dc-dc converters and the simple and low cost controller structure is always in demand for most industrial and high performance applications [2, 4]. Every control method has some advantages and drawbacks due to which that particular control method consider as a suitable control method under specific conditions, compared to other control methods. The control method that gives the best performances under any conditions is always in demand. The most familiar are switching power supplies[4], DC drives, and photovoltaic systems. The stability is an important aspect in the design of switch mode power supplies; a feedback control is used to achieve the required performance. Ideally the circuit is in steady state, but actually the circuit is affected by line and load variations (disturbances), as well as variation of the circuit component (robustness). These parameters have a severe effect on the behaviour of switch mode power supply and may cause instability. Design

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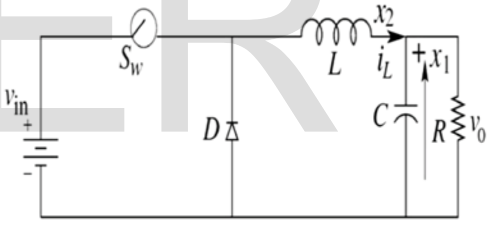
of controller for these converters is a major concern in power converters design. The commonly used control methods for dc-dc converters are pulse width modulated (PWM) voltage mode control, PWM current mode control with proportional (P),proportional integral (PI), and proportional integral derivative (PID) controller[6,8]. These conventional control methods like P, PI, and PID are unable to perform satisfactorily under large parameter or load variation. Therefore, nonlinear controllers come into picture for controlling dc-dc converters. The advantages of these nonlinear controllers are their ability to react suddenly to a transient condition. The different types of nonlinear controllers are hysteresis controller, switching mode controller, boundary controller, etc. The dc-dc converters, which are non-linear and time variant system, and do not lend themselves to the application of linear control theory, can be controlled by means of switching -mode (SM) control, Which is derived from the variable structure control system theory (VSCS)[9,10,11]. Variable structure systems are systems the physical structures of which are changed during time with respect to the structure control law. The instances at which the changing of the structure occurs are determined by the current state of the system. Due to the presence of switching action, switched-mode power supplies (SMPS) are generally variable structured systems. Therefore, SM controllers are used for controlling dc-dc converters. SM control method has several advantages over the other control methods that are stability for large line and load variations, robustness, good dynamic response, simple implementation. Ideally, SM controllers operate at infinite switching frequency and the controlled variables generally track a particular reference path to achieve the desired steady state operation. The dc-dc switching converters are the widely used circuits in electronics systems. They are usually used to obtain a stabilized output voltage from a given input DC voltage
which is lower (buck) from that input voltage, or higher (boost) or generic (buck–boost)[1] . Most used technique to control switching power supplies is Pulse-width Modulation (PWM). The conventional PWM controlled power electronics circuits are modelled based on averaging technique and the system being controlled operates optimally only for a specific condition. The linear controllers like P, PI, and PID do not offer a good large-signal transient (i.e. large-signal operating conditions).

In this paper, a new switching mode controller is introduced for DC/DC buck converter as the indirect control method. The proposed controller is compared with a simple direct control method as well as the conventional PID controller. The simulation results are presented for a step change in reference voltage and input voltage as well as for a step load variation. The main contribution of this paper is the presentation of a new indirect switching mode controller with good accuracy and performance against load and line as well as reference regulations.

2. DC/DC Converters

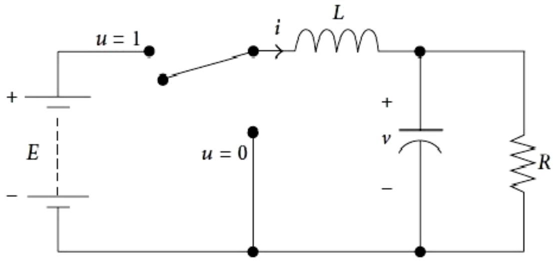
The DC-DC converters can be divided into two main types : hard-switching pulse width modulated (PWM) converters and resonant and soft-switching converters. Advantages of PWM converters include low component count, high efficiency, constant frequency operation, relatively simple control and commercial availability of integrated circuit controllers, and ability to achieve high conversion ratios for both step-down and step-up applications. The circuit diagram of the DC/DC buck converter is shown in Figure 1. In this figure, the circuit schematic is depicted with the transistor-diode symbols. By sensing of the DC output and controlling of the switch duty cycle in a negative-feedback loop, the DC output voltage could be regulated against input line and output load changes.



(FIG – 01 DC-DC BUCK CONVERTER)

3. The State-Space Model of Buck Converter

To obtain the differential equations describing the buck converter, the ideal topology is used as shown in Figure-02.The differential equations describing the DC/DC buck converter dynamics are obtained through the direct application of Kirchhoff's current and Kirchhoff's voltage laws for each one of the possible circuit topologies arising from the assumed particular switch position function value. Thus, when the switch position function exhibits the value $u = 1$, we obtain the topology corresponding to the non conducting mode for the diode obtained. Alternatively, when the switch position exhibits the value $u = 0$, the second possible circuit topology corresponding to the conducting mode for the diode is obtained.



(Fig-2 Switching operation of DC-DC Buck converter)

The system dynamics is described by the following differential equations.

For $u = 1$,

$$L\frac{di}{dt} = -v + E \qquad C\frac{dv}{dt} = i - \frac{v}{R} \quad \text{....(3.1)}$$

For $u = 0$,

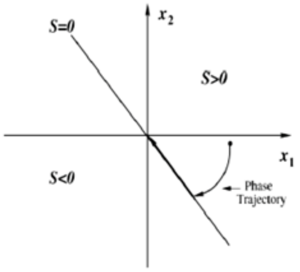
$$L\frac{di}{dt} = -v \qquad C\frac{dv}{dt} = i - \frac{v}{R} \quad \text{..........(3.2)}$$

By comparing the obtained particular dynamic systems descriptions, the following unified dynamic system model can be obtained:

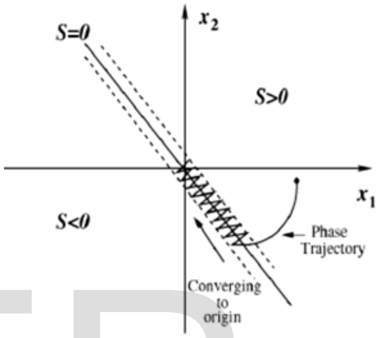
$$L\frac{di}{dt} = -v + uE \qquad C\frac{dv}{dt} = i - \frac{v}{R} \quad \text{..............(3.3)}$$

4. Principles of SM control

The basic idea of SM control is to design first a sliding surface in state space and then the second is to design a control law direct the system state trajectory starting from any arbitrary initial state to reach the sliding surface in finite time, and finally it should come to a point where the system equilibrium state exists that is in the origin point of the phase plane. The existence, stability and hitting condition are the three factors for the stability of sliding mode control. SM control principle is graphically represented in Figure 3, where S 0, represent the sliding surface and $x1$ and $x2$ are the voltage error variable and voltage error dynamics respectively. The sliding line (when it is a two variable SM control system in two-dimensional plane) divides the phase plane into two regions. Each region is specified with a switching state and when the trajectory arrives at the system equilibrium point, the system is considered as stable. If the hysteresis band around the sliding line becomes zero, then system is said to be operated with ideal SM control. But, from the practical point of view, this is not possible to achieve. Hence, the actual SM control operation that is when the hysteresis band is not ideal having a finite switching frequency is shown in figure 4 .



(FIG 3 : phase plot for ideal SM control)



(FIG 4 : phase plot for actual SM control)

5. SM Control Theory

The SM control theory is a well discussed topic. In this section a general review on SM control theory is presented. Let us consider a general system with scalar control as an example for better understanding of design procedure of SM control.

$$\frac{dx}{dt} = f(x,t,u) \quad \text{............(5.1)}$$

where x is the column vector that represents the state of the system, f is a function vector with n dimension, u is the control input that makes the system discontinuous. The function vector f is discontinuous on the sliding surface $S(x, t) = 0$, which can be represented as,

$$f(x,t,u) = \begin{cases} f^{+}(x,t,u^{+}) \text{ for } S(x,t) > 0 \\ f^{-}(x,t,u^{-}) \text{ for } S(x,t) < 0 \end{cases} \quad \text{..........(5.2)}$$

where S(x, t) = 0 is the sliding surface (sliding manifold). The system is in sliding mode if its representative point (RP) moves on the sliding surface S(x, t) = 0. Existence condition and reaching condition are two requirements for a stable SM control system. The existence condition of sliding mode requires that the phase trajectories belongs to the two regions, created by the sliding line, corresponding to the two different values of the vector function f must be directed towards the sliding line. While approaching the sliding line from the point which satisfies $S(x, t) > 0$, the corresponding state velocity vector f^+ must be directed toward the sliding surface, and the same happens for the points above $S(x, t) < 0$for which the corresponding state velocity vector is f^- . The normal vectors (f_N^+, f_N^-) of the function f are orthogonal to the sliding surface or the sliding line, which is given by,

$$\lim_{s\to 0} f_N^+ < 0 \Rightarrow \lim_{s\to 0^+} \nabla S.f^+ < 0 \qquad \ldots\ldots\ldots 5.3$$

$$i_{SA} = I_{ph} - I_0\{\exp((\frac{q}{AKT}).(v_{SA} + R_s i_{SA})) - 1\} \qquad \ldots\ldots 5.4$$

where ∇S is the gradient of surface S . This is expressed as –

$$\frac{dS}{dt} = \sum_{i-1}^{N} \frac{\delta S}{\delta x_i}\frac{dx_i}{dt} = \nabla S.f \qquad \ldots\ldots\ldots\ldots\ldots\ldots 5.5$$

Therefore, in mathematical terms the sliding-mode existence condition is represented as

$$\lim_{s\to 0} S\frac{ds}{dt} < 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.6$$

The reaching condition means the system RP will reach the sliding surface within finite time interval. The scalar discontinuous input u at any instant depends upon the system RP in state space at that instant. Hence, the control input for the system in (5.1) can be written in mathematical form as,

$$u = \begin{cases} u^+ & \text{for } S(x,t) > 0 \\ u^- & \text{for } S(x,t) < 0 \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.7$$

where u^+ and u^- are the switching states which belong to the region $S(x) > 0$ and $S(x) < 0$ respectively. Let $[e^+]$ and $[e^-]$ be the steady state RPs corresponding to the inputs u^+ and u^-.Then a sufficient condition for reaching the sliding surface is given by:

$$\begin{aligned} &[e^+] \in S(x,t) < 0 \\ &[e^-] \in S(x,t) > 0 \end{aligned} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.8$$

If the steady state point for one substructure belongs to the region of phase space reserve to the other substructure, then sooner or later the system RP will hit the sliding surface. Then, the behaviour of dc-dc switching converter when operated in sliding mode with the equivalent input is described below.

For the dc-dc converter system the state space model can be written as,

$$\frac{dx}{dt} = f(x,t) + g(x,t)u \qquad \ldots\ldots\ldots\ldots\ldots\ldots 5.9$$

The control input u is discontinuous on sliding surface $S(x,t) = 0$, while f and g are continuous function vectors. The sliding surface is a combination of state variables as

$$S(x,t) = kx + \varphi \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.10$$

Under SM control, the system trajectories stay on the sliding surface, therefore:

$$\begin{aligned} &S(x,t) = 0 \\ &\Rightarrow \frac{d}{dt}S(x,t) = 0 \end{aligned} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.11$$

$$\begin{aligned} \frac{dS}{dt} &= \sum_{i=1}^{n} \frac{\partial s}{\partial x_i}\frac{dx_i}{dt} \\ &= \nabla \mathrm{S}\frac{dx}{dt} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.12 \\ &= \mathrm{k}\frac{dx}{dt} \end{aligned}$$

where k is a 1 by n matrix, the elements of which are the derivatives of the sliding surface with respect to the state variables (gradient vector) and φ is some constant value. Using equations (5.9) and (5.12) leads to

$$k\frac{dx}{dt} = kf(x,t) + kg(x,t)u_{eq} = 0 \qquad \ldots\ldots 5.13$$

where the discrete control input u was replaced by an equivalent continuous control input u_{eq} , which maintains the system evolution on the sliding surface. The expression for the equivalent control is given as

$$u_{eq} = -(kg)^{-1}kf(x,t) \qquad \ldots\ldots\ldots\ldots\ldots\ldots 5.14$$

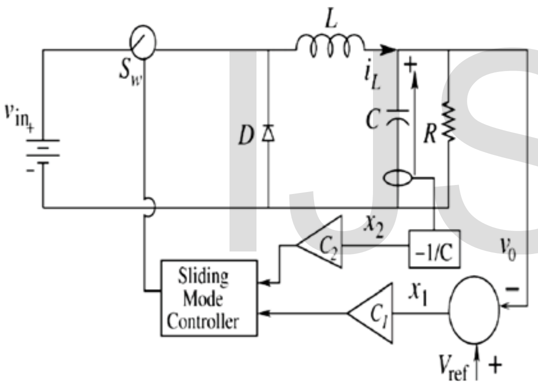
Substituting equation (5.14) into equation (5.9) gives

$$\frac{dx}{dt} = [I - g(kg)^{-1}k]f(x,t) \qquad \ldots\ldots\ldots\ldots\ldots 5.15$$

Equation (5.15) describes the system motion under the SM control. The system should be stable around any operating point. For satisfying the stability condition of the SM control, the created sliding surface will always direct the state trajectory towards a point where system stable equilibrium exits. This is generally accomplished through the design of the sliding coefficients to meet the desired dynamical property. This is possible by using the invariance property. Since in sliding mode operation, the state trajectory will track the path of the sliding surface to a point of stability, the dynamical property of the system can be determined by proper selection of sliding coefficient.

6. SM Control for DC-DC Buck Converter Modelling

Switching mode control is well known for its good dynamic response and stability due to its insensitive for parameters change and easier in implementation, so this control technique is used extensively for the control of dc-dc power converters. Figure - 5 shows the schematic diagram of a SM voltage controlled buck converter. Here the state space description of the buck converter under SM voltage control, where the control parameters are the output voltage error and the voltage error dynamics is described.



(Fig-05 SM Control Buck Converter)

Hence the voltage error x_1 and the voltage error dynamics (i.e. the rate of change of voltage error) x_2 under CCM operation can be expressed as

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} V_{ref} - v_0 \\ \frac{d}{dt}(V_{ref} - v_0) \end{bmatrix} \quad \ldots\ldots\ldots\ldots(6.1)$$

$$i.e \begin{cases} x_1 = V_{ref} - v_0 \\ x_2 = \frac{dx_1}{dt} = -\frac{dv_0}{dt} = -\frac{i_c}{C} \end{cases}$$

where V_{ref} represents the reference voltage, v_0 is the output voltage, and i_c denotes the capacitor current. Here the reference voltage V_{ref} is assumed to be constant and capacitor ESR is zero. Then, by differentiating with respect to time

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\frac{1}{C}\frac{d}{dt}i_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.2)$$

The capacitor current equation when the switch is on can be expressed as

$$i_c = i_L - i_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.3)$$

From the above equations .

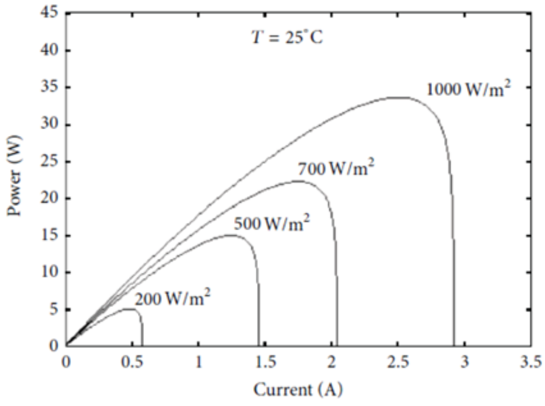
$$\dot{x}_2 = -\frac{1}{C}\left[\frac{d}{dt}i_L - \frac{d}{dt}i_0\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots(6.4)$$

7. Solar Array Characteristic

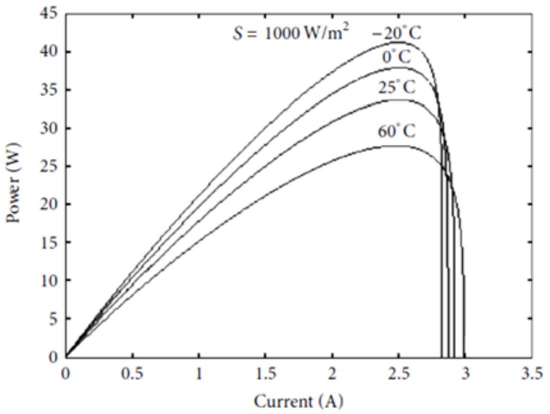
The solar arrays have nonlinear V-I characteristics which depend on the environmental conditions: ambient temperature and insulation. The nonlinear characteristic of a solar sell is obtained as the following equation :

$$i_{SA} = I_{ph} - I_0\{\exp((\frac{q}{AKT}).(v_{SA} + R_s i_{SA})) - 1\} \quad \ldots.(7.1)$$

where I_{ph} is the generated current under a given insulation condition, I_0 is the reverse saturation current, q is the charge of an electron, v_{SA} and i_{SA} are the output voltage and current of the solar cell, respectively, A is the ideality factor for a p-n junction, K is Boltzmann's constant, T is the temperature, and R_s is the series resistance of the solar cell. Figures 4 and 5 indicate the power-current (*P-I*) characteristic of a solar cell for different insulation and temperature, respectively.



(Fig – 06 P-I characteristics of the solar array according to different insulation (for *T* = 25∘ C)



(Fig – 07 P-I characteristics of the solar array according to different temperature (for *S* = 1000W/m2)

8. Design of SM Controller

In SM controller, the controller employs a sliding surface to decide its input states to the system. For SM controller, the switching states u which corresponds the turning on and off of the converter' switch is decided by sliding line. The sliding surface is described as a linear combination of the state variables. Thus the switching function is chosen as

$$S = c_1 x_1 + c_2 x_2 = C^{\mathrm{T}}\mathrm{x}=0 \ldots\ldots\ldots\ldots\ldots\ldots(8.1)$$

Where $C^{\mathrm{T}} = [c_1, c_2]$ is the vector of sliding surface coefficients and $x = x_1 x_2^{\,T}$ .This equation describes a sliding line in the phase plane passing through the origin, which represents the stable operating point for this converter (zero output voltage error and its derivative). The sliding line acts as a boundary that splits the phase plane into two regions. Each of this region is specified with a switching state to direct the phase trajectory toward the sliding line. When the phase trajectory reaches and tracks the sliding line towards the origin, then the system is considered to be stable, i.e., $x_1 = 0$ and $x_2 = 0$.

Substituting equation (6.4) into (8.1) results in

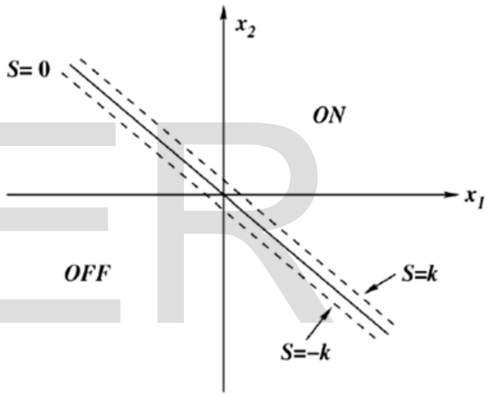
$$S = c_1 x_1 + c_2 \dot{x}_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8.2)$$

This describes the system dynamic in sliding mode. Thus, if existence and reaching conditions of the sliding mode are satisfied, a stable system is obtained. To ensure that a system follows its sliding surface, a control law is proposed. In this system, the control law is defined as

$$u = \begin{cases} 1 = \text{ON} \ \text{ when } S > k \\ 0 = \ \text{OFF} \ \text{ when } S < -k \ \ldots\ldots\ldots(8.3) \\ \ \text{previous, otherwise} \end{cases}$$

where k is an arbitrarily small value. The reason for choosing $S > k$ and $S < -k$ as the switching boundary is to introduce a hysteresis band which determines the switching frequency of the converter. If the parameters the state variables are such that $S > k$, switch S_w of the buck converter will turn on. When $S < -k$, it will turn off. In the region $-k \le S \le k$, switch remains in its previous state.

Thus, this prevents the SM controller from operating at a high frequency for the power switch to respond. It also alleviates the chattering effect which induces extremely high frequency switching. The switching conditions in equation (8.3) are graphically shown in figure 8



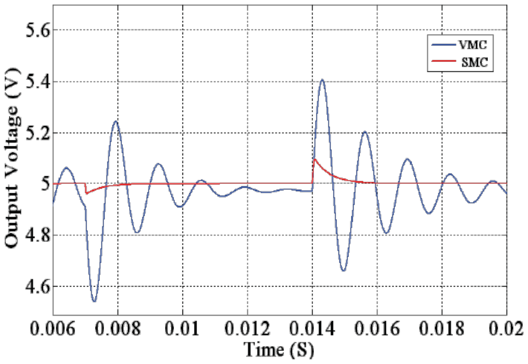
(Fig-8 Sliding Line X1 - X2 phase plane)

9. Simulation Results and Discussions

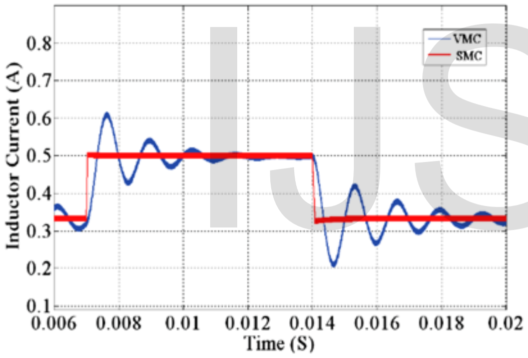
In this section the simulation results are presented for comparison between the different control methods that are discussed in above sections undergoing load current step transient, input voltage step transient. The results of comparison are explained. There are two different types of comparison study are presented. The first one is the performance comparison between PWM based voltage-mode controlled buck converter and SM controlled buck converter. The second one is the performance comparison between peak current-mode controlled buck converter with SM controlled buck converter. The control methods have the same power circuit parameters and operate at the same input and output voltages. The design specifications and the circuit parameters, for simulation are chosen as: input voltage $v_{in} = 20\mathrm{V}$,desired output voltage $v_0 = 5\mathrm{V}$,inductance $L = 3\mathrm{mH}$,capacitance

C=69μF and minimum load resistance $R_{min} = 10\Omega$, maximum load resistance $R_{max} = 15\Omega$, voltage reduction factor $k_1 = 0.4$,proportional gain $k_p = 2$ and the upper and lower threshold of ramp voltage $V_L = 3.8$ and $V_U = 8.2$ .The sliding coefficients $c_1 = 2$ and $c_2 = 0.001$.The switching frequency f_s is set to 100 kHz.

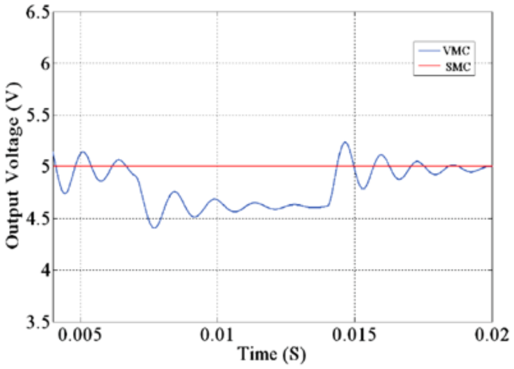
9.1 PWM based Voltage-Mode Controller versus SM Controller



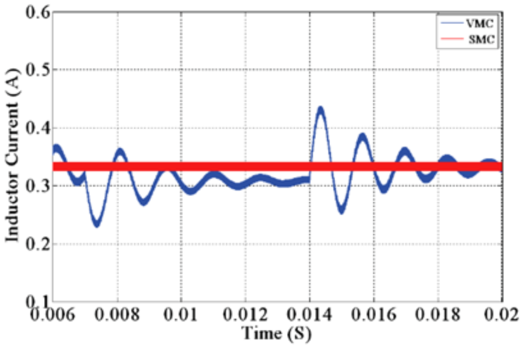
(Fig-9 Output voltage response due to a step change in load resistance from 15Ω to 10Ω back to 15Ω)



(Fig-10 Inductor Current response due to a step change in load resistance from 15Ω to 10Ω and back to 15 Ω)

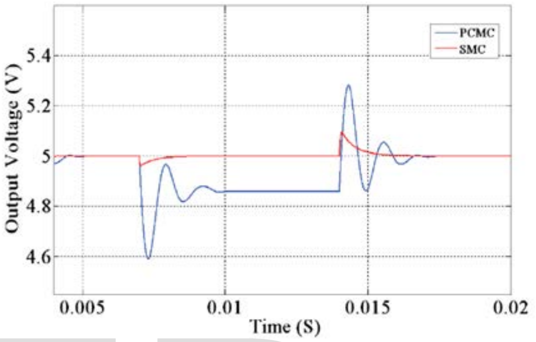


(fig-11 Output Voltage response for a change in input voltage from 20V to 15V and back to 20V)

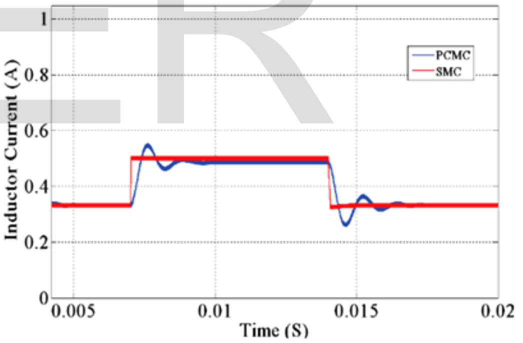


(Fig-12 Inductor Current response for a change in input voltage from 20V to 15V and back to 20V)

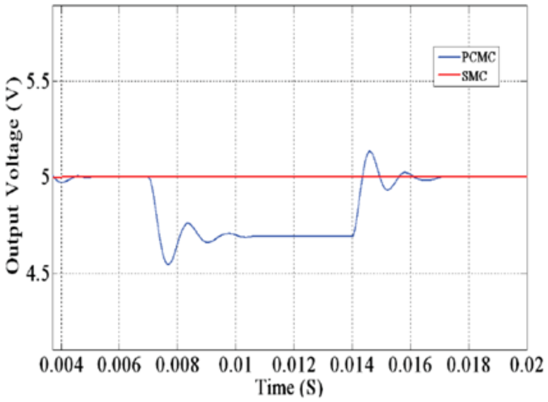
9.2 Peak-Current-Mode Controller versus SM Controller



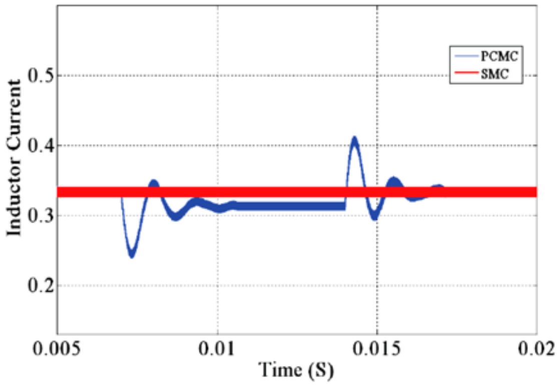
(fig-13 Output Voltage response with step load transient from 15Ω to 10Ω and then back to 15 Ω)



(fig-14 Inductor Current response with step load transient from 15Ω to 10Ω and then back to 15 Ω)

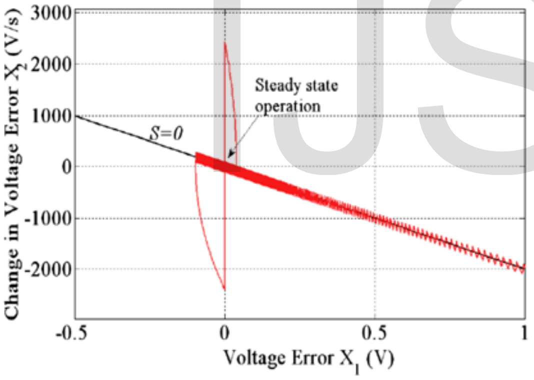


(Fig-15 Output Voltage response for a change in input voltage from 20V to 15V and back to 20V)



(fig-16 Inductor Current response for a change in input voltage from 20V to 15V and back to 20V)

The transient response of SM controlled buck converter can be understood from phase plane analysis method. The phase plane plot of SM control for a step change in load from 15Ω to 10Ω and then back to 15Ω is shown in figure 2.23. From figure we can see that the phase trajectory starting from any initial position always tries to settle at the stable equilibrium point (origin) and when the load changes the trajectory located at some other initial position again tracks the sliding line by reaching back to origin.



(Fig-17 Phase plane plot under step load transient for SM control)

10. **Conclusion**

The different control methods for dc-dc buck converter are discussed. The simulation results are also presented. The results of comparison are explained. The dynamic results in order to validate the disturbance rejection in larger range of variations are presented. The SM control method shows better dynamics for changes in input voltage and load compared to the PWM voltage-mode and current-mode control methods. It can be seen that the SM control method can well regulate the output voltage even in large range of load and line variation. This chapter summarizes the contributions and the main results of the thesis. The thesis has explained about the merits and demerits of different control methods such as the PWM voltage mode control, peak current mode control, hysteresis control and sliding mode control for dc-dc buck converter. A fixed frequency current hysteresis control has been designed for buck converter. a detailed explanation and classification of existing control techniques for switched mode power supplies have been given. The chapter also defined and summarized, with the aid of mathematical equations for dc-dc buck converter. The information about the different modes of operations that are continuous conduction mode (CCM), discontinuous conduction mode (DCM) has been given. A comparison study has been carried out for studying the effects of PWM controllers and SM control on the dc-dc buck converter response in steady state, under line variations, load variations, and
different component variations.

11. Scope of Future Work

The area of future study which can be considered for further research Work is using the sliding mode control concept used for studying the behavior of hysteretic controlled dc-dc buck converter can be extended for other converter topologies

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