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Modeling, Control and Design of DC-DC Boost Converter for Grid Connected Photo-Voltaic Applications

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Abstract - This article presents a design and development method of a DC-DC boost converter with constant output voltage. This system has a nonlinear dynamic behavior, as it works in switch-mode. Moreover, it is exposed to significant variations which may take this system away from nominal conditions, due to changes on the load or on the line voltage at the input. From a fluctuating or a variable input voltage, boost converter is able to step up the input voltage to a higher constant dc output voltage using the Non-linear feedback controllers such as PID controller and the Sliding Mode controllers. By this technique, the output of the converter is measured and compared with a reference voltage. The differential of the compared value will be used to produce a pulse width modulation signal to control switch in the boost converter. Simulation results describe the performance of the proposed design.

Keywords - PV system, dc-dc converter, variable structured systems (VSS's), feedback controller, (proportional + Integral +Derivative) controller, Sliding-Mode controller, MATLAB/SIMULINK.

I. INTRODUCTION

The interest of renewable energy sources has grown rapidly in the recent years. One of the most available and promising renewable energy sources is solar energy. PV energy generates electricity from solar radiation. With an increasing worldwide interest in renewable energy sources and its use, there is renewed focus on the power electronic converter interface for dc energy sources. One of the major problems of PV systems is that the output voltage of PV panels is highly dependent on solar irradiance and ambient temperature [9]. Hence, loads cannot be directly connected to the output of PV panels. A DC-DC converter is required to operate as an interface between PV panels and loads. The switched-mode DC-DC converters are power electronic systems that convert one level of electrical voltage into another level by switching action. They are very popular these days because of their high efficiency and smaller size. Switched-mode dc-dc converters are used extensively in personal computers, computer peripherals, and adapters of consumer electronic devices to provide dc voltages.

Nowadays, several techniques are used to improve the converter dynamic response. Some of them are based on improving the linear control [1] and others introduce the non-linear control [7]. From the linear controls: Good load and line regulation in steady-state operation; low output voltage ripple; and switching

frequency independent of the filter parasitics. From the non-linear controls: Optimized transient response under load current steps; transient response independent of the load current steps amplitude; good stability in transient-state operation; and easy to design and to implement. Incidentally, characterized by switching, dc-dc converters are inherently variable-structured systems. In this paper the Boost converter with the parasitic elements is discussed with the control techniques of non-linear controls such as PID controller and the Sliding-Mode controller [3]. By substituting the linear PWM controllers with SM (nonlinear) controllers in power converters, better regulation can be achieved for a wider operating range.

II. DESIGN OF THE BOOST CONVERTER

A DC-DC boost converter provides the output voltage higher than the input voltage. There are two modes of operation of the boost converter. They are continuous conduction mode and discontinuous conduction mode [8]. The mode of operation i.e., CCM or DCM is decided by the inductor current. If the inductor current remains positive, the dc-dc boost converter is said to operate in CCM [6]. The boost converter of Fig.1 operates in CCM, the relationship between the input voltage (V_{in}) and the output voltage (V_O) is given as:

$$\frac{V_{in}}{V_o} = \frac{1}{1-D} \quad (1)$$

Where, $D=TON/TS$ is the duty-cycle, TS is the switching period and TON is conducting time of the switch. The boundary condition of CCM and DCM of the Boost converter critical value of the inductor 'Lc' and is given by

$$L_c = \frac{V_{IN}}{2\Delta I_L} DT_s \quad (2)$$

Where, T_s is the switching frequency. The selected inductance should be greater than LC for CCM. However, the inductor value determines the magnitude of ripple current in the output capacitor as well as the load current at which the converter enters discontinuous mode. Normally, a ripple of less than 30% of the average output current is considered for design [8] so as to provide the reasonable efficiency.

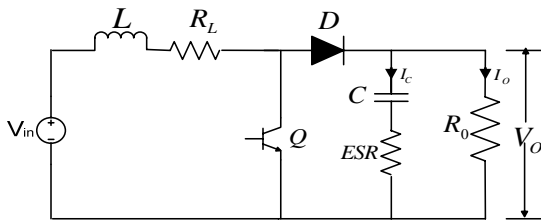


Fig. 1 : power stage of boost converter

The initial choice of the capacitor C is then determined by the allowed voltage ripple ΔV , which is typically 2% of output voltage. The overall output voltage ripple is the sum of the voltage spike caused by the $ESR (RC)$ of the output capacitor plus the voltage ripple caused by charging and discharging the Output capacitor and is given as [8]:

$$\Delta V_C = \frac{V_o}{2R_e C} * D * T_s \quad (3)$$

III. MODELLING OF DC-DC BOOST CONVERTER

The boost-type dc-dc switching converter with a switch is an example of a SIMULINK model (Fig. 1). The dynamics of this converter operating in the continuous conduction mode (CCM) can be easily understood by applying Kirchhoff's voltage law on the loop containing the inductor and Kirchhoff's current law on the node with the capacitor branch connected to it [1]. When the switch is at 'OFF' position, the dynamics

of the inductor current $i_L(t)$ and the capacitor voltage $v_C(t)$ are

$$\begin{aligned} \frac{di_L(t)}{dt} &= \frac{1}{L}(V_g - i_L(t)R_L - V_o) \\ \frac{dV_C(t)}{dt} &= -\frac{V_o}{CR_o} \end{aligned} \quad (4)$$

When the switch is at 'ON' position, the dynamics of the circuit are

$$\begin{aligned} \frac{di_L(t)}{dt} &= \frac{1}{L}(V_g - i_L(t)R_L) \\ \frac{dV_C(t)}{dt} &= \frac{1}{C}(i_L(t) - \frac{V_o}{R_o}) \end{aligned} \quad (5)$$

In both the cases, capacitor voltage $v_C(t)$ and output voltage $v_o(t)$ are related via the following equation:

$$V_o(t) = R_c C \frac{dV_C(t)}{dt} + V_C(t) \quad (6)$$

The constraints that the inductor current $i_L(t)$ and the capacitor voltage $v_C(t)$ can only be positive in the circuit are fulfilled by setting the integration blocks in the SIMULINK model to give only positive outputs. The inputs for the masked subsystem as shown in fig 2, are duty ratio and input voltage, and the outputs are chosen to be inductor current, capacitor voltage, and output voltage.

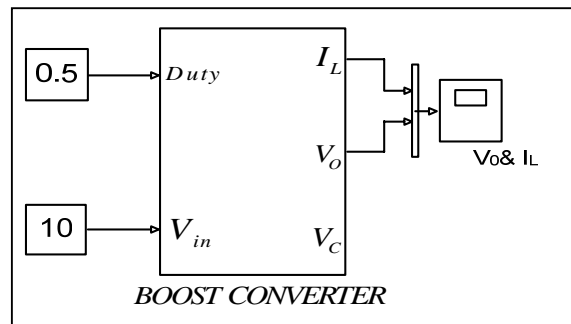


Fig. 2 : Boost Type Converter System

The circuit parameters of the above boost-type switching converter circuit are as follows: Switching frequency=5 KHz, $V_{in}=10V$, $D=0.5$, $L=500\mu H$, $C=200\mu F$, $rL=0.5\Omega$, $rC=0.25\Omega$ and $R0=25\Omega$. The simulation results are shown in Fig. 3.

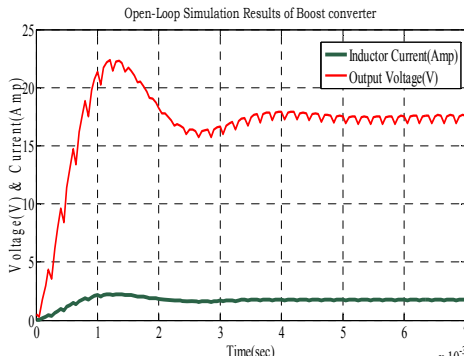


Fig. 3 : Simulation Results of Boost Type Converter by Simulink.

The open-loop frequency response of the linearized control to the output transfer of the switching circuit can then be plotted via the sisotool (“bode”) command and the switching converter linearized average model is shown in fig 4.

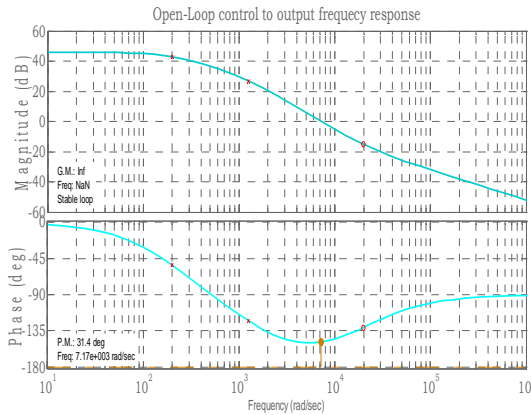


Fig. 4 : Open Loop Frequency Response of Boost Converter in MATLAB/SIMULINK.

IV. FEEDBACK CONTROLLER DESIGNS OF SWITCHING CONVERTERS

Boost converters are usually regulated with simple linear lead-lag compensators designed using the averaged linear approximation of the model [1]. The main difficulty encountered is that the converter models are nonlinear systems [7] and so the use of the well-known transfer function control design is not straight forward. The state-space-averaging method is widely used to derive expressions for small-signal characteristics of pulse width modulated (PWM) converters. On the other hand, modern control theory-based controllers such as state-feedback controllers, self-tuning controllers, hysteretic control or sliding-mode control [3] (SMC) and model reference adaptive

controller’s and PID controller’s etc. are using in the present days in the many industries.

V. PID CONTROL OF THE BOOST CONVERTER

PID controllers are widely used in industrial control systems because of the reduced number of parameters to be tuned [4]. They provide control signals that are proportional to the error between the reference signal and the actual output (proportional action), to the integral of the error (integral action), and to the derivative of the error (derivative action), namely

$$u(t) = \left[k_p e(t) + k_i \int e(t) dt + k_d \frac{d}{dt} e(t) \right] \quad (7)$$

Where $u(t)$ and $e(t)$ denote the control and the error signals respectively. k_p, k_i, k_d and , and are the parameters to be tuned. The corresponding transfer function is given as

$$K(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s \right) \quad (8)$$

The main features of PID controllers are the capacity to eliminate steady-state error of the response to a step reference signal (because of integral action) and the ability to anticipate output changes (when derivative action is employed). The entire feedback control system with the PID control is shown in Fig.5 The state space Matrices of the boost type DC-DC converter with the relevant expressions by assuming that the derivatives of the averaged inductor current $i_L(t)$ and capacitor voltage $v_C(t)$ are as follows.

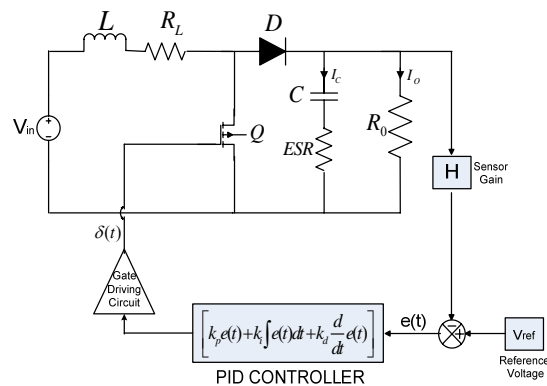


Fig. 5 : Block Diagram of a PID Control of Boost Type

$$A_1 = \begin{bmatrix} -\frac{r_L}{L} & 0 \\ 0 & -\frac{1}{C(R_L+r_c)} \end{bmatrix}, A_2 = \begin{bmatrix} \frac{r_L+R_L//r_c}{L} & \frac{R_L}{L(R_L+r_c)} \\ \frac{R_L}{(R_L+r_c)C} & \frac{1}{C(R_L+r_c)} \end{bmatrix} \quad (9a)$$

$$B_1 = B_2 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \quad (9b)$$

$$C_1 = \begin{bmatrix} 0 & \frac{R_L}{R_L+r_c} \end{bmatrix}, C_2 = \begin{bmatrix} r_c // R_L & \frac{R_L}{R_L+r_c} \end{bmatrix} \quad (9c)$$

The matrixes in equation (9) represent different operating Modes (subscript 1 stands for switch on, and subscript 2 stands for switch is off) of the switching circuit. By using the sisotool (“bode”) command the tuned values of the PID controller are $k_p = 0.0825$, $k_i = 9.4713$, $k_d = 1.5917e-5$. The closed loop control to frequency response of the PID Control of boost converter is shown in fig 6.

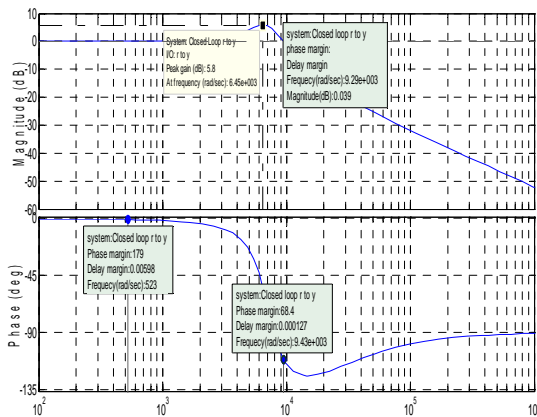


Fig. 6 : Closed-Loop frequency of Boost Converter in MATLAB/SIMULINK

The Simulation Results of the Boost converter with the PID controller are show in fig 7.the parameter values are same as in open-loop boost converter simulation.

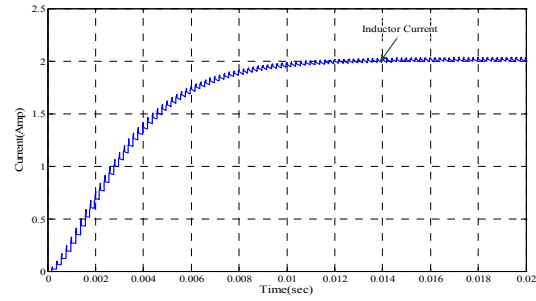
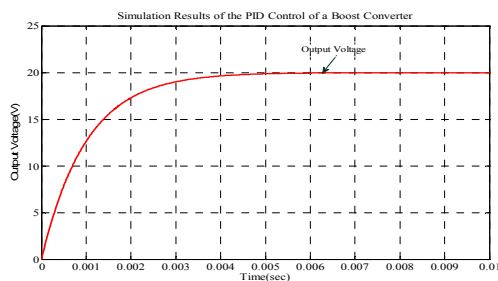


Fig. 7 : Simulation Results of Boost Type Converter by Simulink.

VI. SLIDING-MODE CONTROL OF BOOST CONVERTER

The sliding-Mode (SM) controller is a kind of nonlinear controller which was introduced for controlling variable structure systems (VSSs). The SM controller is relatively easy to implement as compared with other types of nonlinear controllers. The basic principle of a SM controller is to employ a certain sliding surface as a reference path such that the controlled state variable’s trajectory can be directed toward the desired equilibrium.

Principle of operation:

The basic principle of sliding mode controller is to design a certain sliding surface in its control law that will direct the trajectory of the state variables toward a desired origin when coincided, in the case of a single switch dc-dc converter, it is appropriate to have a control law that adopts a switching function such as

$$u = \frac{1}{2}(1 - \text{sgn}(S)) \quad (10)$$

Where ‘u’ is the logic state of the converter’s power switch, and ‘S’ is the instantaneous state variable’s trajectory which, in the case of a second-order controller, is described as

$$\text{Where } V_0 = \text{Desired Output Voltage}, \quad (11)$$

V_{in} =Input Supply Voltage

And R_0 =Load Resistance.

$$u = \begin{cases} 1, & \text{for } S < 0 \\ 0, & \text{for } S > 0 \end{cases} \quad (12)$$

Its major advantages are guaranteed stability and the robustness against parameter, line and load uncertainties. This explains the wide utilization of SM controllers in various industrial applications, e.g., automotive control, furnace control etc. some recent works on SM control and its application can be found in [3]. The Block diagram of Sliding mode control of boost converter is shown in fig 8.

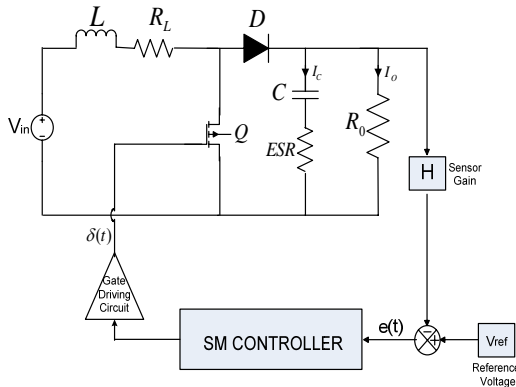


Fig. 8 : Block Diagram of a SM Control of Boost Type Converter

The circuit parameters of the above boost-type switching converter circuit are as follows: Switching frequency=25 KHz, $V_{in}=15V$, $L=170mH$, $C=1000\mu F$, $rL=0.5\Omega$, $rC=0.25\Omega$ and $RL=25\Omega$. The simulation results are shown in Fig. 9.

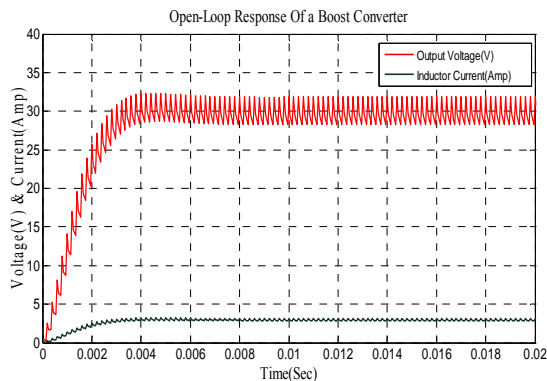


Fig. 9 : Simulation Results of the SM Control of Boost Type Converter

VII. CONCLUSIONS

This paper concerns with design and simulation of DC/DC boost converter to operate in PV system. From the results obtained above, the following are the salient conclusions that can be drawn from this paper:

- Design the DC/DC converter for all operating condition have studied and proposed.
- Detailed modeling and simulation of a DC/DC converter for photo-voltaic applications is studied.
- This paper has explained a novel technique for feedback Controller designs such as PID controller and Sliding-Mode controllers for a boost converter.

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