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Design and Implementation of Gain Scheduling PI-Controller for DC-DC Boost Converter Control System

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Abstract: *This paper provides design and implementation of a DC-DC boost converter control system by using gain scheduling PI-controller to achieve stable regulated output voltage with improved dynamic performance. The proposed controller parameters are obtained from system output response based on step input signal. A test step input is applied to the system and the three parameters of the plant are obtained from the corresponding response of the plant, which is independent to initial values of the system. Then the PI-controller is designed based on pole-placement method. For improving transient response and rise time of the converter, PI-controller parameters are continuously modified based on gain scheduling method. The efficacy of algorithms is verified through MATLAB simulation and finally, applied proposed algorithms into the DC-DC boost converter. Simulation results are presented to verify the effectiveness of the proposed DC-DC boost converter control system.*

Keyword: *Boost Converter; Gain-Scheduling; Parameter Identification; PI-Controller; PWM Signal.*

1. INTRODUCTION

The DC-DC converters have been widely used and studied at various application such as Maximum-Power-Point-Tracking (MPPT) control of wind turbine [1-2] and Photovoltaic System [3], Batter Charging [4-5], Water Pumping system [6] and Voltage Regulator [1,3] etc. The three basic dc-dc power converters are the buck, boost and buck-boost configurations. The problem of regulating the output voltage of these converters has been a subject of great interest for many years. Various control methods have been developed to control the DC-DC converters, for example, linear design [7], and fuzzy control [8-9] and sliding mode control [10-13].

A commonly used linear controller is based on Proportional-Integral-Derivative (PID) control method. Linear PID controllers for dc–dc converters are usually designed by classical Ziegler-Nichols (ZN) frequency response techniques applied to the small-signal models of converters [7]. The PID controller is typically designed for one nominal operating point, but a dc–dc converter's small signal model changes with variations in the operating point.

For a boost converter, both poles and a right-half-plane zero are dependent on the duty cycle, so the Bode plots can exhibit significant variation. Therefore, a PID controller may not respond well to significant changes in operating points [14].

Fuzzy control has also been applied to control dc-dc converters [9, 15]. Fuzzy controllers are capable of good performances than linear control techniques. Fuzzy controller are well suited to nonlinear time-variant systems and do not need an exact mathematical model for the system being controlled. They are usually designed based on expert knowledge of the converters. However, this control technique relies on human heuristic knowledge to design of fuzzy controller but there are few tools for the design and analysis of fuzzy controllers. In the absence of expert understanding, extensive trial and error tuning is required. A more systematic approach for designing and tuning fuzzy control is desirable [14].

Sliding mode control is a powerful method that is able to yield a very robust closed-loop system under plant uncertainties and external disturbances. In theory, the system can be entirely independent of effects due to modeling uncertainties, parameter fluctuations and disturbances [9-12]. DC-DC converters are inherently variable structured because of the switching action. There are several disadvantages exist for variable structure control with sliding mode. In the real time implementation the switching control in

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sliding mode control is impossible to change infinitely because of the time delay and physical limitations of switching devices. As a result, the duty cycle oscillates in steady state, which induces oscillation in the output voltage [13]. With some implementations, the switching frequency is not constant. These practical issues prevent variable structure control from being extensively applied to DC-DC converters [14].

The gain scheduling is another controller design for nonlinear voltage compensator of a boost converter [16], which provides a significant improvement in performance over a conventional ZN turned PI-controller for a water level control system [17]. A great advantage of this method is that the controller adapts quickly to changing conditions [17-18]. However, more sophisticated algorithms [19] for smooth scheduling have been introduced which provide significantly improved performance robustness guarantees for uncertain systems. But is it increased complexity of programming (i.e. convex semi-definite programming) and implementation, where increased computational requirements associated with the solution of linear programming problems which are amenable to linear matrix inequality programs via a gridding of the parameter space and a selection of basis function at each time step.

This paper we propose and implement a gain-scheduling approach using multiple local linear PI-controllers, each controller is designed by pole-placement method based on linear first order time delay (FOTD) model which is identified using methods and software described by Mohammed Sowket Ali, Jun-Sung Lee and Young-Il Lee in [20]. The open-loop converter system is considered for plant identification and Proportional-Integral (PI)-controller design at various adjustable voltage output. Then parametric scheduling of the PI-controller is properly designed to ensure better transient response and stability for the closed-loop system. We described how to implement the proposed PI-gain-scheduling algorithm using MATLAB SIMULINK.

2. PROPOSED SYSTEM

The functional block diagram of the proposed control scheme is illustrated in Figure 1.

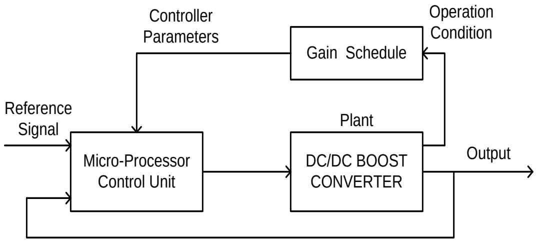
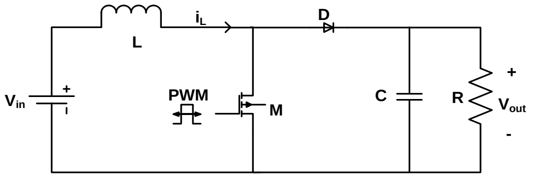


Figure 1 Block Diagram of a Gain Scheduling Scheme

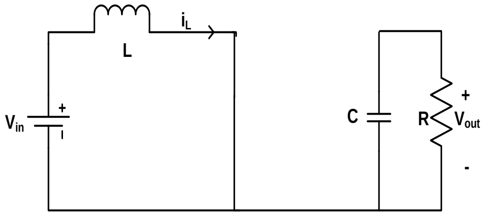
The output voltage of the DC-DC boost converter is sensed by voltage divider and is used to retrieve the corresponding parameters of the controller from the gain schedule algorithm. Based on parameters the controller regulates the output voltage and provides a stable output voltage with respect to the reference voltage.

2.1 Operation of Boost Converter

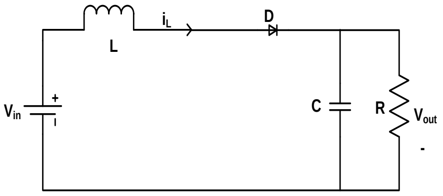
The voltage V_{in} is used as an input voltage of DC-DC boost converter to regulate the voltage. An equivalent circuit of the boost converter is shown in Figure 2(a).



(a) DC-DC Boost Converter



(b) ON State of the Power Switch



(c) OFF State of the Power Switch

Figure 2 DC-DC Boost Converter

The dynamics of this converter operation is in the continuous conduction mode (CCM), can be understood by using analysis of the circuit and the conduction status of the Metal-Oxide-Semiconductor-Field-Effect-Transistor (MOSFET) switch M is shown in Figure 2(a). The CCM Mode is used for efficient power conversion, has two states 'ON' and 'OFF' states, are shown in Figure 2(b) and Figure 2(c) respectively. The states of converter's power switch M is represented by a switching variable S_M, defined as,

$$S_M = \begin{cases} 1 & \text{if M is driven ON} \\ 0 & \text{if M is driven OFF} \end{cases} \tag{1}$$

The equations describing the operation of the boost converter can be written as

$$\mathrm{L}\frac{\mathrm{di_L}}{\mathrm{dt}} = \mathrm{V_{in}} - (1 - \mathrm{S_M})\mathrm{V_{out}} \quad , \tag{2}$$

and

$$\mathrm{C}\frac{\mathrm{dV_{out}}}{\mathrm{dt}} = (1 - \mathrm{S_M})\mathrm{i_L} - \frac{\mathrm{V_{out}}}{\mathrm{R}}. \tag{3}$$

State 1: In this stage, the switch M is ON. The current through the inductor increases and inductor gains energy. The energy stored in the capacitor C (if capacitor charged before) dissipates in the load resistance R that subsequently reduces the voltage V_{out} across it.

State 2: In this stage, the switch M is OFF. The current that was flowing through the MOSFET M would now flow through L, D, C and R. In this stage, the energy stored in the inductor in the inductor is now transferred to the capacitor C until the inductor current i_L falls below the load current. In this stage, capacitor voltage increases and the inductor current decreases.

2.2 The Idea of Parameter Identification

In steady state, for small-signal disturbances, a power converter can be approximated with first order time delay (FOTD) system, which transfer-function can be represented as,

$$G(s) = \frac{K}{(Ts+1)}e^{-Ls} \tag{4}$$

The system has dead time andis characterized by three parameters, K, L(L>0) and T(T>0), where K is the static process gain, L is the dead time and T is the time constant.

The following three parameter identification method from step response is used in [20] by Mohammed Sowket Ali, Jun-Sung Lee and Young-Il Lee. Where the process gain K for FOTD model is obtained by using Equation (5):

$$K = \frac{y(\infty) - y_0}{a} \tag{5}$$

where$y(\infty)$represents the $y(t)$ for some time t and $y_0$represent $y(0)$. The step input size is represent by'a'.

Parameter, T is obtained from the time difference between the time index of the maximum value of$y'(t)$ and that of 36.7% decay from the maximum of $y'(t)$. Where $y'(t)$ is represent of $\frac{dy(t)}{dt}$.The equation becomes,

$$y'(T) = y'_{max} \times 0.367 \tag{6}$$

The time delay L can be estimated as the consumed time to reach the maximum value of $y'(t)$. The time delay can be defined by Equation as,

$$L = t_{max} \tag{7}$$

Wheret_{max} represents the elapsed time to reach the maximum$y'(t)$ from the application of step signal, under the condition$\left.\frac{d^i y(t)}{dt^i}\right|_{t=0} = 0$, where $(i \geq 1)$.

2.3 Controller Design

Consider the structure of the control system shown in Figure 3. The controller receives the error signal Ep(s), Ei(s) and Ed(s) as shown in Equations (8)-(10), respectively.

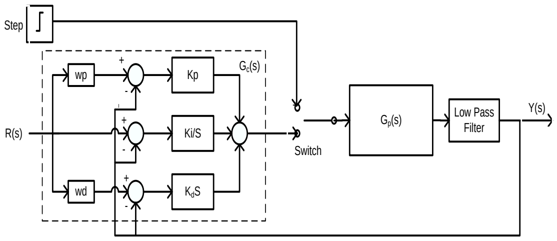


Figure 3 System structure

Based on error signals the controller generate the control signal to regulate the output response Y(s), referred to the input R(s), where Gp(s) and Gc(s) are the plant and the controller transfer functions, respectively.

$$E_p(s) = w_p R(s) - Y(s) \tag{8}$$

$$E_i(s) = R(s) - Y(s) \tag{9}$$

$$E_d(s) = w_d R(s) - Y(s) \tag{10}$$

Where $E_p(s)$, $E_i(s)$ and $E_d(s)$ are the error signals and w_p and w_d are the weighting factor of P and D elements, respectively. The transfer function of the system based on Eitelberg method is shown in Equation (11) for PI controller where K_d=0.

$$\mathrm{T(s)} = \frac{\left(\mathrm{w_p k_p} + \frac{\mathrm{k_i}}{\mathrm{s}}\right)\mathrm{G_p(s)}}{1 + \left(\mathrm{k_p} + \frac{\mathrm{k_i}}{\mathrm{s}}\right)\mathrm{G_p(s)}} \tag{11}$$

Where k_p, and k_i are the PI controller parameters.
By using the approximation,

$$e^{-Ls} \approx \frac{-\left(\frac{L}{2}\right)+1}{\left(\frac{L}{2}\right)+1} = \frac{-Ls+2}{Ls+2} \tag{12}$$

The FOTD process can be described by the following model by using Equation (4) and Equation (12),

$$G_p(s) = \frac{-sl+1}{s^2 d_2 + s d_1 + d_0} \tag{13}$$

Where,

$$d_2 = \frac{TL}{2K}, d_1 = \frac{2T+L}{2K},\ d_0 = \frac{1}{K}, \text{ and } l = \frac{L}{2} \tag{14}$$

By using Equation (11) we can get,

$$N(s) = (-sl + 1)(sk_P w_p + k_i)$$

$$D(s) = s^3 + s^2 \frac{(d_1 - lK_p)}{d_2} + s \frac{(d_0 + K_p - lK_i)}{d_2} + \frac{K_i}{d_2} \tag{15}$$

Where N(s) and D(s) are the numerator and dominator of transfer function T(s).

The general characteristic Equation is,

$$\Delta(s) = s^3 + c_2 s^2 + c_1 s + c_0 \tag{16}$$

In order to controller parameter identification D(s)=Δ(s) must be satisfied, from Equation (15) andEquation (16) we can get,

$$\left.\begin{aligned} d_1 - lk_p &= c_2 d_2 \\ d_0 + k_p - lk_i &= c_1 d_2 \\ k_i &= c_0 d_2 \end{aligned}\right\} \tag{17}$$

By using Equation (17) we can get,

$$k_i = c_0 d_2 \text{and} k_p = c_1 d_2 - c_0 d_2 l \tag{18}$$

From Equation (17), By putting values of k_p from Equation (17) we will get,

$$c_2 d_2 = d_1 + (d_0 - c_1 d_2) l - l^2 c_0 d_2 \tag{19}$$

Now suppose that the desired closed-loop poles are characterized by their relative damping (ζ) and their frequency (w). The desired characteristic equation then becomes,

$$\Delta(s) = (s + \alpha w)(s^2 + 2\zeta w s + w^2) \tag{20}$$

For the form of,

$$\Delta(s) = s^3 + c_2 s^2 + c_1 s + c_0 \tag{21}$$

Where,

$$\left.\begin{aligned} c_0 &= \alpha w^3 \\ c_1 &= 2\alpha\zeta w^2 + w^2 \\ c_2 &= \alpha w + 2\zeta w \end{aligned}\right\} \tag{22}$$

Put the values of c0, c1 and c2 to Equation (19), we will get

$$\alpha d_2 l^2 w^3 + (2\alpha\zeta + 1) d_2 l w^2 + (\alpha + 2\zeta) d_2 w - d_1 - d_0 l = 0 \tag{23}$$

This equation is used for finding real roots. Bisection algorithm is used to finding the roots at Sections 3. From Equation (23) which is 3rd degree equation satisfied the Routh-Hurwitz criterion, the number of roots with positive real parts is equal to the number to changes in sign of the first column of the Routh array described in [21-22].

2.4 Gain Scheduled Algorithm

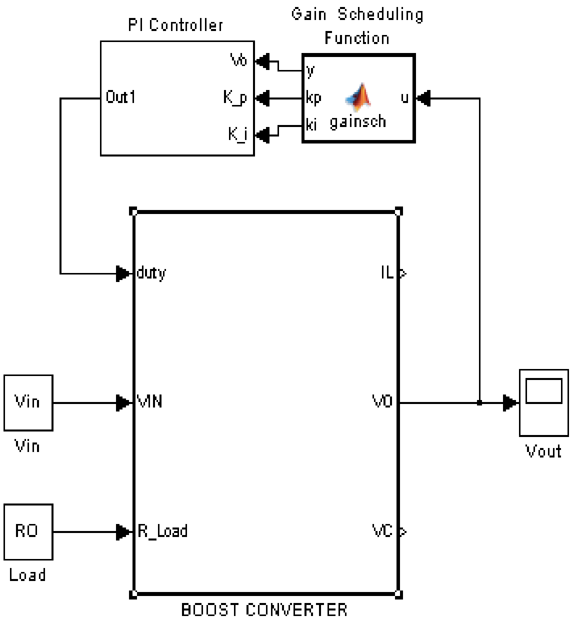
For gain scheduled controller design requires to design the controller parameters multiple operating points over the working rang of the system. The controller is scheduled according to rules based on the designed parameters. The gain scheduled design procedure for the DC-DC Boost converter is as follows,

Step1: Select several operating points which cover the range of operations of the DC-DC boost converter dynamics.

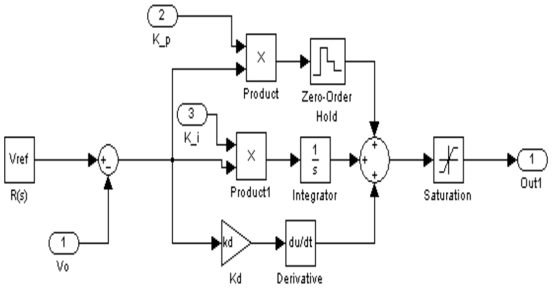
Step2: At each of these operating points, the FOTD parameter identification and PI-Controller design algorithm is applied and identified the control parameters.

Step3: Identified parameters from Step 2 is used to constructs a gain scheduling algorithm for PI-Controller in between the operating points, thus the controller interpolated the parameters.

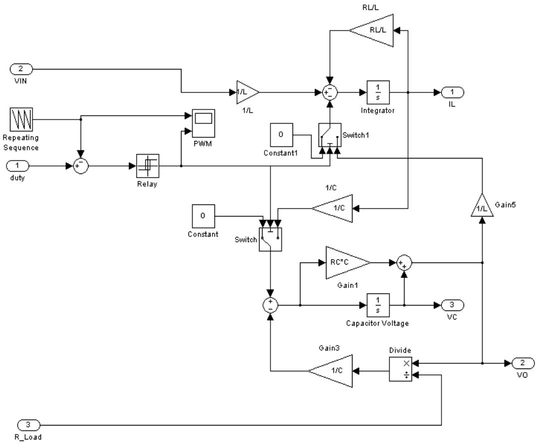
3. IMPLEMENTATION OF THE PROPOSED SYSTEM USING MATLAB SIMULINK



(a) Proposed System in MATLAB Simulink



(b) PID-Controller



(c) DC-DC Boost Converter

Figure 4 Constructed Proposed System Block in MATLAB SIMULINK

The simulation studies using MATLAB Simulink can be shown in Figure 4. The input voltage of this converter is labeled V_{in} in this Figure with 15V. The boost converter and PI-Controller are implemented as a subsystem block. The gain scheduling algorithm is implemented as a MATLAB-Function block. The output voltage V_{out} is observed by using scope block as well as workspace by saving the data. A 100kHz switching frequency is implemented into boost converter block at Pulse-Width-Modulation (PWM) signal generating part.

After design numerically the DC-DC boost converter in Section 2.1. The system equations are used to develop the Simulink model as shown in Figure 4(c) DC-DC boost converter. Where the values of inductor L is 50mH, capacitor is 250µF, Load resistance Ro is 10Ω, inductor series resistance R_L is 0.15Ω and capacitor series resistance R_C is 0.01Ω. The PID controller derived in Figure 4 (b), where parameters of the controller V_o, K_p, K_i are getting from the Gain Scheduling Function block, shown in Figure 4(a). The digital pulse width modulation signals generating by using repeating sequence compare with the output signal of the PID-controller signal (error signal).

The Gain Scheduling Function block in Figure 4(a) has one input signal define as u and three outputs signals y, kp and ki, where input u is the output voltage of the DC-DC boost converter. The block diagram of the Scheduling algorithm of Scheduling Function block is shown in Figure. 5.

The above algorithm is used for PI-controller gain scheduling. At the beginning the output voltage of DC-DC boost converter is measured by using voltage divider rules. Based on the output voltage level the parameters of the controller parameters will be reset.

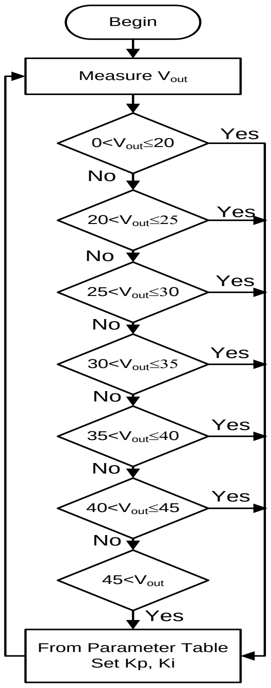


Figure 5 Gain Scheduling Algorithm

4. SIMULATION RESULTS

The simulation results are given in this section by the proposed gain scheduling scheme. The boost converter is a nonlinear system because of switching duty ration. In this case, using stable input voltage, fixed duty ration and output load can linearization the model. The plant identification and controller design are based on Figure. 6.

Our identification method is based on step response of the plant. Here the step input signal is generated by the step function mention as Duty. From the parameters properties of the step function, we set the step time, initial value and final values to generate proper output responses shown in Figure 7.

From data shown in Figure 7 are used to identification of the plant and controller parameters. The parameters of the plant identification processes gain K, time delay L and time constant T, and controller parameters weighting factor w, proportional gainKp and gainKi are tabulated in the Table I, is shown below.

TABLE I GAIN SCHEDULE PARAMETERS UNDER VARIOUS VOLTAGE CONDITIONS

Output Voltage Range	Controller Parameters			Identified Plant Parameters			Step Input	
	Kp	Ki	w	K	T	L	Initial	Final
0<Vout≤20	0.0725	0.1883	0.0949	0.279	5.70	1.80	0.03	0.05
20<Vout≤25	0.5100	0.2181	0.1235	0.3841	5.70	1.30	0.20	0.22
25<Vout≤30	0.7106	0.2125	0.1547	0.5858	5.60	1.00	0.40	0.42
30<Vout≤35	0.6493	0.1806	0.1696	0.816	5.60	0.90	0.54	0.56
35<Vout≤40	0.5005	0.1392	0.1696	1.059	5.60	0.90	0.65	0.67
40<Vout≤45	0.4556	0.1234	0.1692	1.208	5.70	0.90	0.72	0.74
Vout>45	0.2699	0.0893	0.1426	1.199	5.60	1.10	0.80	0.82

TABLE II GAIN SCHEDULE PARAMETERS UNDER VARIOUS VOLTAGE CONDITIONS

Output Voltage Range	Controller Parameters			Identified Plant Parameters			Input Value	
	Kp	Ki	w	K	T	L	Initial	Final
0<Vout≤20	0.9123	0.2384	0.2120	0.94	5.60	0.70	0.01	0.06
20<Vout≤30	0.7386	0.1930	0.2120	1.16	5.60	0.70	0.13	0.18
30<Vout≤40	0.2718	0.0746	0.2878	5.47	5.70	0.50	0.36	0.41
Vout>40	0.3387	0.0883	0.2434	3.35	5.70	0.60	0.65	0.70

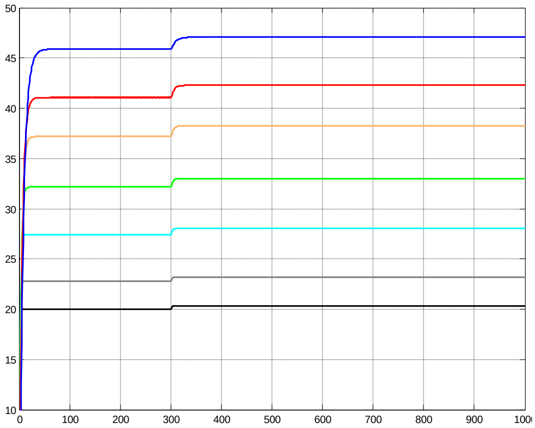


Figure 7 Step response of the open-loop system

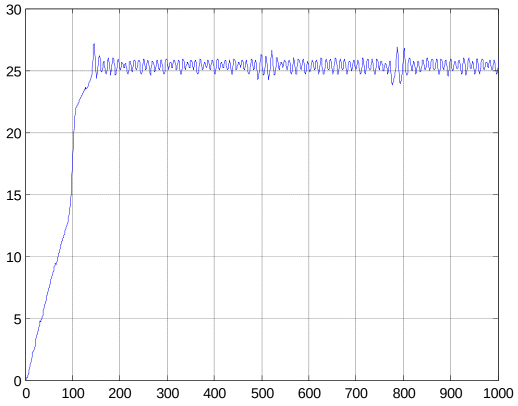


Figure 8 Close-loop System Output (Vref=25V)

Finally simulation results after implementing gain scheduling algorithm based on Table I with close loop PI-Controller is shown in Figure 8, where the reference voltage is set at 25V.

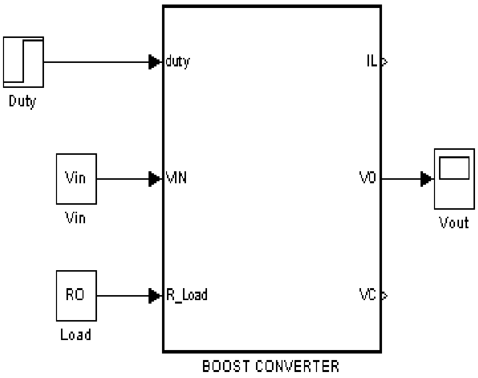


Figure 6 System identification block in MATLAB

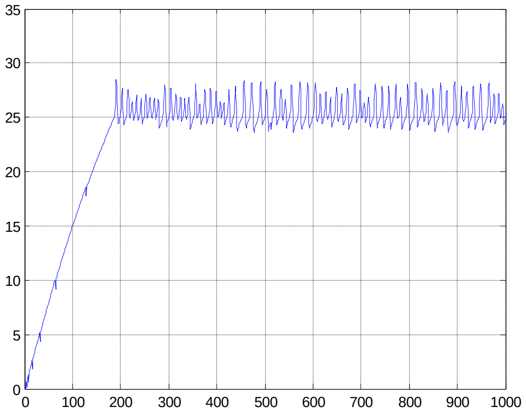


Figure 9 Close-loop System Output (Vref=25V)

On the other hand, if we reduce the level of gain schedule 7 to 4 the transient response and performance of the plant is decreeing. The simulation results of the reduce gain schedule level is tabulated in Table II and plot in the Figure 9.

5. CONCLUSION

A PI gain-scheduled controller based on the plant output is designed and implemented in a DC-DC boost converter control system. A new approach to determine the plant parameters is also presented and illustrated through this controller design. The proposed control scheme has better transient performance than fixed gain or reduces gain schedule levels. The results of MATLAB simulation presented that the gain-scheduled controller increases the output efficiency of the system.

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