TRANSIENT RESPONSE ANALYSIS FOR DC-DC BOOST CONVERTER

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ABSTRACT

DC-DC Boost Converter and Hybrid Posicast Controller is developed and simulated using MATLAB Simulink software. DC-DC Boost converter has a very high overshoot and a very high settling time which produce oscillated output response. In order to overcome this weakness, Hybrid Posicast Controller is used in order to regulate the output voltage to a desire value. Hybrid Posicast Controller operated within the feedback loop of the system. Transfer function of DC-DC Boost Converter are derived and Posicast elements of δ and T_d can be calculated directly from the transfer function. Single gain, K is used in order to eliminate the overshoot and minimize the settling time. Simulation results show that Hybrid Posicast Controller effectively regulate the output voltage to a desire value even though load resistance and duty cycle have been changed with a various values. DC-DC Boost Converter using Posicast Controller has an excellent performance to overcome unregulated input voltage, eliminate overshoot and minimize the settling time.

ABSTRACT

DC-DC Boost Converter dan *Hybrid Posicast Controller* dibina dan disimulasikan dengan menggunakan perisian MATLAB Simulink. *DC-DC Boost Converter* mempunyai lajakan isyarat yang sangat tinggi dan mengambil masa yang sangat lama untuk mencapai takat stabil yang mana keadaan ini menghasilkan sambutan keluaran yang berayun. Untuk mengatasi kelemahan ini, *Hybrid Posicast Controller* digunakan untuk menstabilkan voltan keluaran kepada nilai yang dikehendaki. *Hybrid Posicast Controller* beroperasi di dalam gelung tertutup sistem. Unsur-unsur Posicast, δ dan T_d boleh dikira terus dari rangkap pindah *DC-DC Boost Converter*. *Single gain*, K digunakan untuk menghapuskan lajakan isyarat dan meminimumkan masa untuk mencapai takat stabil. Keputusan simulasi menunjukkan bahawa *Hybrid Posicast Controller* berkesan untuk menstabilkan voltan keluaran kepada nilai yang dikehendaki walaupun rintangan beban dan kitar kerja telah berubah dengan pelbagai nilai. *DC-DC Boost Converter* menggunakan *Hybrid Posicast Controller* mempunyai prestasi yang sangat baik untuk menangani voltan masukan yang berubah-ubah, menghapuskan lajakan isyarat dan meminimumkan masa untuk mencapai takat stabil.

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CHAPTER 1

INTRODUCTION

Converters required power electronic circuit in order to match the voltage and current requirements of the load to those of the source. Converters are classified by the relationship between input and output (Hart D. W., 2011).

DC-DC converters are used to convert the unregulated DC input to a controlled DC output at a desire voltage output. It classified as a regulator as it useful when a load requires a specified dc voltage or current but the source is at a different or unregulated dc value. It used widely in dc motor drive application (Quansheng Xu, 2005) and it provides smooth acceleration control, high efficiency and fast dynamic response (Fathi S. J., 2011).

In order to compensate any disturbance or error in the converter system, control system has been designed. Control design for any system involves a mathematical description of the relation among inputs to the process, state variables, and output. This control parameters will be presented in the form of mathematical equations which describe behavior of the system is called model of the system.

The advantages/primary reasons of building control system are to get power amplification, remote control, convenience of input form and compensation for disturbance (Nise N. S., 2000).

1.1 Problem statement

DC-DC Boost converter (DC-DC BC) also known as a regulator was a designed power electronics circuit which capable to regulate unregulated dc input to a desire voltage output. The dynamics of the DC-DC converter can be described as nonlinear and lightly damped (Feng, Q. et al., 2002). The converter is nonlinear lightly damped dynamics, which are described as a function of load parameters, duty cycle and make the control design difficult and challenging one (Krauter, S. C. W., 2006). Boost converter has a limitation as it has a characteristic of overshoot in the step response of lightly damped systems.

PWM signal with high switching is used in order to minimize output voltage ripple and Hybrid Posicast Controller (HPC) to overcome DC-DC BC limitation as HPC able to produce a good transient state performance.

1.2 Project objectives

The objectives of this project are:

i) To develop ideal DC-DC BC in Continuous Conduction Mode (CCM).
ii) To develop HPC.
iii) To analyze transient response of DC-DC BC.

1.3 Project scope

The scope of this project is to develop ideal (without parasitic elements) DC-DC BC in CCM and then develop HPC as a controller. DC-DC BC using HPC will be simulate using MATLAB Simulink software in order to analyze transient response characteristics.

CHAPTER 2

LITERATUR REVIEW

2.1 Previous research

There are many previous researched focusing in DC-DC converters such as DC-DC BC. And, in order to get maximum performance and stability of designed system, various type of controller have been used. Table 2.1 shows DC-DC BC using different types of converter.

Table 2.1: Boost converter using different types of controller.

No.	Author & Title	Contents
1.	Liping Guo et al. (2005). Comparative Evaluation of Linear PID and Fuzzy Control for a Boost Converter. *IEEE, pp.555-560*.	Design and implementation issue, and experimental results for the linear PID and PI controller and fuzzy controller were compared. The design of linear PID and PI controllers and fuzzy controllers requires quite different procedures. Design of the fuzzy controller does not require a mathematical model, while a small signal model is necessary for the design of PID controllers using frequency response method. **Pros:** Fuzzy controller is able to achieve faster transient response, less overshoot, better rejection to disturbances and less dependence on the operating point. **Cons:** Implementation of fuzzy controllers demands more computation power and memory than implementation of linear controllers.

Table 2.1 (continued)

No.	Author & Title	Contents
2.	Kapat, S. (2011). Formulation of PID Control for DC-DC Converters Based on Capacitor Current: A Geometric Context. *IEEE, pp. 1-21*.	Formulation of a PID controller is introduced to replace the output voltage derivative with information about the capacitor current, thus reducing noise injection. This formulation preserves the fundamental principle of a PID controller and incorporates a load current feed-forward as well as inductor current dynamics. **Pros:** The proposed formulation preserves the basic principle of a PID controller and formulation of a conventional PID controller is introduced to replace the output voltage derivative with information about the capacitor current, thus reducing noise injection. **Cons:** Derivative gain never changes, even at switching transition. Therefore, impulse noise injection due the derivative term of a conventional PID control is avoided using the proposed PID formulation (Boost converter).
3.	Kumar, K. R. & Jeevananthan, S. Design of a Hybrid Posicast Control for a DC-DC Boost Converter Operated in Continuous Conduction Mode. *Proceedings of ICETECT*. IEEE. 2011. pp. 240-248.	Hybrid Posicast Controller (HPC) for a DC-DC Boost Converter (BC) operated in Continuous Conduction Mode (CCM). A HPC is a feed-forward compensator, which eliminates the peak overshoot in the step response of lightly damped systems. **Pros:** to reduce this undesirable sensitivity of system and independent of computational delay and does not require any of the additional modifications.
4.	Feng, Qi et al. (2003). Digital Control of a Boost Converter using Posicast. *IEEE*. pp. 990-995.	Analysis, design, simulation and DSP-based implementation of a digital controller using a Posicast element are presented for the boost converter. **Pros:** Superior damping qualities, while reducing the sensitivity. The Posicast elements Td and δ can be straightforwardly computed from the dynamics of the boost converter. A simple integral compensator with a single gain K is used with the Posicast element to ensure the

Table 2.1 (continued)

No.	Author & Title	Contents
		proper steady state response.
5.	Sugiki, A. & Furuta, K. (2006). Posicast Control Design for Partameter-Uncertain Plants. *Proceedings of the 45th IEEE Conference on Decision & Control*. San Diego: IEEE. pp. 3192-3197.	Using Internal Model Control and Model Reference Control structures of Posicast-based control scheme applicable to parameter uncertain plants. **Pros**: Posicast IMC structure is simple and useful as a base system for more advanced studies on Posicast control. **Cons:** Theoretical investigations including stability analysis still need more investigation.

2.2 Power electronics circuit

Power electronics circuits convert electrical power from one form to another using electronic devices (Hart D. W., 2011). Power electronics circuit convert one type or level of a voltage or current waveform to another and hence are called converters. Basically, converter is an interface between a source (input) and a load (load).

In order to control an output voltage or current in power electronics circuit, semiconductor devices is used as a switches device. High frequency switching capability assures improvement of switching efficiency and performance of electrical devices.

2.3 Control systems

2.3.1 Overview of control systems

A control system consists of subsystems and processes (or plants) assembled for the purpose of controlling the outputs of the processes (Nise N. S., 2000). With existing of control systems, most of difficulty in controlling a process has been overcome. For example lifting heavy objects using forklift and move a huge antennas to desire grid with highly precision positioning.

There are four primary reasons of control design namely power amplification, remote control, convenience of input form and compensation for disturbances (Nise N. S., 2000).

Power amplification is needed as sometimes a control system needs to produce certain level of power or normally called power gain, in order to activate a system such as rotate an antennas which requires large amount of power.

Remote control basically used in a robot control technology. It compensates human disabilities such as using a remote control robot for underwater/deep sea scientific research.

Control systems can also be used to provide convenience by changing the form of the input (Nise N. S., 2000). For example, in forklift operation, the input is a weight detector and the output is a torque (motor).

Control systems have a capability to compensate for disturbances. That mean, even there are disturbance of input signal, a process or a system still able to produce a correct output. In a process of positioning an antenna for example, if antenna position changes because of a wind forces, the system should be able to detect the disturbance and correct the antenna's position.

The objectives of a control system can be achieved by employing two possible control strategies (Hishamuddin Jamaluddin *et al.*, 2011). These control strategies are open-loop control system (feedforward control system) and close-loop control system (feedback control system). Figure 2.1 and Figure 2.2 shows open-loop control system and close-loop control system respectively.

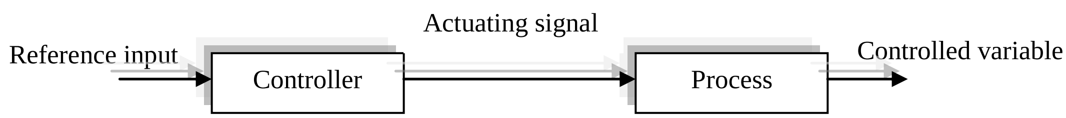


Figure 2.1: An open-loop control system.

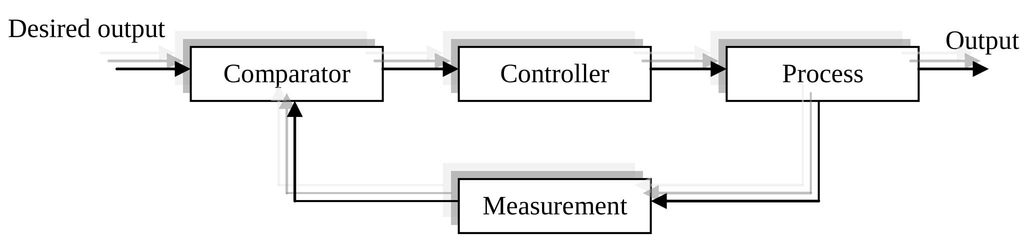


Figure 2.2: Close-loop control system.

2.3.2 Elements used in control systems

There are many elements in control systems that need to be considered when develop and analyze a process. Thus, an efficient and reliable system can be produce together with desire control method.

In order to analyze DC-DC BC using HPC, three major elements need to considered,

i) Transfer function.
ii) Control system block diagram.
iii) Time domain response.

2.3.2.1 Transfer function 0f control systems

Transfer function is defined as a ratio output to the input with all its initial condition is considered zero. Transfer function parameters as in Table 2.2.

Table 2.2: Transfer function parameters.

Parameter	Function
C(s)	Input signal
R(s)	Output signal
Z_m	✓ Zeroes ✓ Is the point that make the transfer function is zero if the value of Z = 0 and P has a value.

Table 2.2 (Continued)

Parameter	Function
	✓ Zero equation can be obtained from the numerator equation.
P_n	✓ Poles ✓ Are the points that make the transfer function has a value of infinity if Z = P = 0. ✓ Poles equation can be obtained from denumerator equation.

<u>Note:</u>

Z_m and P_n consists of real and imaginary number. For example, $Z_m = a + jb$.

Thus,

$$\frac{C(s)}{R(s)} = \frac{(S+Z_1)(S+Z_2)(S+Z_3)...(S+Z_m)}{(S+P_1)(S+P_2)(S+P_3)...(S+P_m)} \quad \begin{matrix} \leftarrow \text{Numerator} \\ \leftarrow \text{Denumerator} \end{matrix} \qquad (2.1)$$

2.3.2.2 Block diagram of control systems

Block diagram is component of transfer function (in one direction) to show the relationship between input and output. A subsystem is represented as a block with an input, output and transfer function as shown in Figure 2.3. When multiple subsystem are connected, a few more schematic elements must be added to the block diagram.

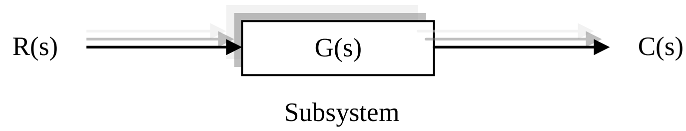


Figure 2.3: Block system.

From Figure 2.3, G(s) = transfer function forward path or gain. Therefore, transfer function of a block diagram is given as $C(s) = G(s)R(s)$.

There are three basic form of block diagram arrangement, namely cascade form, parallel form and feedback form, as shown in Figure 2.4, Figure 2.5 and Figure 2.6, and each one of it can be simplified into a simple representation and produced a its own transfer function as shown in Figure 2.7, Figure 2.8 and Figure 2.9.

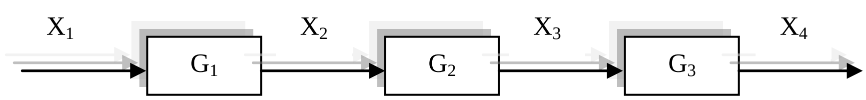


Figure 2.4: Cascade form.

Simplified cascade block diagram,

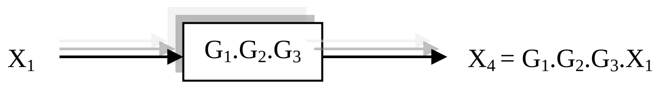


Figure 2.5: Simplified cascade form.

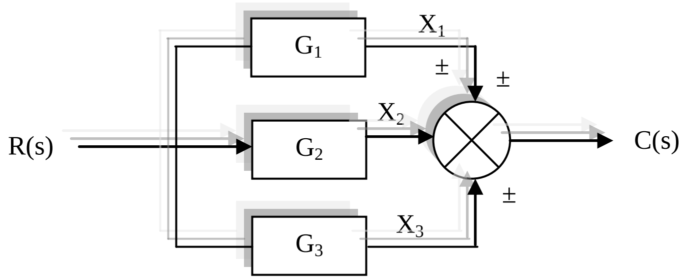


Figure 2.6: Parallel form.

Simplified parallel block diagram,

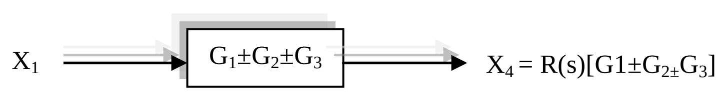


Figure 2.7: Simplified parallel form.

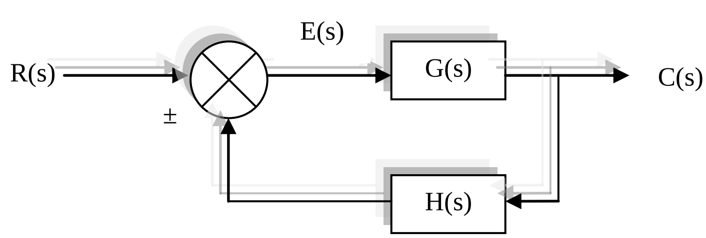


Figure 2.8: Feedback form.

Simplified feedback block diagram,

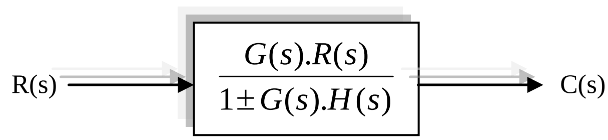


Figure 2.9: Simplified feedback form.

For feedback block diagram, a close-loop transfer function is given as,

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 \pm G(s)H(s)}$$

2.3.2.3 Time domain response

Control system are dynamic as it capable to response to an input by undergoing a transient respond before reaching steady-state response that generally resembles the input. Transient response is occurs when there are gradual change of a signal before the steady-state response. Steady-state response occurs after the transient response, which it is approximation to the desired response. Meanwhile, the differences between input and output are called steady-state error. Figure 2.10 shows a dynamic of control system response.

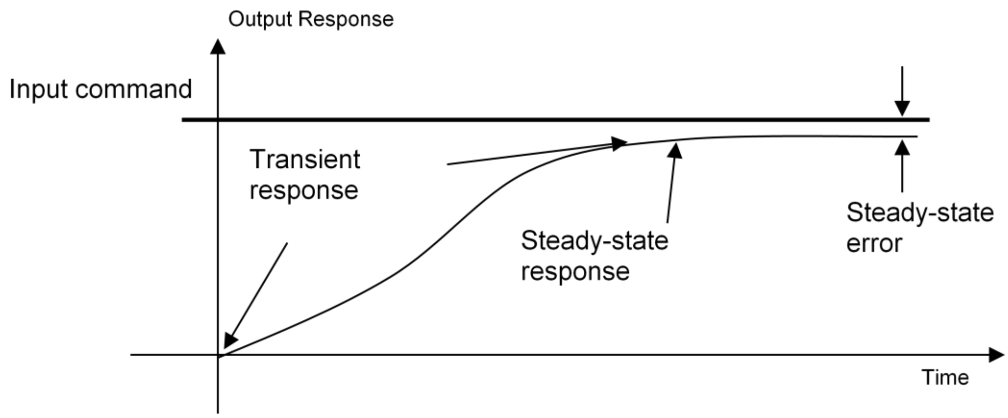


Figure 2.10: Time domain response.

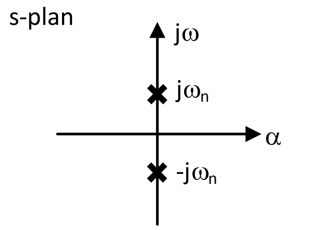
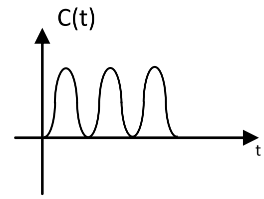
For any control systems design, final assessment of performance should based on transient response, $C_t(t)$, and steady state response, $C_{ss}(t)$. The whole system should presented as, $C(t) = C_t(t) + C_{ss}(t)$.

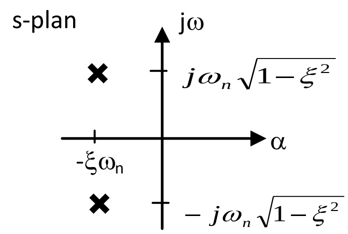
Response characteristic and system configuration are depend on input, output, transient response, steady-state response and steady-state error as shown in Figure 2.11. Second order system normally used to analyze a system because it offer a wide range of responses, as shown in Table 2.3.

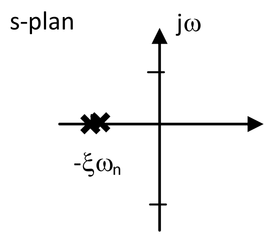
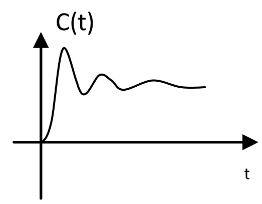
Underdamped second order response is a response that normally found in the develop systems. Studies should be done to ensure that the system used is effective and efficient, as shown in Figure 2.12.

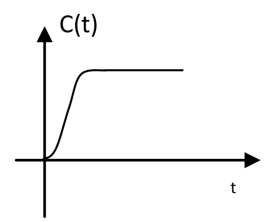
Table 2.3: Second order response.

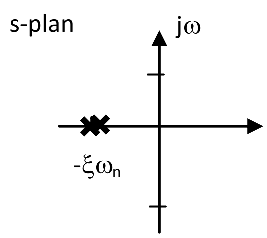
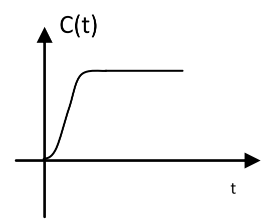
<table>
<tr><th>ξ</th><th>Poles</th><th>Step Response</th></tr>
<tr><td>ξ = 0

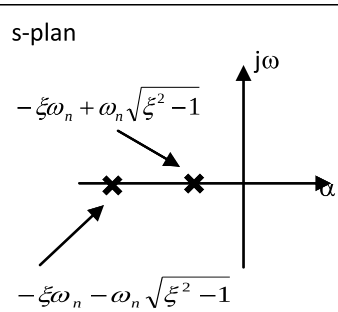
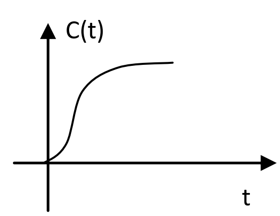
Undamped</td><td>
</td><td>
</td></tr>
<tr><td>0< ξ < 1

Underdamped</td><td>


</td><td>


</td></tr>
<tr><td>ξ = 1

Critically damped</td><td>
</td><td>
</td></tr>
<tr><td>ξ > 1

Overdamped</td><td>
</td><td>
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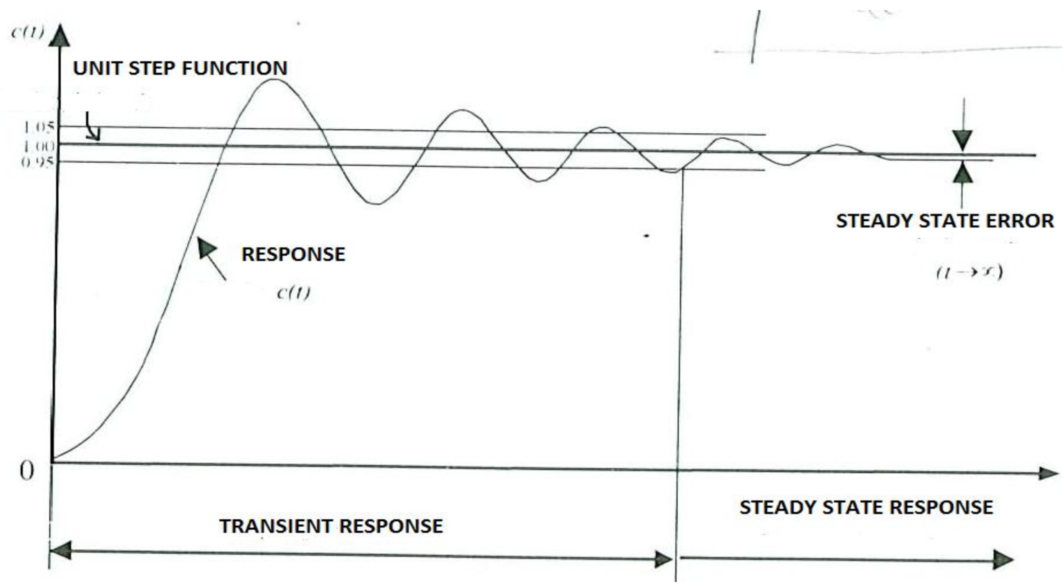

Figure 2.11: Second order response with unit step function input.

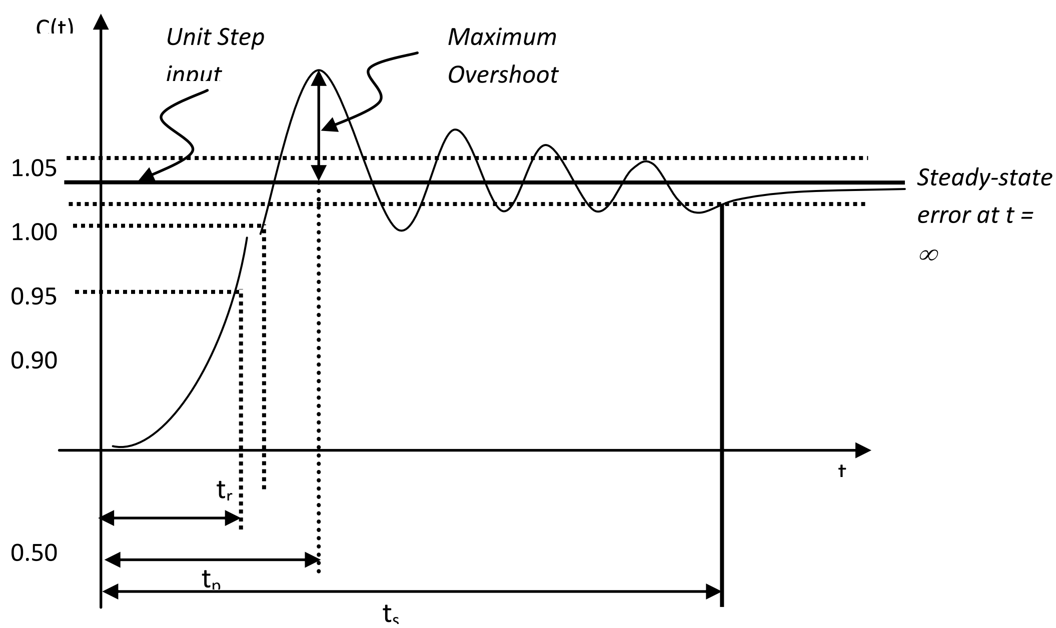

Figure 2.12: Underdamped second order response.

Specification of the performance characteristics for a second order control system with underdamped response can be analyze based on overshoot, delay time, rise time, settling time and peak time, as shown in Table 2.4.

Table 2.4: Parameters used to analyze performance characteristics.

Specification	Description	Equation
Overshoot	The amount that the waveform overshoots the steady state value.	$OS = \left[e^{\frac{-\pi\xi}{\sqrt{1-\xi^2}}} \right]$ and $\xi = \left[\frac{-\ln(OS)}{\sqrt{\pi^2 + \ln^2(OS)}} \right]$
Delay time	The time required for the response to achieve 50% from the final value.	$t_d = \frac{1+0.6\xi+0.15\xi^2}{\omega_n}$
Rise time	The time required for the response rise from 10% to 90% of the final value.	$t_r = \frac{\pi-\theta}{\omega_n\sqrt{1-\xi^2}}$ where, $\theta = \tan^{-1}\left[\frac{\sqrt{1-\xi^2}}{\xi} \right]$

Table 2.4 (Continued)

Settling time	The time required for the transient's damped oscillations to reach and stay $\pm 2\%$ of the steady state value.	$t_s \frac{4}{\omega_n \xi}$ (for $\pm 2\%$) and $t_s = \frac{3}{\omega_n \xi}$ (for $\pm 4\%$)
Peak time	The time required to reach the first or maximum peak.	$t_p = \frac{\pi}{\omega_n \sqrt{1-\xi^2}}$

2.4 Converters

Converters serve as an interface between the source and load (Nise N. S., 2000) as shown in Figure 2.13. It convert one type or level of a voltage or current waveform to another and classified by the relationship between input signal and output signal as shown in Table 2.5.

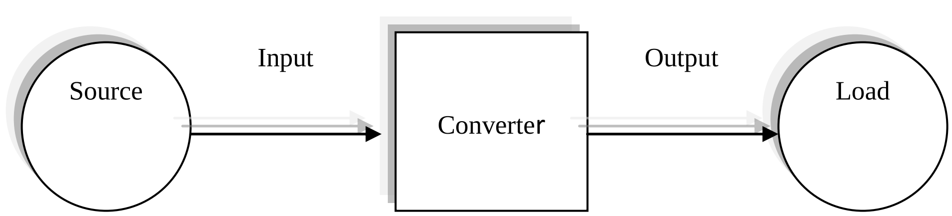

Figure 2.13: Basic converter system.

Converter circuits capable to operate in different mode, depending on electronic circuit used, high frequency switching semiconductor and applied control system. Thus, converters are capable to operate in multiple stages in a process with different type of converter involve as shown in Figure 2.14.

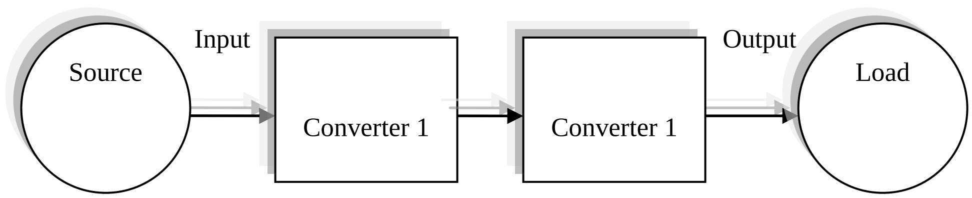

Figure 2.14: Two converters are used in a multistep process.

(Nise N. S., 2000)

Table 2.5: Classifications of converters.

Type of converter	Functions
ac input/dc output	The ac/dc converter that produces a dc output from an ac input. It classified as a rectifier.
dc input/ac output	The dc/ac converter produces an ac output from a dc input. It classified as an inverter.
dc input/dc output	The dc/dc converter produces a dc output from a dc a dc input. It classified as a regulator.
ac input/ac output	The ac/ac converter produces an ac output from an ac input. Used to change the level and/or frequency of an ac signal.

2.5 DC-DC converter

2.5.1 General overview of DC-DC converter

DC-DC converters are used to convert the unregulated DC input to a controlled DC output at a desire voltage output. It classified as a regulator as it useful when a load requires a specified dc voltage or current but the source is at a different or unregulated dc value. General DC-DC converter block diagram shown in figure 2.15.

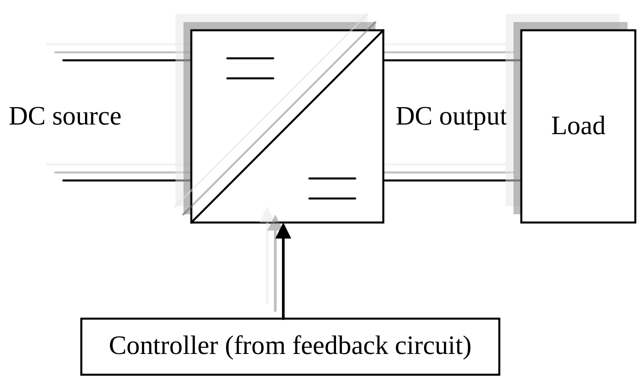

Figure 2.15: General DC-DC converter block diagram.

DC-DC converters include buck converters, boost converters, buck-boost converters, Cuk converters and full-bridge converters (Liping Guo, 2006). The DC-DC converter is considered as the heart of the power supply, thus it will affect the overall performance of the power supply system (Fathi S. J., 2011).

Switched DC-DC converters offer a method to increase or decrease an output voltage depend on application or system. DC-DC converters may be operated in two modes, according to the current in its main magnetic component, inductor. The current fluctuates but never goes down to zero is called Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM) occur when the current fluctuates during the cycle, going down to zero at or before the end of each cycle.

Energy is periodically stored into and released from a magnetic field in an inductor. Usually, this is applied to control the output voltage so that the output voltage remains constant even though input voltages keep changing. There are two general categories of DC-DC converters that is non-isolated DC-DC converter (Buck, Boost, Buck-Boost) and isolated DC-DC converter (Flyback, Forward, Push-Pull, Full-Bridge, Half-Bridge).

Non-isolated DC-DC converter were used when the input to these converters is often an unregulated DC voltage, which is obtained by rectifying the line voltage, and therefore it will fluctuate due to changes in the line voltage magnitude. Switched-mode DC-DC converters are used to convert the unregulated DC input to a controlled DC output at a desired voltage level (Emadi, A. et al., 2009).

Isolated DC-DC converter, full-bridge converter and half-bridge converter are derived from the step-down converter. Flyback converters are derived from the buck-boost converters. Forward converters and push-pull converters are derived from the step-down converters with isolation.

2.5.2 DC-DC converter switching

There are two switching condition that need to be applied, that is when ON and OFF as shown in figure 2.16.

When ON,
Output voltage is the same as the input voltage and the voltage across the switch is 0V.

When OFF,

Output voltage = 0V and current through the switch = 0A. In ideal condition, power loss = 0W since output power equal to input power.

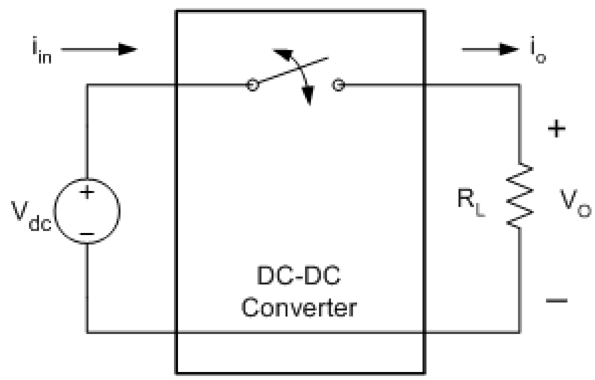

Figure 2.16: Switching ON and OFF of DC-DC converter.

ON and OFF resulting in pulse as shown in Figure 2.17 where switching period, T , is a one full cycle (360°) of a waveform ranging from t_{ON} to t_{OFF} pulse.

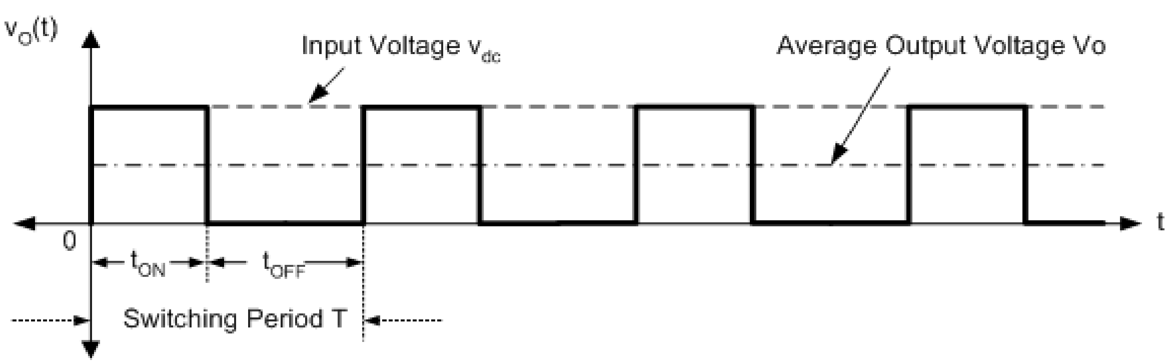

Figure 2.17: t_{ON} and t_{OFF} pulse.

Thus, duty cycle, D, which depends on t_{ON} and range of duty cycle is $0 < D < 1$. If switching frequency, f_s, is given,

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} = t_{on} f_s \tag{2.2}$$

Average DC output voltage,

$$\overline{V}_0 = \frac{1}{T}\int_0^T v_o(t)\,dt = \frac{1}{T}\int_0^{DT} V_i\,dt = V_i D \tag{2.3}$$

There are two modes of operation in DC-DC converters based on inductor current, i_L,

i) Continuous Conduction Mode (CCM), when $i_L > 0$.

ii) Discontinuous Conduction Mode (DCM) when i_L goes to 0 and stays at 0 for some time.

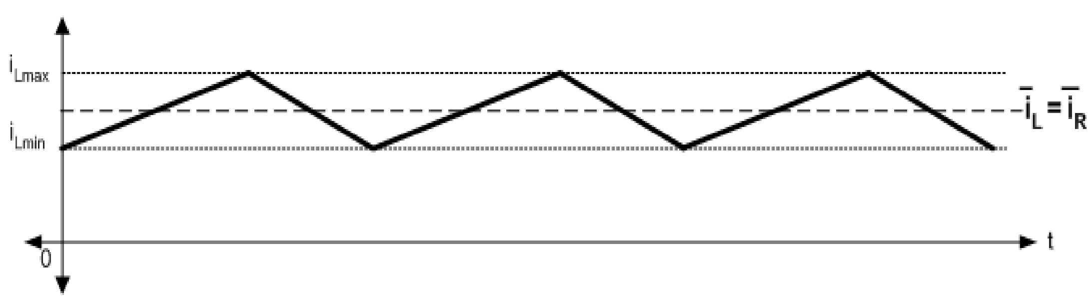

Figure 2.18: Continuous Conduction Mode.

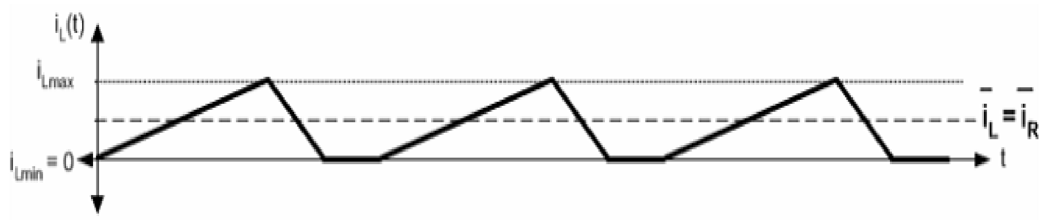

Figure 2.19: Discontinuous Conduction Mode.

In steady state and periodic operation, inductor charges and discharges with V_{avg} DC voltage across inductor in one period = 0. Thus, inductor looks like a short circuit as shown in Figure 2.20.

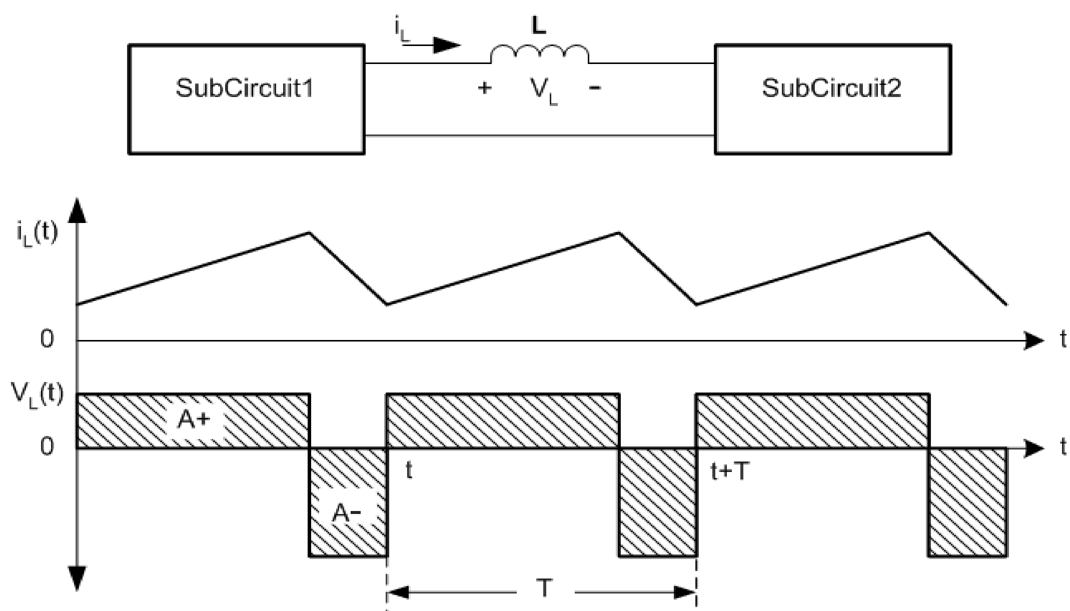

Figure 2.20: i_L and V_L when inductor looks like short circuit.

2.6 Boost converter

2.6.1 Boost converter overview

DC-DC converter is called Boost converter when average output voltage is higher than input voltage. Power stage also consists of a switch, diode and inductor. Boost converter as shown in Figure 2.21, converts an unregulated source voltage, V_s, into a higher regulated load voltage, V_o.

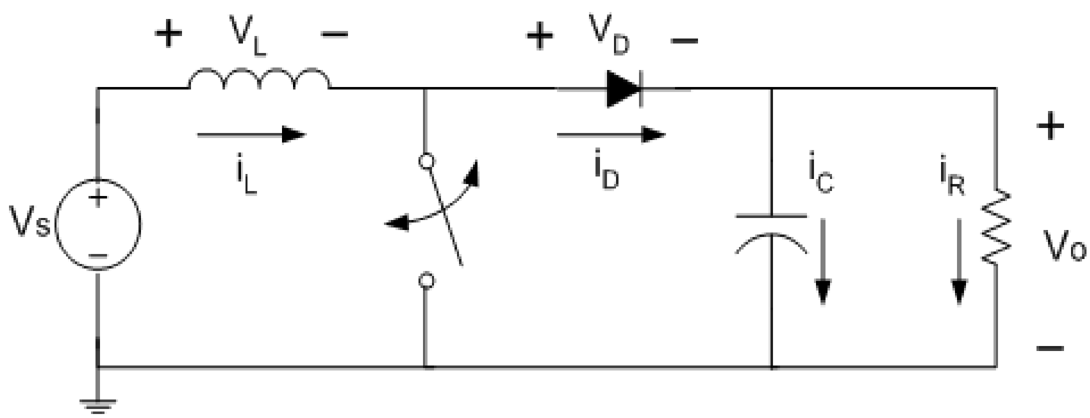

Figure 2.21: Boost converter circuit.

When the switch is closed, as shown in Figure 2.22, the diode is reverse biased and the source voltage charge the inductor. Input is disconnected from the output, therefore no energy flows from input to output. The capacitor discharges into the load.

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