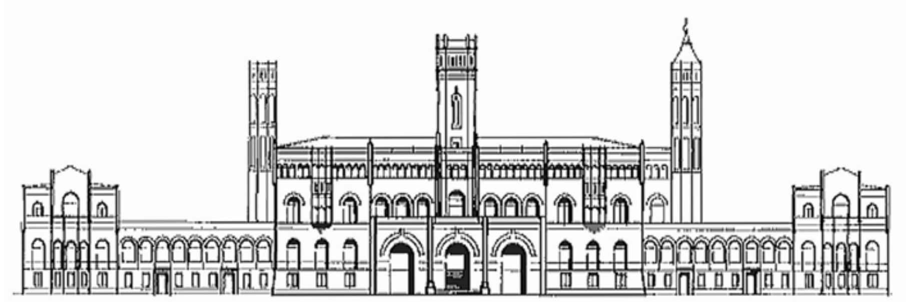

Design and Control of a Programmable Voltage Source for a Power Semiconductor Switching Test Set Up

Master thesis

of

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Hereby I, Bijan Amani Komaei, certify that I have written this thesis independently and used no words and ideas from another person, otherwise I announced it as reference.

Hannover, November 2012

Abstract

In many cases it is necessary to change a DC voltage. DC-DC converters are proposed for this reason. Flyback DC-DC converter is one type which can increase and decrease DC voltage. The main advantage of this converter is isolation between primary and secondary side. In our case the aim is designing a DC-DC voltage to regulate output voltage between 0 and 800V with 1% error. Output current is limited to 80mA. This converter is used as a programmable voltage source for semiconductor tests.

In this thesis flyback state space equations will be describe for CCM and DCM. For DCM reduced order equations will be used. After that according to these equations a controller will be designed. Due to two operating mode two controllers is required. Obviously we need a mode detector to detect operating mode and apply appropriate duty cycle to PWM generator.

Finally simulations will be run in order to check the controller. This will be shown that controller has weakness and it should be compensated.

Contents

Symbols and Abbreviations

Abbreviations:

CCM	⇔	Continuous Conduction or Current Mode
DCM	⇔	Discontinuous Conduction or Current Mode
LVR	⇔	Linear Voltage Regulator
SMPS	⇔	Switch Mode Power Supply
RHPZ	⇔	Right Half Plane Zero
SSA	⇔	State Space Averaging
RMS	⇔	Root Mean Square

Symbols:

V_g	Input or source voltage
L	Magnetizing inductance
C	Output capacitor
R	Load resistance
d, D	Duty cycle
v_c, V_c	Output voltage
i_c	Capacitor current
i_{load}	Additional current source
n	Transformer turn ratio $(\frac{n_2}{n_1})$
i_s	Switch current
x	State variable
V_{ref}	Reference voltage
I_{ref}, I_L^*	Reference current

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1 Introduction

Changing DC voltage is necessary as well as changing AC voltage. For AC voltage, it is very simple because a normal transformer can be used for this purpose. But, what can we do for DC voltage? The simplest method is using a Linear Voltage Regulator (LVR). But this simple method has some serious problems. The efficiency of LVR is low, due to dissipating the difference voltage between input voltage and regulated voltage. Also regulated voltage is not desirable enough. Therefore, finally scientists invented Switch Mode Power Supply (SMPS). SMPS regulates output voltage based on switching operation. Therefore, more reliable voltage is provided. Also in comparison with LVR, SMPS has fewer losses; it means efficiency of SMPS is much higher than LVR.

The aim of this project is to design a programmable voltage source with minimum size. This power supply is a programmable voltage source that will be used to test power electronics devices in laboratory. A flyback converter is used for this reason to regulate output voltage. The 230V AC grid voltage is rectified and fed the DC-DC converter. The output voltage can change between 0 and 800V. Maximum value of output current is 80mA. For having a small SMPS it is necessary to have a small transformer.

Now, assume that the circuit is designed. The next step is designing controller. First of all a simple controller was selected. In this control method output voltage was sampled and compared with reference voltage. Based on the normalized error duty cycle was set by controller. This method has acceptable behavior but it could not regulate output voltage correctly in low voltages. After that a linear controller was used to control behavior of system, but due to nonlinear behavior of flyback converter, especially in Discontinues Conduction Mode or Discontinues Current Mode (DCM), linear controller did not have acceptable performance. Another option was nonlinear controller. It should be mentioned that there were many nonlinear controlling methods which could be used, but due to the fact that simplicity of controller is important for implementation and construction, a simple controlling method was selected.

There is a question which should be answered. Why flyback converter was selected? It is clear that buck-boost converter can increase and decrease voltage as well as flyback converter. The main disadvantage of buck-boost converter is that, it has a discontinuous input current. Mathematically, it means higher harmonics in Fourier transform of input current which causes more complicated input filter. The transformer in flyback converter gives us this chance to change the output voltage by factor of “n”, which is transformer turn ratio. Also transformer has another advantage which is isolation between input and output. Latter is the most important advantage of flyback converter. Additionally it is simply possible to have more than one output in flyback converter, by adding more output windings. Obviously flyback converter has some problems, for example:

1. High output and input ripple currents
2. Right half plane zero

Nevertheless, it is possible to use buck-boost converter instead of flyback converter.

In the next chapters, these topics are explained. Chapter 2 describes flyback converter behavior. Some basic subjects about how flyback converter works will be presented. After that equations of flyback converter will be introduced in detail. Large signal, small signal and state space equations of flyback converter will be derived. After that, it is possible to find transfer function of flyback converter. Based on transfer function a very interesting topic will be discussed which is Right Half-Plane Zero (RHPZ). At the end of this chapter it is possible to answer these questions:

1. What is flyback converter and how does it work?
2. What are small signal and large signal equations of flyback converter?
3. What is RHPZ and why it is important?
4. Why transfer function of flyback converter in DCM is a little bit strange?

Chapter 3 describes the approach to derive value of elements which are used in flyback converter. The main elements such as switch, transformer, diode and capacitor, after finishing this chapter will get their values.

Now, the under control system is identified. Next step is designing controller. This will be done in chapter 4. This chapter will propose linear and nonlinear control methods which are used to regulate output voltage. Due to operation of flyback converter in Continues Conduction Mode or Continues Current Mode (CCM) and DCM, and because behavior of flyback converter is entirely different in CCM and DCM; therefore, different types of controller should be used for each one. Additional part is necessary to find in which mode of operation the converter is. Finally these questions are answered:

1. Which types of controller are used?
2. Does linear controller have acceptable performance?
3. How does mode tracker work?

Chapter 5 proposes simulation results. Most important block and waveforms will be shown here. At the end; summary, conclusions and future work form the last chapter.

2 Flyback Converter

This chapter will describe the flyback converter. At the beginning, the topology of converter will be described. After that, large signal, small signal and transfer function of flyback converter will be derived.

One of the most important advantages of flyback converter, as mentioned earlier, is isolation between ground of primary and secondary side. Most general advantages and disadvantages of flyback converter are listed in Table 2.1 [1].

Table 2.1: Flyback converter advantages and disadvantages

Advantages	Disadvantages
1. Input and output grounds are isolated 2. Voltage Step-down or Step-up by duty cycle and turns ratio 3. Multiple outputs are easy to implement 4. Does not need a separate output inductor 5. Best suited for lower power levels	1. High output ripple current 2. High input ripple current 3. Loop bandwidth may be limited by the RHPZ

2.1 Flyback Converter Topology

Figure 2.1 shows a DC-DC flyback converter. The circuit is formed by a switch[1], transformer, diode and output capacitor. All DC-DC converters can operate in 2 modes: CCM and DCM. Behavior of converter depends on its operation mode. But there are same rules for both modes:

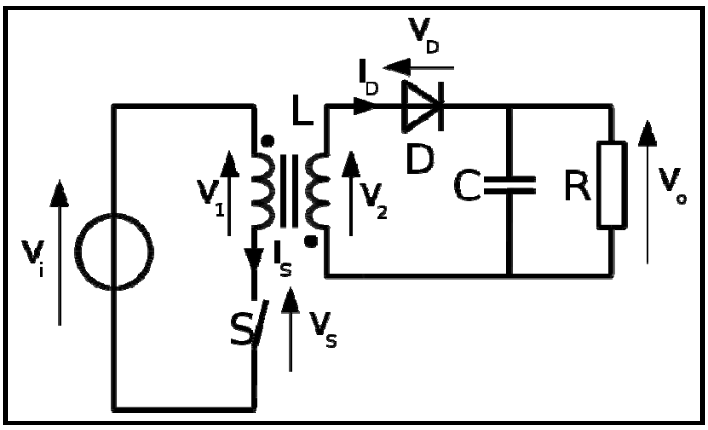

Figure 2.1: Flyback converter

1- Depending on its current and reverse bias voltage, different type of power electronics switches can be selected.

1. If the switch is on, the diode is off and vice versa.
2. If the switch is on, regarding to the construction of circuit, the transformer primary winding will be connected to the DC voltage source. As a result, transformer will be charged. Because diode is off, capacitor has to provide energy for load, and consequently capacitor will discharge.
3. If the diode is on, the switch is off. Therefore, stored energy in the transformer will be transferred to capacitor and load, consequently capacitor will charge.

There is one important point in flyback converter. The transformer is a place to store energy. It is a path for energy. It stores energy for a while, and then transfer energy to the load side. Regarding to this fact it is possible to explain CCM[1] and DCM[2].

2.2 Modes of Operation

Generally all DC-DC converters have two modes of operation: CCM and DCM. In CCM the magnetic energy or the current through main inductor does not reach zero at the end of each switching period. It means that at the beginning of each switching period initial condition of inductor current is not zero: $i_L\left(t = nT_s\right) \neq 0$.

But in DCM, current through main inductor reaches zero before finishing switching period. So, initial condition of inductor current is zero.

$$i_L\left(nT_S - \varepsilon < t < nT_s\right) = 0 \qquad 0 < \varepsilon < T_S$$

Here, concentration is just on flyback converter. Each mode has its advantages and disadvantages:

- In CCM transfer function has RHPZ[3] (or non-minimum phase zero). Positive zeros can cause initial undershoot, zero crossings and overshoot. Also it can limit bandwidth of system, which means lower loop crossover frequency. It will be shown that RHPZ can make some instability problems and some resonance around specific frequencies [2].
- In DCM, the input to output and control to output transfer functions are first order transfer function which makes the controller design procedure much easier.
- In DCM converter's conversion ratio depends on the load.

1- Continuous Conduction Mode

2- Discontinuous Conduction Mode

3- Right-Zero-Half-Plane

- Ringing[1] occurs in DCM. When the inductor current reaches zero, the voltage drop over inductor must reach zero immediately. Due to some inductive and capacitive parasitic elements, ringing phenomena could occur. Also it can create EMI in the input or output.

2.3 Flyback Converter Equations

In this section flyback equations in CCM and DCM will be derived. The main idea is based on the concept which is used in "Fundamental of Power Electronics" by Erickson. But, some changes have been done. Let's just go through the derivation! Also unlike most references, which begin with steady state equations and after that derive small signal equations; this part is begun directly with large signal and small signal equations and after that steady state behavior has been mentioned.

2.3.1 Equations in CCM

In this mode each switching period in divided into two subintervals. In first subinterval the switch in on and diode is off and vice versa in second subinterval. There are two energy storage elements, magnetizing inductance of transformer and output capacitor. So the system has two state spaces.

During first subinterval:

$$\left.\begin{aligned} v_L &= v_g \\ i_c &= -\frac{v_c}{R} - i_{load} \end{aligned}\right\} \Rightarrow \begin{bmatrix} L\dfrac{di_L}{dt} \\ C\dfrac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} v_g \\ -\dfrac{v_c}{R} - i_{load} \end{bmatrix} \tag{2.1}$$

During second subinterval:

$$\left.\begin{aligned} v_L &= -\frac{v_c}{n} \\ i_c &= \frac{i_L}{n} - \frac{v_c}{R} - i_{load} \end{aligned}\right\} \Rightarrow \begin{bmatrix} L\dfrac{di_L}{dt} \\ C\dfrac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{v_c}{n} \\ \dfrac{i_L}{n} - \dfrac{v_c}{R} - i_{load} \end{bmatrix} \tag{2.2}$$

In these equations v_g is DC source voltage, n is transformer turn ratio ($n = n_2 / n_1$), i_{load} is additional current source[2] in parallel with R.

1- Simply, ringing is undesired oscillations in voltage or current.

2- This additional source can be used in order to discharge output capacitor faster during DCM, which R has high value.

To derive an equation for both subintervals it is possible to average these equations:

$$\begin{bmatrix} L\dfrac{di_L}{dt} \\ C\dfrac{dv_c}{dt} \end{bmatrix} = d\begin{bmatrix} v_g \\ -\dfrac{v_c}{R} - i_{load} \end{bmatrix} + (1-d)\begin{bmatrix} -\dfrac{v_c}{n} \\ \dfrac{i_L}{n} - \dfrac{v_c}{R} - i_{load} \end{bmatrix} \tag{2.3}$$

Where "d" is duty cycle.

Let's write this equation in state space form:

$$\begin{bmatrix} \dfrac{di_L}{dt} \\ \dfrac{dv_c}{dt} \end{bmatrix} = \begin{pmatrix} 0 & -\dfrac{1-d}{nL} \\ \dfrac{1-d}{nC} & -\dfrac{1}{RC} \end{pmatrix}\begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{pmatrix} \dfrac{d}{L} & 0 \\ 0 & -\dfrac{1}{C} \end{pmatrix}\begin{bmatrix} v_g \\ i_{load} \end{bmatrix} \tag{2.4}$$

$$x = \begin{bmatrix} i_L \\ v_c \end{bmatrix} \qquad u = \begin{bmatrix} v_g \\ i_{load} \end{bmatrix}$$

"x" is state variables and "u" is input vector.

This is averaged large signal equation of flyback in CCM. This equation describes behavior of flyback converter. But it is not useful for designing a linear controller. For such a purpose it is necessary to have a linear model of flyback.

Note: Nonlinearity of this equation is because of "d". Terms like "d*i_L" and "d*v_c" make this equation nonlinear. Keep in mind that "d" is not fixed; it will change by controller. Generally multiplying two variables makes nonlinearity.

Linearizing nonlinear equations can be done with different methods such as Taylor series. Here, it is done with a simple method. Assume that each signal has a DC term and an AC term:

$$x = X + \hat{x} \tag{2.5}$$ [1]

"x" is the main signal, "X" is its DC term and "$\hat{x}$" is small AC term. But with one important condition:

$$\frac{\hat{x}}{X} \ll 1$$

For equation (2.4), "x" is: $v_g, v_c, i_L, d, i_{load}$.

1- Here, "x" is not state variable.

Substituting equation (2.5) into (2.4) yields to small signal equations of flyback converter. Let's do it for one equation. Assume inductor current equation:

$$\frac{di_L}{dt} = \frac{dv_g}{L} - \frac{1-d}{nL} v_c \tag{2.6}$$

Substituting gives:

$$\frac{d\left(I_L + \hat{i}_L\right)}{dt} = \frac{\left(D + \hat{d}\right).\left(V_g + \hat{v}_g\right)}{L} - \frac{1 - \left(D + \hat{d}\right)}{nL}\left(V_c + \hat{v}_c\right) \tag{2.7}$$

Next step is simplification. DC terms are absolutely constant, so their derivative is zero. Also second order terms, which are AC term multiplied by AC term, are negligible. Therefore:

$$\frac{d\hat{i}_L}{dt} = \frac{DV_g + D\hat{v}_g + \hat{d}V_g}{L} - \frac{\left(1-D\right)V_c + \left(1-D\right)\hat{v}_c - \hat{d}V_c}{nL} \tag{2.8}$$

DC terms and AC terms in left-hand side of this equation should be equal to respective terms in the right-hand side. Therefore:

$$0 = nDV_g - \left(1-D\right)V_c \Rightarrow V_c = \frac{nDV_g}{1-D} \tag{2.9}$$

This is output voltage in steady state. And:

$$\frac{d\hat{i}_L}{dt} = \frac{D\hat{v}_g + \hat{d}V_g}{L} + \frac{(D-1)\hat{v}_c + \hat{d}V_c}{nL} \tag{2.10}$$

This equation is small signal equations of inductor current. Same procedure can be done for capacitor voltage. The result is:

$$I_L = \frac{n}{1-D}\left(\frac{V_o}{R} + I_{load}\right) \tag{2.11}$$

$$\frac{d\hat{v}_o}{dt} = \frac{(1-D)\hat{i}_L - \hat{d}I_L}{nC} - \frac{\hat{v}_o}{RC} - \frac{\hat{i}_{load}}{C} \tag{2.12}$$

The operating point is: $V_g, V_c, I_L, D, I_{load}$. These values can be achieved based on steady state equations of flyback converter.

Equations (2.10) and (2.12) describe small signal behavior of flyback converter. In other word, these equations tell us if the system is in specific operating point and a small variation happens in a variable, how other variables change. Also steady state equations can be achieved, if in equation (2.4), $\frac{dx}{dt}$ set to zero.

After finding small signal equations it is easy to find transfer function. There are 2 important transfer functions: duty cycle to inductor current and inductor current to output voltage.

By using Laplace transform and equations (2.10) and (2.12):

$$G_{di}(s) = \frac{\hat{i}_L}{\hat{d}}\Big|_{\hat{v}_g, \hat{i}_{load}=0} = \frac{s\left(nV_g + V_c\right)nRC + n^2V_g + nV_c + (1-D)RI_L}{n^2RLCs^2 + n^2Ls + R(1-D)^2} \tag{2.13}$$

$$G_{iv}(s) = \frac{\hat{v}_c}{\hat{i}_L}\Big|_{\hat{v}_g, \hat{i}_{load}=0} = \frac{-RI_LnLs + R(1-D)\left(V_c + nV_g\right)}{\left(V_c + nV_g\right)nRCs + n\left(V_c + nV_g\right) + RI_L(1-D)} \tag{2.14}$$

Where is the zero of second transfer function? Zeros are roots of numerator, so for second transfer function:

$$-RI_LnLs + R(1-D)\left(V_c + nV_g\right) = 0 \Rightarrow s_z = +\frac{(1-D)\left(V_c + nV_g\right)}{I_LnL} \tag{2.15}$$

This is right half plane zero.

2.3.2 Equations in DCM

Let's begin with subintervals in DCM. DCM has one more subinterval. In this subinterval switch and diode are off. So:

$$1: \begin{cases} L\frac{di_L}{dt} = v_g \\ C\frac{dv_c}{dt} = -\frac{v_c}{R} - i_{load} \end{cases} \quad 2: \begin{cases} L\frac{di_L}{dt} = -\frac{v_c}{n} \\ C\frac{dv_c}{dt} = \frac{i_L}{n} - \frac{v_c}{R} - i_{load} \end{cases} \quad 3: \begin{cases} L\frac{di_L}{dt} = 0 \\ C\frac{dv_c}{dt} = -\frac{v_c}{R} - i_{load} \end{cases} \tag{2.16}$$

In this case:

$$x = \begin{bmatrix} i_L \\ v_c \end{bmatrix} \qquad u = \begin{bmatrix} v_g \\ i_{load} \end{bmatrix}$$

Following same procedure as CCM for DCM yields to: