Advanced Production and Industrial Engineering
R.M. Singari and P.K. Kankar (Eds.)

doi:10.3233/ATDE220784

Small-Signal Analysis and Voltage Mode Controller Design for Active-Clamp Forward Converter

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Abstract. This paper provides circuit analysis of low-side active-clamp forward converter with synchronous rectification which is widely used as an efficient power supply in various applications. With the use of active clamp technique and synchronous rectification techniques, the losses of the converter reduces and efficiency increases but the number of components also increases. A variety of soft-switching strategies are employed in the forward converter to reduce switching and conduction losses, as well as the overall efficiency. Different clamping circuits, including as active clamping and passive clamping circuits, have been used in the forward converter, which has resulted in a significant reduction in the losses of the converter. Additionally, interleaved and cascaded forward converters are employed in a variety of applications. A forward converter with several outputs is employed for a variety of applications.

Keywords. Forward Converter, Active Clamp, Rectification, Voltage controller

1. Introduction

Forward DC-DC converter is an isolated version of buck converter which are widely used in telecommunication, space application and computer applications because of its simple circuit, low ripple voltage and high current carrying capability. Forward DC-DC converter is a buck-derived transformer isolated converter which has a transformer reset capability when the switch is OFF. There are different variations in classical forward converter topology such as single transistor and two transistors. Different soft-switching techniques are used in forward converter which reduces the switching as well as conduction losses [1-4]. Different clamping circuits such as active clamping and passive clamping circuit has been used in forward converter which reduces the losses of the converter significantly. Interleaved and cascaded forward converter are also used for different applications. Multiple output forward converter is used for different applications [5-7].

Performance analysis of input parallel output series (IPOS) modular forward converter has been discussed in [8-10]. Classical proportional-integral (PI) controller and fuzzy logic controller (FLC) has been compared in this paper. Peak current control of forward converter has been discussed in [11] whereas a comparative analysis of magnetic design for forward converter has been discussed in [12]. Control of Multiple output forward converter has been discussed in [13]. In an isolated converter, there are number of ways by which the transformer can be reset. One of the widely used technique to reset the transformer is active clamp method where auxiliary switch and capacitor are used for the purpose [14-16]. The additional capacitor provides requisite energy to the different cycle and keeps the voltage ripple to minimum. Effect of optocoupler feedback dynamics on peak current mode controlled active-clamp forward converter (ACFC) has been discussed in [8]. In [9], modeling of buck converter is investigated. In [17-19], different high gain DC-DC converter topologies are reviewed and compared. In [20], the authors provide detailed modelling and analysis of high-side ACFC whereas in [21] authors have provided detailed circuit analysis and controller design for low-side ACFC.

This paper provides the circuit operation of classical forward converter, low-side ACFC with synchronous rectification (SR). Circuit analysis, small signal modelling and controller design for the converter has been discussed in this work. Second paragraph.

2. Forward Converter: Circuit Analysis

The circuit diagram of classical single-switch forward converter is illustrated in Figure 1. It comprises of a primary winding and a secondary winding with uncontrolled as well as controlled switches. Q1 is the controlled switch (MOSFET) whereas D1, D2 and D3 are the uncontrolled switch (diode).

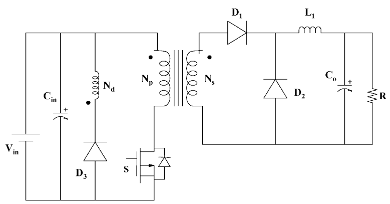


Figure 1. Circuit diagram of practical forward converter

The secondary side inductance is calculated as

$$L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2} \tag{1}$$

The current ripple is calculated as

$$I_r = \frac{1}{L_1}\left(V_{in}\left(\frac{n_s}{n_p}\right) - V_f - V_o\right)t_1 \tag{2}$$

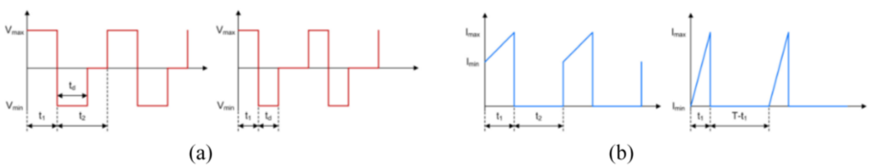


Figure 2. Output forward converter (a) Square wave (b) positive part output

Figure 2 illustrates the working principle of forward converter and waveforms of voltage and current of forward converter during continuous conduction mode (CCM) and discontinuous conduction mode (DCM) [16- 19].

3. Low Side Active Clamp Forward Converter

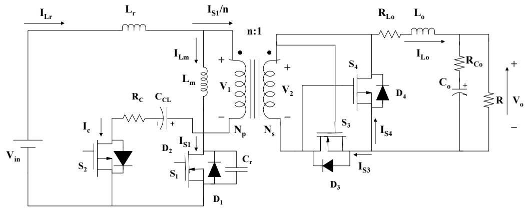


Figure 3. Circuit diagram of low side active clamp forward converter

Figure 3 illustrates a low-side ACFC with SR where a p-channel MOSFET is used as an auxiliary switch in both primary and secondary side. The clamp circuit resets the transformer magnetizing inductance because of the clamp circuit, the forward converter achieves zero voltage switching capability and the converter is capable to operate at duty cycle more than 0.5. The following assumptions are considered for the converter

a. Magnetizing inductance is larger than resonant inductance
b. Clamp capacitor larger than resonant capacitor

The minimum value of inductor is represented as

$$L = \left(\frac{V_o}{\Delta I_L I_o f_{osc\_\min}} \right) (1 - d_{\min}) \tag{3}$$

The minimum value of clamping capacitor is represented as

$$C_c = 10 \left(\frac{1}{L_m \left(2\pi f_{osc\_\min} \right)^2} \right) (1 - d_{\min})^2 \tag{4}$$

In low side clamp,

$$V_{DS} = \frac{V_{in}}{1-d}, \quad V_{reset} = \frac{V_{in} d}{1-d} \tag{5}$$

4. Small Signal Modelling

The small signal model of low-side ACFC with SR has been computed in this section. Four different state variables are considered and a 4th order model has been created for the converter. The state variables are (a) magnetizing current, (b) voltage across clamp capacitor, (c) output filter inductor current and (d) output filter capacitor voltage.

A. Converter with parasitics

Figure 4 represents the different parasitics involved in low side ACFC with SR with parasitics. The state-space model of low side ACFC with SR with parasitics has been discussed below. In this model, the input voltage output current is 4 considered as control variable. When the switch is ON, the state space model can be represented. When the switch is OFF, then the state space model of the converter can be represented. Resulting transfer function of voltage to duty cycle transfer function of low-side ACFC with SR and parasitics has been provided here.

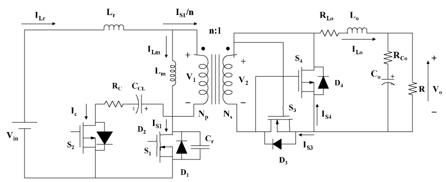


Figure 4. Circuit diagram of low-side ACFC with SR with parasitic

5. Feedback Control Scheme

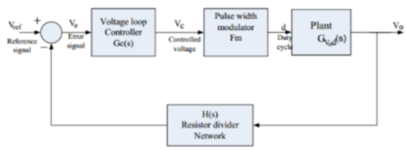


Figure 5. Feedback control scheme for power converter

Figure 5 illustrates the feedback control scheme for power converter where voltage mode control scheme is used. The PWM modulator is used to provide gate pulse to the converter. The converter dynamics is obtained from the small signal model. Resistor divider network is used for voltage sensing. The generalized form of controller for power converter can be represented as

$$G_c(s) = K\frac{\left(1+\frac{s}{\omega_{z1}}\right)\left(1+\frac{s}{\omega_{z2}}\right)}{s\left(1+\frac{s}{\omega_{p1}}\right)\left(1+\frac{s}{\omega_{p2}}\right)} \tag{6}$$

6. Simulation Analysis

The specification of a low-side ACFC with SR are as follows

a. Nominal voltage = 48 VDC
b. Output voltage = 5 V DC
c. Output current = 20 A
d. Output current ripple = 30 mA (p-p)
e. Output voltage ripple = 10%
f. Switching frequency = 100 kHz

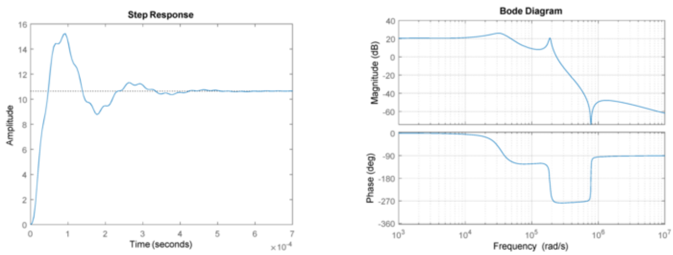
The converter parameters are Lo = 3.5 µH, Lm = 38 µH, Co = 240 µF and C_{CL} = 240 nF. Transformation ratio is 4.5

The voltage to duty ratio of low side ACFC with SR can be represented as

$$G_{vd}(s)=\frac{8067.2269\left(s+9.259\times10^{4}\right)\left(s^{2}+1.328\times10^{4}s+5.997\times10^{11}\right)}{\left(s^{2}+2.079\times10^{4}s+1.193\times10^{9}\right)\left(s^{2}+1.328\times10^{4}s+3.528\times10^{10}\right)} \tag{7}$$

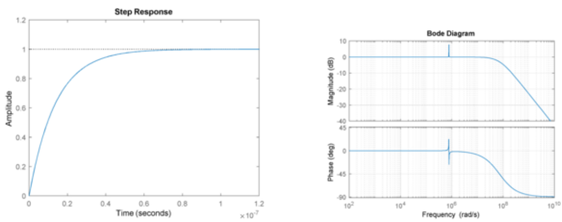
The controller designed for the converter can be represented as

$$G_{c}(s)=9003\frac{(s+350)(s+26666)}{s(s+500)(s+133333)} \tag{8}$$



(a) (b)

Figure 6. Response of uncompensated converter (a) step response, (b) bode diagram



(a) (b)

Figure 7. Response of compensated converter (a) Step response and (b) frequency response

Figure 6 and Figure 7 provides the uncompensated and compensated response of the low-side ACFC with SR along with parasitic devices.

7. Conclusion

This paper provides a detailed circuit analysis of low-side ACFC with SR. Small signal modelling and controller design of the converter has been discussed in this paper. Simulation results and experimental analysis have been provided for the converters. Various methods of soft-switching are employed in forward converters in order to minimize switching and conduction losses. By utilizing active and passive clamping circuitry, the forward converter's losses have been greatly reduced by this technique. Cascaded forward converters are also utilized for a variety of purposes. Different applications call for the employment of several output forward converters.

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