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Design of Digital Current Mode Controller for Active Clamp Forward Converter

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ABSTRACT

With the rapid development of Microprocessors/Microcontrollers digital controllers are becoming viable one as compared to conventional controllers. To overcome the drawbacks in single loop simple Voltage Mode Controllers and improve the performance of the converter, two loop current mode Controllers need to be designed. This paper presents the step by step design procedure to design a Digital Current Mode Controller for Active Clamp Forward Converter. Small Signal Discrete-time Model of the converter is first designed. Control dynamics of the converter are explained in detailed to design a current mode controller for Active Clamp Forward Converter. A continuous – time current mode controller is first designed and with the help of digital redesign method a digital current mode controller is designed. Finally, the behavior of the Active clamp Forward Converter with designed controllers and achievement of desired compensation is verified by applying disturbances at both ends of the converter.

Key words: Active Clamp, Current Mode control, Digital Redesign, Forward converter, Small Signal Model

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INTRODUCTION

Due to rapid development of power electronics industry primary trends moving towards for low voltages and high current power supply circuits for various applications like Telecom Power Supply; Distributed Power supply Circuits, fuel cell Power generation systems, etc [1-3]. Forward converter is a promising topology for low and medium power applications where low voltages at high currents are required with higher efficiency. But transformer in forward converter requires resetting at each and every switching cycle to overcome the saturation problem. There are different resetting techniques are available to reset the transformer, between which active clamp resetting technique becoming viable one due its simplicity and power reversal capability. In this method power is transferred back to the source while resetting the transformer hence the efficiency of the converter is improved [3-6]. Fig.1 shows the basic circuit diagram for Forward converter with the active clamp circuit.

To get desired performance from switching converters a controller is required. But with continuous advancement in the technology, digital controller is the preferable one due its advantages as compared to analog controller. The advantages of digital controllers are accurate, less sensitive to disturbances, programmable characteristics and less in cost. And also suffers from drawbacks like delay in sampling a signal, requires time to compute a specific function [7-9]. Some of the authors are concentrating on the converter circuit to improve the efficiency of the converters and the others are concentrating on the controller circuit to achieve better performance from the converter. In [3] methods to determine mathematical model of the converter and procedure to design a linear controller is presented. But to improve the performance of the converter and to get accurate results digital controllers are preferable one. In [8-9] some efforts have been made towards the design of digital controller for simple buck and boost converter. But no one is discussed regarding the design of digital controller for an Active Clamp Forward Converter. In [10], the authors are presented design procedure of small signal discrete-time model of Active Clamp Forward Converter and design of digital controller by using a digital redesign method. In the presented paper [10] simple digital voltage mode controller is designed in continuous form and then discretized into digital form by using the bilinear approximation method. But voltage mode controller also suffers from some drawbacks like a slower response and compensation is further complicated by the fact that the loop gain varies with input voltage.

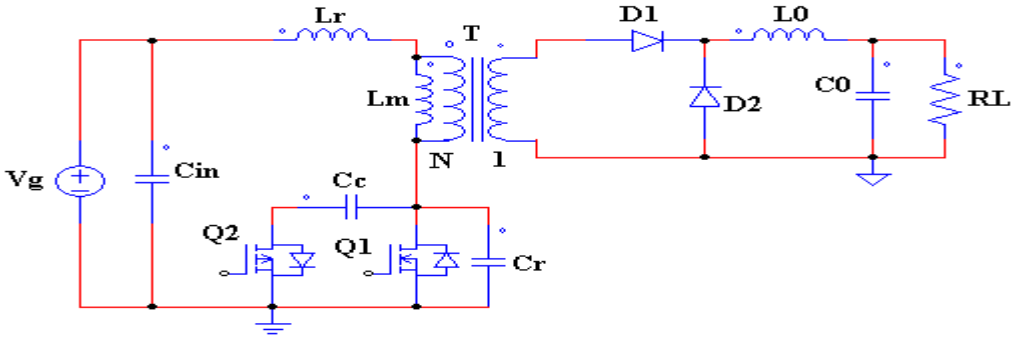

Fig.1. Basic circuit diagram of Forward Converter with Active Clamp Circuit

The main objective of this paper is to present the simple design procedure to design discrete-time current mode controller for isolated DC-DC converter by determining the discrete-time model of the ACFC by using a digital redesign method. Design procedure of discrete-time model of the ACFC is presented by using the bilinear transformation method and the exact design procedure and analysis of the converter is presented. Theoretical analysis of the designed digital current mode controller is confirmed by the results of MATLAB, the performance of the controller are observed by applying disturbance at supply side and load side and results are presented. Finally, conclusions are made based on the obtained results from the designed digital current controller.

MATHEMATICAL MODELING OF THE CONVERTER

Small Signal Model of the Converter

First step in designing the controller for any type of converter is the determination of its mathematical model. This represents a physical phenomenon by its mathematical equivalent. There are different methods available to model the DC-DC converters. But the small signal model is very suitable for converters are having nonlinear characteristics like ACFC [11]. Consider the Active Clamp Forward Converter as shown in Figure. 1. In deriving the small signal model, the leakage inductance of the transformer, L_r, and the parasitic capacitance of the main switch, C_r are neglected [12]. It is assumed that the small letters denotes the time varying quantities, capital letters denote DC quantities and small letters with hat denotes small ac perturbations. Also, it is assumed that the converter is operating in continuous current mode.

Applying KVL to the primary side of transformer and averaging over a switching period.

$$v_m = v_g d + (v_g - v_c)(1-d) \tag{1}$$

Perturbing (4.1) with small ac quantities such that $\hat{d} << D$, $\hat{v}_g << V_g$

$$V_m + \hat{v}_m = (V_g + \hat{v}_g)(D + \hat{d}) + (V_g + \hat{v}_g - V_c - \hat{v}_c)(1 - D - \hat{d}) \tag{2}$$

$$\Rightarrow V_m + \hat{v}_m = [V_g - (1-D)V_c] + [\hat{v}_g - (1-D)\hat{v}_c + V_c \hat{d}] + \hat{v}_c \hat{d} \tag{3}$$

Neglecting the small terms, $\hat{v}_c \hat{d}$, (3) gives the steady state and perturbed components:

$$V_m = [V_g - (1-D)V_c]$$

$$\hat{v}_m = [\hat{v}_g - (1-D)\hat{v}_c + V_c \hat{d}] \tag{4}$$

Assuming ideal behavior, the steady state voltage in the transformer primary side must satisfy $V_m = 0$ (5)

Thus from (4) steady state equation becomes

$$0 = V_g - (1-D)V_c$$

$$\Rightarrow V_c = \frac{V_g}{1-D} \tag{6}$$

Hence the small-signal components of (4) becomes

$$\hat{v}_m = \hat{v}_g - (1-D)\hat{v}_c + \hat{d}\frac{V_g}{(1-D)} \tag{7}$$

The magnetizing current, i_m flows through clamp capacitor C_c when the main switch is OFF.

$$i_c = i_m(1-d) \tag{8}$$

Perturbing (4.8) with small ac quantities

$$I_c + \hat{i}_c = (I_{lm} + \hat{i}_m)(1-D-\hat{d}) \tag{9}$$

⇨ In steady state $I_m=0$ $I_c=0$ (10)

The small signal components of (9) are

$$\hat{i}_c = \hat{i}_m(1-D) - I_m\hat{d} \tag{11}$$

Substituting (10) in (11) $\hat{i}_c = \hat{i}_m(1-D)$ (12)

Now consider the ideal classic forward converter, i.e without any resetting circuit. The relationship between the primary and the secondary voltages is given as

$$v_s = \frac{d}{N}v_g \tag{13}$$

Perturbing (13) with small ac quantities

$$V_s + \hat{v}_s = \frac{1}{N}\left(D + \hat{d}\right)\left(V_g + \hat{v}_g\right) \tag{14}$$

The small signal components are

$$\hat{v}_s = \frac{\hat{v}_g D + V_g\hat{d}}{N} \tag{15}$$

Similarly the relation between primary and secondary currents is given as

$$i_p = \frac{di_0}{N} \tag{16}$$

The small signal components of (16) are

$$\hat{i}_p = \frac{I_0\hat{d} + \hat{i}_0 D}{N} \tag{17}$$

Also the relationship between the main switch current and the input current is

$$i_q = i_{in}d \tag{18}$$

The complete model of an active clamp forward converter can be obtained as shown in Fig.2 by combining equation (7), (12), (15) and (17) and by referring clamp capacitor C_c to the primary side.

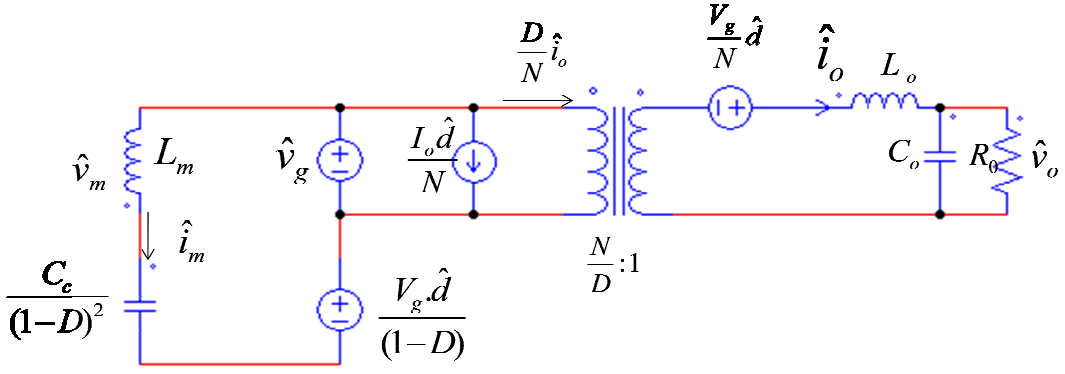

Fig.2 Small signal model of Active Clamp Forward Converter

It is observed from the small signal model shown in Figure 2, the inputs are $\hat{v}_g$, $\hat{d}$ and the output are $\hat{v}_0$, $\hat{i}_0$ and $\hat{i}_m$. The mathematical model of active clamp forward converter that relates the input and output variables can be given by (19), (20) and (21).

$$\hat{v}_0 = G_{vg}.\hat{v}_g + G_{vd}.\hat{d} \tag{19}$$

$$\hat{i}_0 = G_{ig}.\hat{v}_g + G_{id}.\hat{d} \tag{20}$$

$$\hat{i}_m = G_{img}.\hat{v}_g + G_{imd}.\hat{d} \tag{21}$$

The transfer functions in (19), (20) and (21) are obtained by considering each input at a time while other input is zero. The transfer functions G_{vg} , G_{ig} , G_{img} are given by (22), (23) and (24) when $\hat{d} = 0$.

$$G_{vg}(s) = \frac{D \times R_0}{N\left(S^2 L_0 C_0 R_0 + SL_0 + R_0\right)} \tag{22}$$

$$G_{ig}(s) = \frac{D\left(1 + SC_0 R_0\right)}{N\left(S^2 L_0 C_0 R_0 + SL_0 + R_0\right)} \tag{23}$$

$$G_{img}(s) = \frac{SC_c}{\left(S^2 L_m C_c + (1-D)^2\right)} \tag{24}$$

Similarly the transfer functions G_{vd} , G_{id} , G_{imd} are given by (25), (26) and (27) when $\hat{v}_g = 0$.

$$G_{vd}(s) = \frac{V_g R_0}{N\left(S^2 L_0 C_0 R_0 + SL_0 + R_0\right)} \tag{25}$$

$$G_{id}(s) = \frac{V_g\left(1 + SC_0 R_0\right)}{N\left(S^2 L_0 C_0 R_0 + SL_0 + R_0\right)} \tag{26}$$

$$G_{imd}(s) = \frac{V_g \times SC_c}{(1-D) \times \left(S^2 L_m C_c + (1-D)^2\right)} \tag{27}$$

Now by considering the design parameters of ACFC continuous time transfer functions are determined and then descritized into a discrete form by using the bilinear transformation method to obtain small signal discrete-time model of the ACFC. Table-1 shows the design parameters of ACFC.

Table-1 Design parameters of ACFC

Parameter	Symbol	Typical	Units
Input Voltage	V_g	48	V
Input Turn-on Voltage	V_{ON}	35	
Input Turn-off Voltage	V_{OFF}	34	
Output Voltage	V_0	5	
Duty Cycle	D	0.4166	--
Full Load Efficiency	η	90%	--
Output Voltage Ripple	ΔV_0	100	mV_{pp}
Output Load Current	I_0	20	A
Output Current Limit	I_{LIM}	32	
Switching Frequency	F_s	100	KHz
Output Filter Components	Lo, Co	8µH, 590µF	
Magnetizing Inductance and Clamp capacitance	Lm, Cc	100µH, 100nF	
Transformer rating		12:3	

By substituting the designed parameters in equations (22) – (27), the continuous-time transfer functions are obtained are as follows,

$$G_{vg}(s) = \frac{22069209.0395}{s^2 + 6780s + 2.119e8} \tag{28}$$

$$G_{ig}(s) = \frac{13020.8333(s + 6780)}{s^2 + 6780s + 2.119e8} \tag{29}$$

$$G_{img}(s) = \frac{1000s}{s^2 + 3.403e10} \tag{30}$$

$$G_{vd}(s) = \frac{254237288.3559}{s^2 + 6780s + 2.119e8} \tag{31}$$

$$G_{id}(s) = \frac{1500000(s+6780)}{s^2+6780s+2.119e8} \quad (32)$$

$$G_{imd}(s) = \frac{822857.14295s}{s^2+5.833e10} \quad (33)$$

Now by using the bilinear transformation technique continuous-time model (28)-(33) into discrete-time model by replacing S by $\frac{2}{T_s}\frac{1+z^{-1}}{1+z^{-1}}$ by considering sampling time$T_s = 5e^{-6}$. The obtained discrete-time transfer functions (34) – (39) are as follows,

$$G_{vg}(z) = \frac{0.00013546(z+1)^2}{z^2-1.962z+0.9667} \quad (34)$$

$$G_{ig}(z) = \frac{0.03251(z-0.9667)(z+1)}{z^2-1.962z+0.9667} \quad (35)$$

$$G_{img}(z) = \frac{0.0020616(z-1)(z+1)}{z^2-1.208z+1} \quad (36)$$

$$G_{vd}(z) = \frac{0.015605(z+1)^2}{z^2-1.962z+0.9667} \quad (37)$$

$$G_{id}(z) = \frac{3.7451(z-0.9667)(z+1)}{z^2-1.961z+0.9667} \quad (38)$$

$$G_{imd}(z) = \frac{1.507(z-1)(z+1)}{z^2-0.9313z+1} \quad (39)$$

CONTROLLER DESIGN

After determining the mathematical model of the converter, it needs to observe the control dynamics of the converter. These dynamics are changing with the type of controller. In simple voltage mode controller controlling of output voltage is very easy. Because it senses only the output signal and compared with a reference value and the error signal is connected to the controller, the controller will take appropriate action to get the desired output. But in case of current mode controller both voltage and current signals need to sense and with the help of these two signals, we need to generate appropriate control signal to get the desired output. As compared to voltage mode control, current mode controller design is difficult. But current mode controller will give better performance as compared to the voltage mode controller. In the case continues-time peak current mode controller, there is a drawback; it requires an external ramp signal to generate the control signal [13]. But in the case of discrete time current mode controller, there is no such type of problem [14-15]. And most of the industries prefer average current mode controller. In this paper Average current mode controller is designed for ACFC by analyzing control dynamics of the converter. The relation between controlled current $\hat{\imath}_c$ and duty cycle $\hat{d}$ can be derived in terms of output inductor current, magnetizing current, output voltage and input voltage.

Output Current Slope

$$M_2 = \frac{\frac{v_g}{N}-V_o}{L_o} = \frac{v_g - Nv_o}{NL_o} \quad (40)$$

The magnetizing current slope is given by (41)

$$M_3 = \frac{v_g}{L_m} \quad (41)$$

The primary current slope is obtained by adding (40) and (41) as given by (42)

$$M_1 = M_2 + M_3 \quad (42)$$

Equating control current with added artificial ramp to the primary side current.

$$\frac{i_o}{N} + m_1\frac{dT}{2} + i_m d = \frac{v_c^{'}}{R_f} - S_e dT \quad (43)$$

Assuming that the atrificial ramp is constant, perturbing with small ac quantities and separating the ac components we get,

$$\frac{\hat{\imath}_o}{N} + M_1\frac{\hat{d}T}{2} + \widehat{m}_1\frac{DT}{2} + \widehat{\imath_m}d = \frac{v_c^{'}}{R_f} - S_e\hat{d}T \quad (44)$$

Solving for $\hat{d}$

$$\hat{d} = \frac{1}{k}\left(\frac{\hat{v}_c^{'}}{R_f} - \frac{\hat{\imath}_o}{N} + \frac{DT}{2L_o}\hat{v}_o + \left(\frac{1}{NL_o}+\frac{1}{L_m}\right)\frac{DT}{2}\hat{v}_g - i_m D\right) \quad (45)$$

Where $k = \left(\frac{M_1}{2} + S_e\right)T$ (46)

Now the gains are given as

$$F_m = \frac{1}{k}; \quad F_i = \frac{1}{N}; \quad F_v = \frac{DT}{2L_o}$$
$$F_g = \frac{DT}{2}\left(\frac{1}{NL_0} + \frac{1}{L_m}\right); \; F_{im} = D \quad (47)$$

Therefore, with the help designed a mathematical model of the converter and control dynamics of the converter, Block diagram representation of the ACFC with ACMC is determined and is shown in Fig.4.

With the help of block diagram representation ACFC with ACMC is simulated in MATLAB software and the controller transfer function is determined to get the desired output in continuous – time. And then designed continuous-time transfer function is discretized into discrete-time to implement the controller in digital mode. And the corresponding equations are as follows,

$$G_i(z) = \frac{0.4365z^2 + 0.02523Z - 0.4112}{Z^2 - 1.119Z + 0.119} \quad (49)$$

$$1 + G_i(z) = \frac{1.436\,z^2 - 1.094\,Z - 0.2923}{Z^2 - 1.119Z + 0.119} \quad (50)$$

$$G_c(z) = \frac{-4.537e5\,Z + 4.402e5}{Z - 0.5073} \quad (51)$$

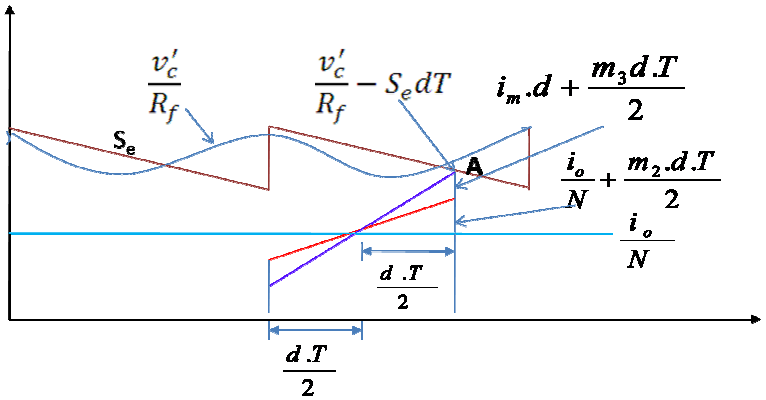

Fig.3 Average Current Mode Control dynamics

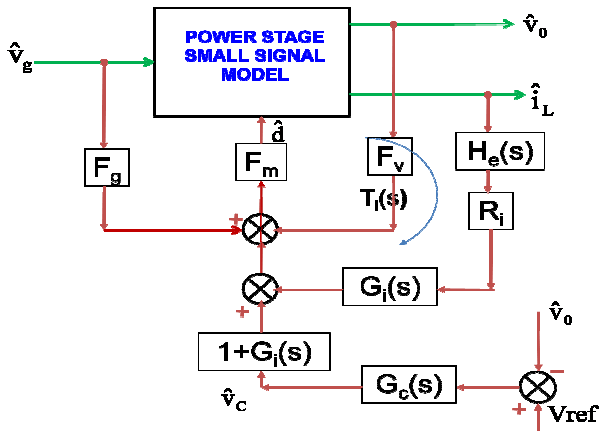

Fig.4 Block diagram representation of ACMC with power stage

RESULTS AND DISCUSSION

Now with the help of complete small signal model block diagram of Active Clamp Forward Converter (ACFC) with Average Current Mode Control (ACMC) shown in Fig.4. is simulated in MATLAB software corresponding simulation diagram and results are shown below. Fig.5. represents simulink mode of the ACFC with continuous-time ACMC, Dynamic response of ACFC with ACMC is shown in Fig.6. and the output voltage waveform of ACFC with continuous-time ACMC is shown in Fig.7.

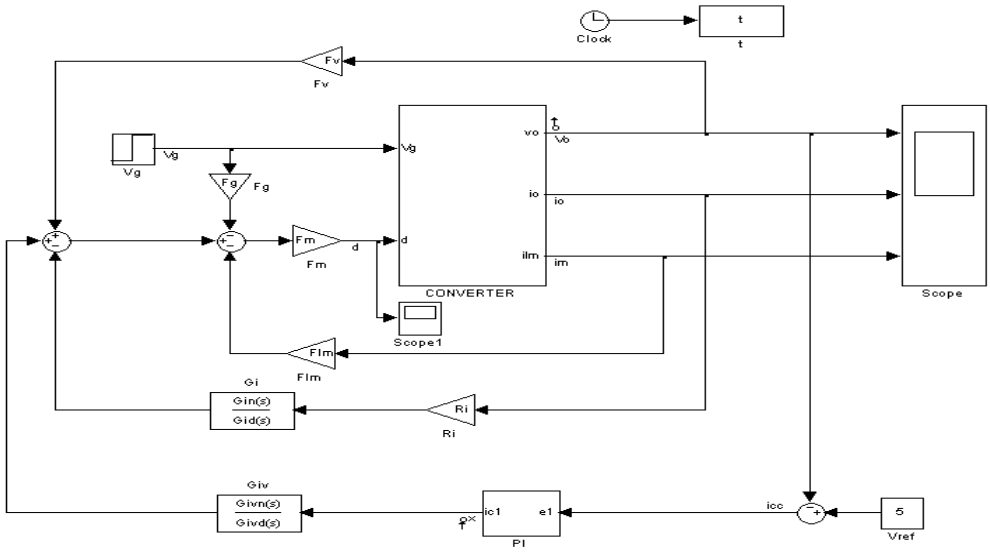

Fig.5. SIMULINK model of ACFC with continuous-time ACMC

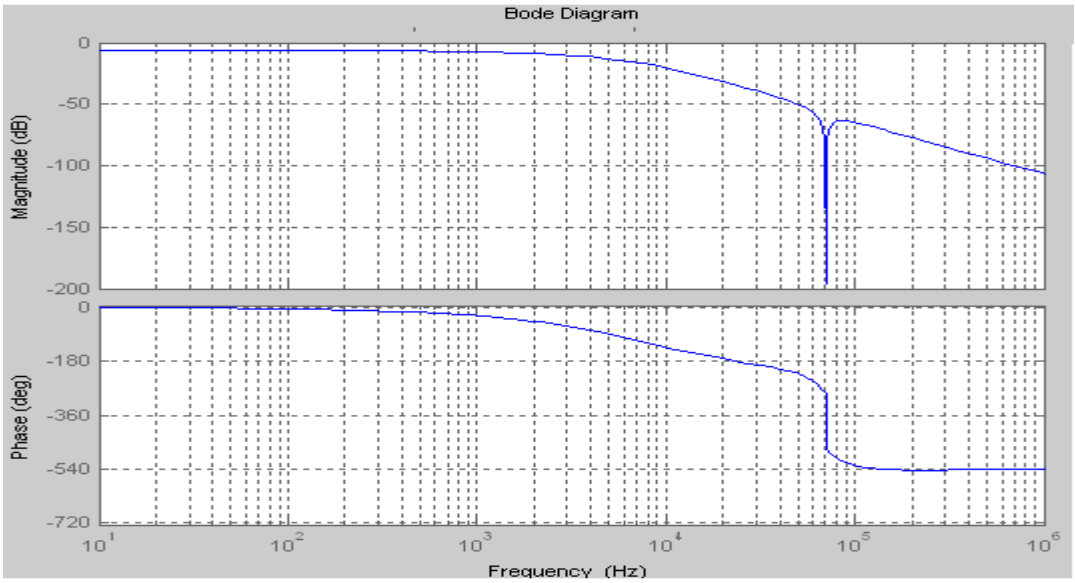

Fig.6. Dynamic response of ACFC with continuous-time ACMC

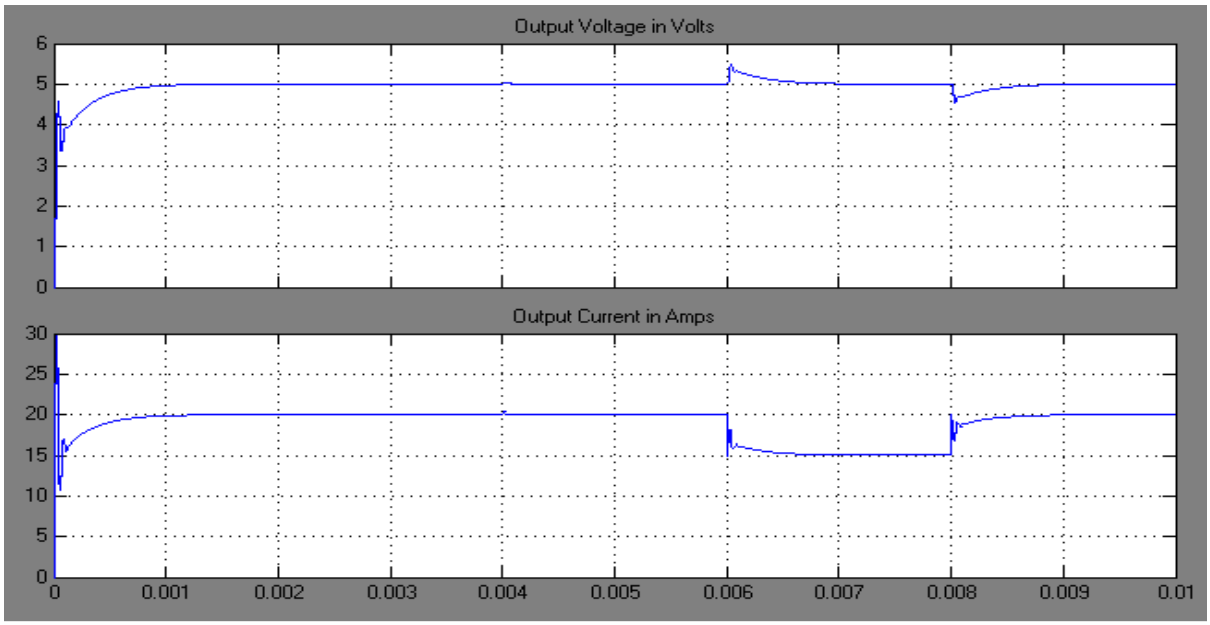

Fig.7. Steady state output voltage and current waveforms with continuous-time ACMC

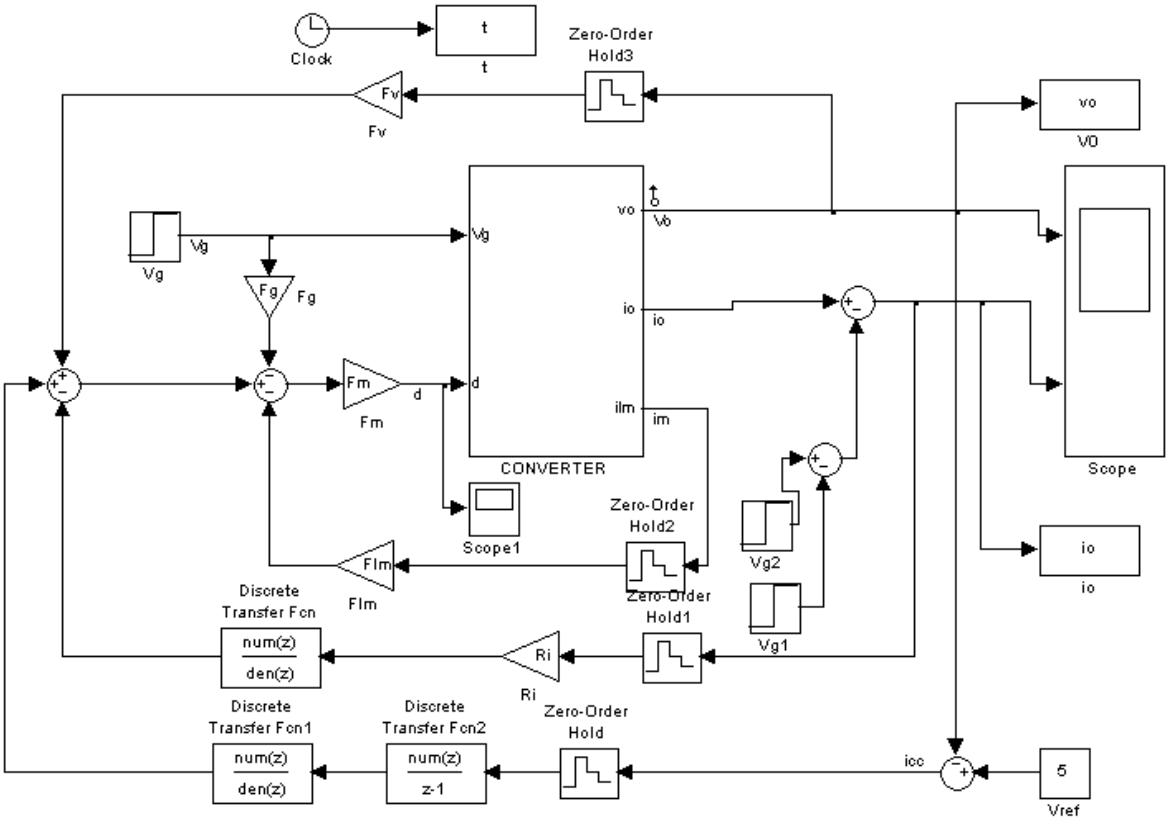

Fig. 8 SIMULINK model of ACFC with Discrete-time ACMC

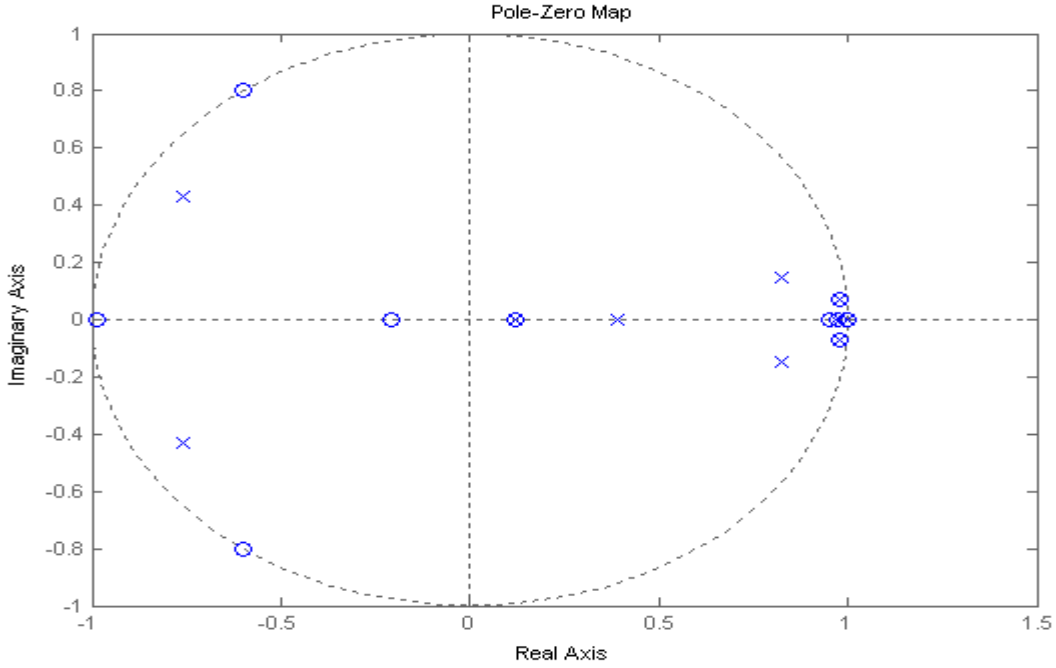

Fig.9. Pole-zero of ACFC with Discrete-time ACMC

With the help designed discrete-time controller transfer functions ACFC is simulated with Digital Average Current Mode Controller. And the results are shown below. Fig.8. shows the simulink model of ACFC with Discrete –time ACMC, Fig.9.shows the location of poles and zero in z-plane. The output voltage and current waveforms of ACFC with Discrete-time ACMC is shown in Fig.10.

To analyze the behaviour of ACFC and achievement of desired compensation is observed by applying the disturbances at supply side and load side. A step change of 10V is applied at 0.004sec and a load step change of 5A is applied between 0.006 sec and 0.008sec. From the obtained results, it needs to observe that both the cases zero voltage regulation is achieved by designed controllers.

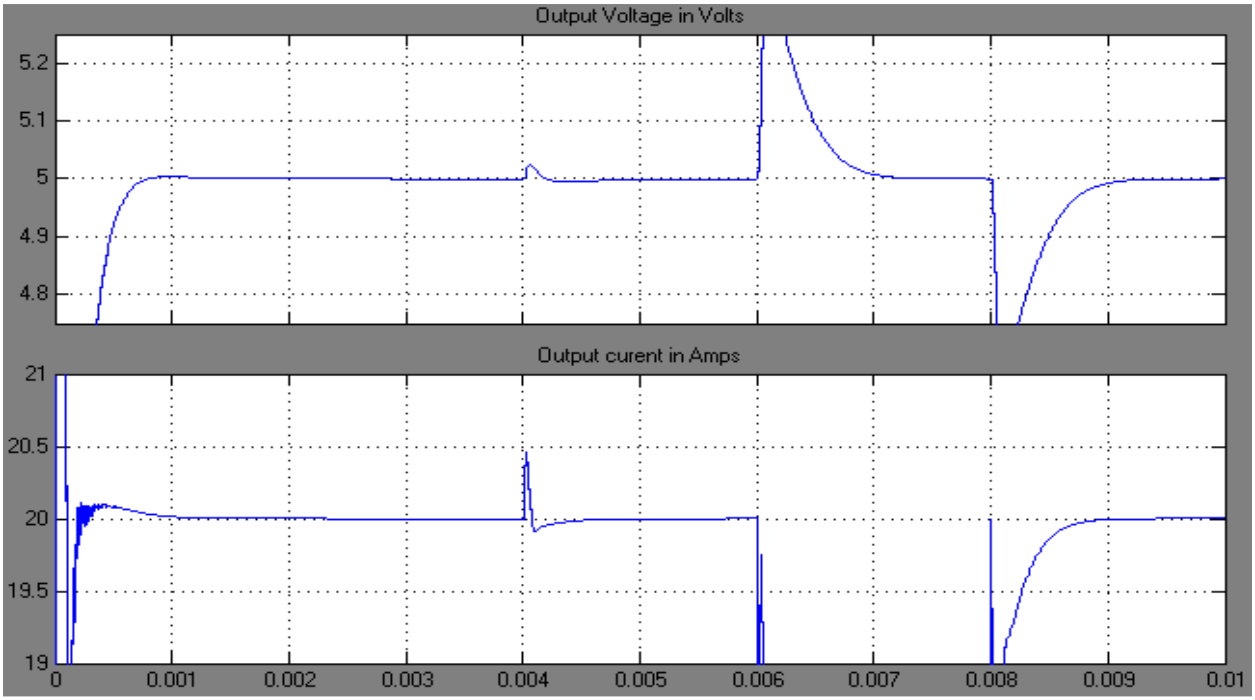

Fig.10. Steady state output voltage and current waveforms with Discrete-time ACMC

CONCLUSION

A step by step design procedure to design a Digital Current Mode Controller for Active Clamp Forward Converter is presented. Small Signal Discrete-time Model of the converter is first designed. A detailed explanation is provided about the control dynamics of the converter and is used to design a current mode controller for Active Clamp Forward Converter. A continuous–time current mode controller is first designed and with the help of digital redesign method a digital current mode controller is designed. Final results confirmed that the achievement of desired confirmation with designed controllers for ACFC and performance of the designed controllers is verified by applying disturbances at both ends of the converter. And with the help of results, it need to observe the bilinear transformation technique is able to shift whole part left side of the s-plane into inside the unit circle in the z-plane.

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