Peak Current Mode Controlled Active Clamp Forward Converter with Magnetic Feedback

Maturi Krishnaja[1], Susovon Samanta[2]
Department of Electrical Engineering
NIT Rourkela
Rourkela, India
[1]krishnaja2803@gmail.com, [2]samanta.susovon@gmail.com

Keya Shukla[3], Rajendra Singh[4],
Space Activity Centre
ISRO Ahmedabad
Ahmedabad, India
[3]keyashukla@sac.isro.gov.in, [4]rsijwali@sac.isro.gov.in

***Abstract*—Active clamp forward converter is used extensively in medium power applications due to galvanic isolation between input and output. The feedback loop is realized using either optocoupler or magnetic feedback for isolating the control loop. Optocoupler feedback uses a combination of optocoupler and an operational amplifier for realizing the control loop. The variation of current transfer ratio and aging effect of the optocoupler limits the usage to commercial applications where temperature variation is minimal. Magnetic feedback withstands high operating temperature compared to optocoupler feedback. It uses the transformer to isolate the feedback and hence used in military and space applications. The operation and analysis of a 48W magnetic feedback isolated peak current mode controlled active clamp forward converter was presented with PSPICE simulation results. In PSPICE simulation, vendor model of all the discrete components has been used such that the PCB can be made directly from the schematic.**

***Keywords—Active clamp reset, forward converter, galvanic isolation, magnetic feedback, optocoupler feedback*.**

Nomenclature

i_{in}	Input current
v_{in}	Input voltage
v_m	Voltage across transformer primary
n	Number of secondary turns in current transformer
R_s	Burden resistor of current transformer
i_p	Reflected load current through transformer primary
i_{L_m}	Magnetizing current of transformer
L_m	Magnetizing inductance of transformer
L_r	Leakage inductance of power transformer
C_C	Clamp capacitor
i_C	Current through clamp capacitor
N_p / N_s	Primary/secondary turns of power transformer
L_o	Filter inductor
C_o	Filter capacitor
R	Load resistor
i_{sense}	Sensed switch current
v_{con}	Control voltage

I. Introduction

Galvanic isolation avoids the stray losses caused due to the flow of stray currents between input and output hence feedback isolation is required for any isolated converter topology. Mammano [1] discussed different control techniques to regulate the isolated converters. The primary side control by sensing the output voltage is normally realized using optocoupler feedback [2-6] and magnetic feedback [7-8]. The optocoupler feedback technique although being used extensively in commercial applications the disadvantages like aging, temperature dependency and degradation of LED performance [5] restricts its usage in military and space applications. Suntio T [3] explained the gain and bandwidth limitations of closed loop system imposed by the optocoupler and the operational amplifier. The analysis of the optocoupler feedback has been explained for both flyback [2] and forward [3-5] converter topology. In [6] the comparative study of a 48W Peak Current Mode Controlled (PCMC) Active Clamp Forward Converter (ACFC) with inductor current sensing using nonisolated feedback and optocoupler feedback has been done with PSPICE simulation results. The magnetic feedback is generally realized using flyback [7] and forward [8] transformer by isolating output voltage or error voltage. Flyback transformer is magnetized and demagnetized over a switching period whereas forward transformer transfers energy all the time and hence resetting of the core is necessary to avoid core saturation. In [7], magnetic feedback was realized for single output forward converter with tertiary winding reset, whereas multiple outputs with resonant reset techniques have been taken in [8]. Irving et al. [7] realized magnetic feedback by modulating and demodulating the error voltage using the flyback transformer. In this paper, the magnetic feedback is implemented by modulating and demodulating the output voltage using a forward transformer with center tapped secondary followed by a bridge rectifier and capacitor filter. The ACFC with high efficiency and high power density along with magnetic feedback is highly beneficial for space and military applications. This paper mainly focuses on the magnetic feedback implementation of ACFC with PCMC using controller IC UC1825 and the ACFC is operating in continuous conduction mode.

II. Overall System Description

The overall system is shown in Fig. 1. The system comprises of power stage which is ACFC, a current sensing unit to sense the switch current, a controller in the feedback loop to regulate the duty cycle of the switch.

978-1-5386-9316-2/18/$31.00 ©2018 IEEE

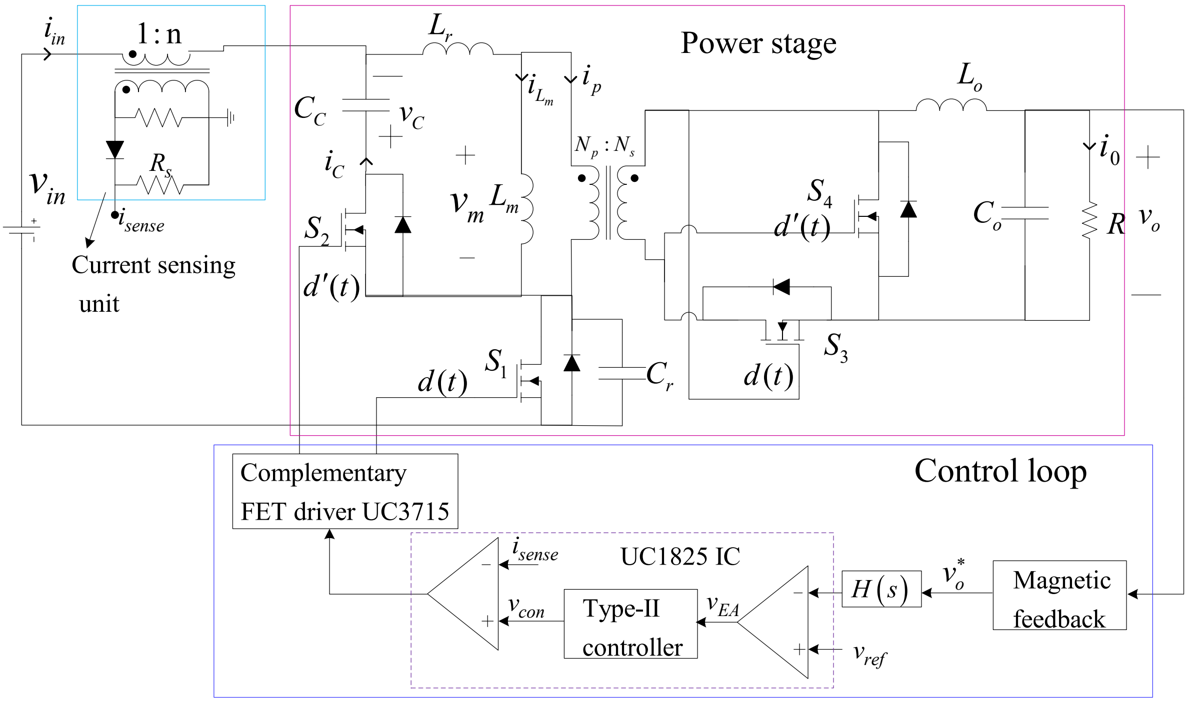

Fig. 1. Peak current mode controlled ACFC

A. Power stage:

ACFC has four operating modes namely power transfer, resonant mode -I, resetting mode and resonant mode –II.

In the power transfer mode, the main switch S1 is turned ON through the gate pulse and the input voltage is applied across the transformer which induces the voltage in the secondary. The voltage across transformer secondary drives synchronous rectifier S3 through which the power is transferred to the load. Also the filter inductor stores energy during this mode. This mode ends with the turn OFF of gate signal to S1.

In resonant mode-I, the voltage across the main switch S1 starts building up until the voltage across the switch is equal to the voltage across the clamp capacitor. When voltage across the main switch increases more the body diode of the clamp switch starts conducting at which this mode ends. Still both the synchronous rectifiers conduct until both S3 is fully turned OFF and S4 is turned ON till the conduction of clamp switch S2 i.e., the end of this mode.

In the resetting mode, when the gate pulse is provided to clamp switch S2 the clamp voltage is applied across the transformer primary which drives the synchronous rectifier S4. During this mode the magnetizing current flowing through the transformer resets it through the clamp capacitor and resonance occurs between them. The energy stored in the filter inductor drives the load continuously and the load current starts flowing through synchronous rectifier S4, inductor and load.

In resonant mode-II, the discharge of parasitic capacitance occurs through the magnetizing current. During this mode the cut off of synchronous rectifier S4 and conduction of S3 happens simultaneously. Also the magnetizing current helps in the Zero Voltage Switching (ZVS) of the main switch and ends when the main switch turns ON.

The duration of resonant modes is small in the order of nanoseconds and are provided to discharge the parasitics leading to the ZVS of the converter main switch S1 and clamp switch S2.

B. Current sensing unit:

The switch current sensing is implemented with a current transformer which is connected in series with the power transformer. A diode is used to reset the transformer core, and sense resistor Rs value is designed to limit the peak sense voltage to 3V.

C. Control loop:

Current mode control has two loops. They are outer voltage loop and self-regulated inner current loop. The outer voltage loop control is realized by magnetic feedback, followed by resistor divider network and a type-II controller to generate the reference for the inner current loop. The current mode control and the type-II controller are realized using UC1825 IC. The OUTA signal generated from the UC1825 IC is fed to complementary FET driver UC3715 IC to generate the gate pulse for S1 and S2 with a required time delay. The magnetic feedback implementation is explained in the section III.

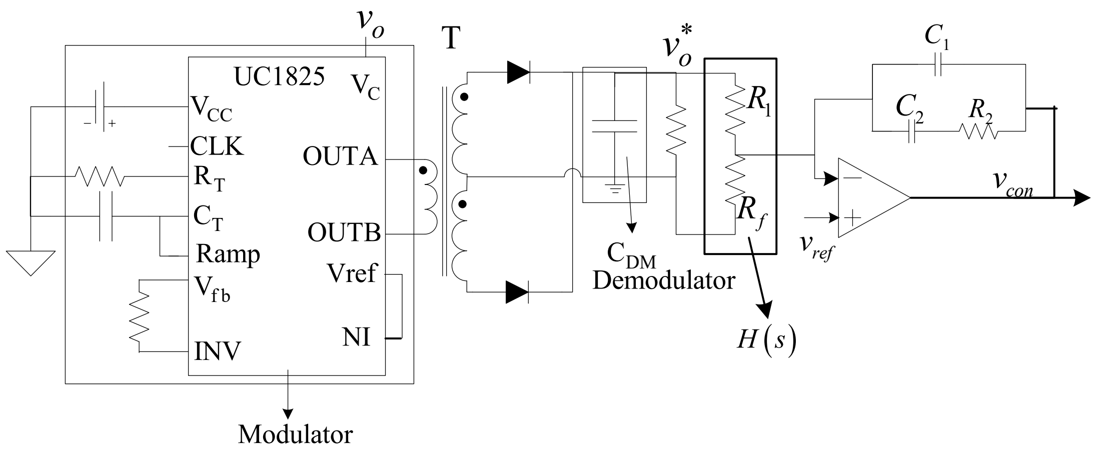

Fig. 2. Magnetic feedback isolation circuitry using UC1825

TABLE I. DESIGN SPECIFICATIONS AND TRANSFER FUNCTION OF THE SYSTEM

Design specification	Input= (26-43) V, Nominal input=34V, Output =48W (8V,6A), f_{sw}=100 kHz
Power stage parameters	S1, S2:IRHMS57260SE; S3, S4:IRF3707Z; Lo=66µH, Co=47µF, Cc=2.2µF, Cr=2.97nF, Transformer core: Toroid F-43205, Np/Ns=13/9, Lm=326µH; Dead time =200ns
Control circuitry	C.T turns ratio=1:100, R_S referred to primary side=0.7 Ω, Magnetic feedback: T turns ratio: 1:1:1, Sampling frequency=265kHz, C_{DM}=100nF
Transfer function	Control to output transfer function [state space averaging [9]] $G_{v_o v_{con}}(s)=\frac{\hat{v}_o}{\hat{v}_{con}}=\frac{9.208*10^9}{(s+3.018*10^5)(s+1.709*10^4)}$
	Feedback gain H(s)=0.33 Controller transfer function $G_C(s)=\frac{1.174\times10^6(s+1.9215\times10^4)}{s(s+2.0546\times10^5)}$

III. MAGNETIC FEEDBACK

The magnetic feedback configuration shown in Fig 2 uses a sampler and center tapped coupling transformer T with a bridge rectifier followed by a capacitor filter. The sampler samples the DC voltage in to symmetric square wave which is the input to the transformer T. The bridge rectifier provides the rectified DC voltage and the filter capacitor reduces the voltage ripple of the rectified isolated output voltage. The transformer gets magnetized and demagnetized during the positive and negative half cycle of the symmetric square wave. The clock of the UC1825 controller IC acts as the sampler. This IC generates symmetrical complementary pulses with the pulse amplitude equal to the magnitude of the output voltage and acts as a modulator. Then the output signal is rectified through a bridge rectifier to generate the isolated dc output voltage v_o^*. The CLK signal of the IC is the input reference, the converter output voltage v_o is the carrier signal, and filter capacitor C_{DM} is the demodulator. The rectified DC output voltage is scaled down and compared with a reference value to generate the error voltage. The controller generates the reference for the inner current loop from the generated error voltage v_{EA}.

In Fig 2 along with magnetic feedback the type-II controller has been realized for the ACFC peak current controlled system to regulate the output. The controller is realized with operational amplifier, resistors R1, R2, and capacitors C1, C2.

The type-II controller transfer function has two poles and one zero given by

$$G_C=\frac{K\left(1+ s/\omega_z\right)}{s\left(1+ s/\omega_p\right)} \tag{1}$$

where, $K = 1/R_1(C_1+C_2)$ = Gain of the controller

$\omega_z = 1/R_2C_2$ =Position of zero in rad/sec

$\omega_p = (C_1+C_2)/R_2C_1C_2$ =Position of pole in rad/sec

IV. SIMULATION RESULTS

The design specifications, power stage parameters and the transfer functions of the system is given in Table - I.

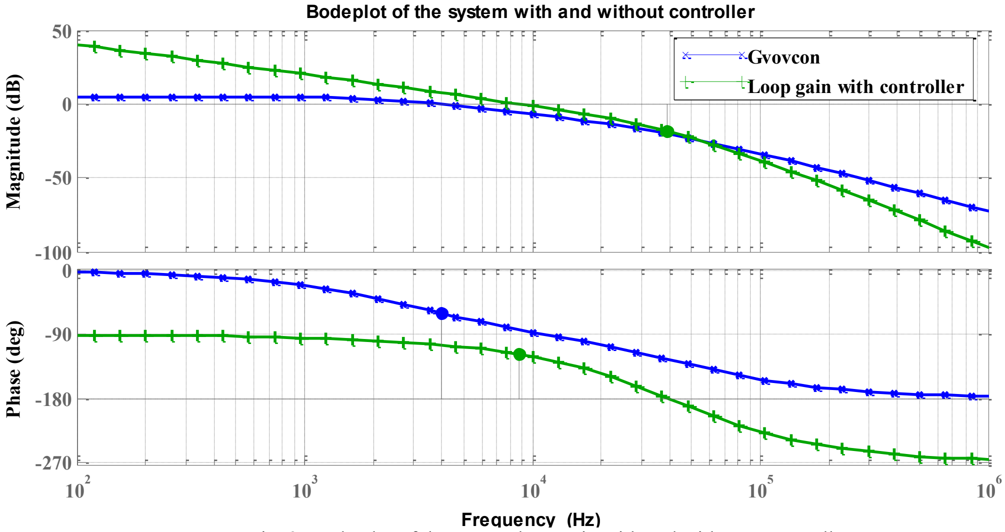

Fig. 3. Bode plot of the system loop gain with and without a controller

The bode plot of the system loop gain with and without a controller is shown in Fig 3. Bode plot of the system has been obtained by deriving the transfer function of the system by incorporating current mode control in to the small signal model and substituting the design specifications from table-I. It is observed that the loop gain of the uncompensated system has a phase margin of 119 degrees with a bandwidth of 4 kHz being a stable system loop gain with the controller has a phase margin of 62 degrees with a bandwidth of 8.8 kHz. The increased bandwidth and low frequency gain of the system improved the transient response and steady state error of the system respectively with the designed type-II controller.

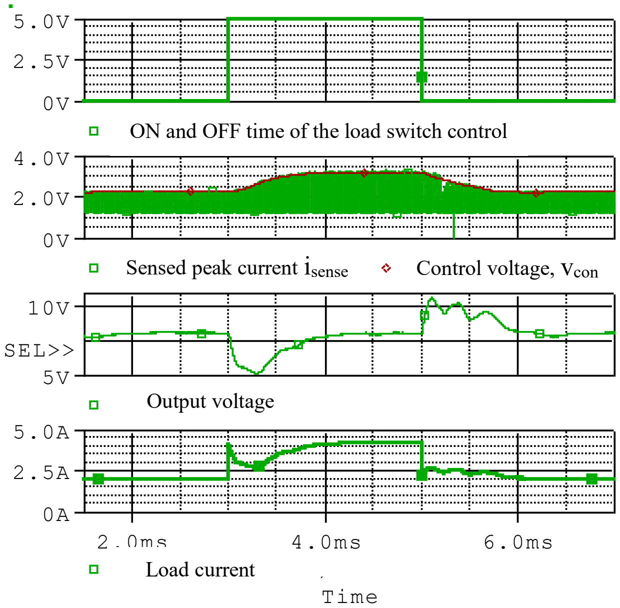

Fig. 4. PSPICE simulation results showing a change in load demand from 2A to 5A at 3ms with type-II controller

It is observed from Fig 4 that with an increase in load demand from 2A to 5A at 3ms the system is settling in 90 switching cycles with 36% undershoot. The operating duty cycle is changing from 0.34 to 0.43. The steady state response has been improved with the compensated magnetic feedback system (Fig 4).

V. CONCLUSION

The peak current mode controlled ACFC with magnetic feedback has been presented in the paper with PSPICE simulation results. The input switch current is sensed with a current transformer instead of filter inductor current sensing in order to avoid the isolation of the current sensing loop, and also it improves the efficiency of the system. The control loop is realized with a transformer of unity turns ratio for isolating the feedback path, a PWM controller IC UC1825 for realizing magnetic feedback and another for implementing current mode control. The load disturbance results show the system is robust in nature and settles quickly.

ACKNOWLEDGMENT

Authors would like to thank the "Indian Space Research Organization (ISRO)" for providing the grant ISRO/RES/3/678/16-17 for carrying out the research work

REFERENCES

[1] B. Mammano, "Isolating the control loop," Unitrode power Supply design seminar, SEM-700. 1990.

[2] T. H. Chen, W. L. Lin, and C. M. Liaw, "Dynamic modeling and controller design of flyback converter," IEEE Transactions on aerospace and electronic systems, vol. 35, no. 4, pp. 1230-1239, Oct 1999.

[3] T. Tepsa and T. Suntio, "Adjustable shunt regulator based control systems," IEEE Power Electronics Letters, vol. 1, no.4, pp. 93-96, Dec 2003.

[4] Y. Panov and M.M. Jovanovic, "Small-signal analysis and control design of isolated power supplies with optocoupler feedback," *IEEE Transactions on Power Electronics*, vol. 20, no. 4, pp. 823–832, 2005.

[5] T. Bajenesco, "CTR degradation and ageing problem of optocouplers," IEEE International Conference on Solid-State and Integrated Circuit Technology, vol 4, pp. 173-175, Oct 1995.

[6] M. Krishnaja and S. Samanta, "Effect of optocoupler feedback dynamics on peak current mode controlled active clamp forward converter," IEEE IEEMA Engineer infinite conference greater Noida, pp. 1-6, Mar 2018.

[7] B. T. Irving and M. M. Jovanovic, "Analysis and design optimization of magnetic-feedback control using amplitude

modulation," IEEE Transactions on Power Electronics, vol. 24, no. 2, pp. 426-433, Feb 2009.

[8] P. K. Rampelli, R. Deekshit, D S Reddy, B K Singh, V Chippalkatti and T. Kanthimathinathan, "Multiple-output magnetic feedback forward converter with discrete PWM for space application," IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), pp. 1-6, 16th Dec 2012.

[9] R. W. Erickson, “Fundamentals of Power Electronics,” 2nd EDITION by University of Colorado Boulder, Colorado,2000.