Comparative Study on Flyback Converter with PID Controller and Neural Network Controller

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1 Introduction

Flyback converter is most widely used switched mode power supply (SMPS) topology. Flyback converter because of its simplicity, less number of components and providing the isolation between the source and load it is used in offline converters, computers, printers. Flyback converter can provide the output voltage which depends on the duty ratio of switch and turns ratio of flyback transformer.

To provide a stable DC output, the regulation of output voltage of converter is necessary. The most widely used control methods, to control the voltage of the system are voltage mode control and current mode control. In voltage mode control, the duty ratio is directly controlled, in which the output voltage is sensed, and pwm signal for the switch is adjusted accordingly. In a current mode control in addition to voltage sensing loop, it has inner current sensing loop, which enables the inherent current protection to the converter.

To analyze the system behavior, mathematical modeling of the converter is carried out using state space method. Frequency response of converter is obtained using bode plot through MATLAB simulation. Compensator for the system is designed to obtain stable operation of converter.

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Sanjeevikumar et al. (eds.), *Advances in Renewable Energy and Electric Vehicles*,
Lecture Notes in Electrical Engineering 767,
https://doi.org/10.1007/978-981-16-1642-6_7

2 Flyback Converter Operating Principle

The isolated type converters provide a galvanic isolation between the source and load. Because of the isolation, the load is protected from high voltage/current operation of the source. The flyback converter provides the isolation by using a high-frequency transformer A4 paper size Fig. 1 shows the basic flyback converter circuit diagram with transformer equivalent model [1]. Depending on the position of switch flyback converter, operation is divided in two different states. When switch is in ON state, the DC source is connected across the primary magnetizing inductor. The energy is stored in the primary magnetizing inductor. The energy will not transfer into the secondary side with the switch closed position. Because of dot polarity, secondary diode is reverse biased; load is supplied by the capacitor.

When switch is in OFF state, the energy which is stored in the magnetizing inductor is delivered to the transformer secondary winding. With OFF state of switch secondary side diode is forward biased, energy is supplied to the load, and capacitor is charged. The relation between converter input and output voltage is given Eq. 1 [2]

$$V_g = V\left(\frac{D}{1-D}\right)\left(\frac{N_2}{N_1}\right) \tag{1}$$

V_g—Converter DC input voltage
V—Converter DC output voltage
D—Duty ratio of the switch
N_2/N_1—Turns ratio of flyback transformer.

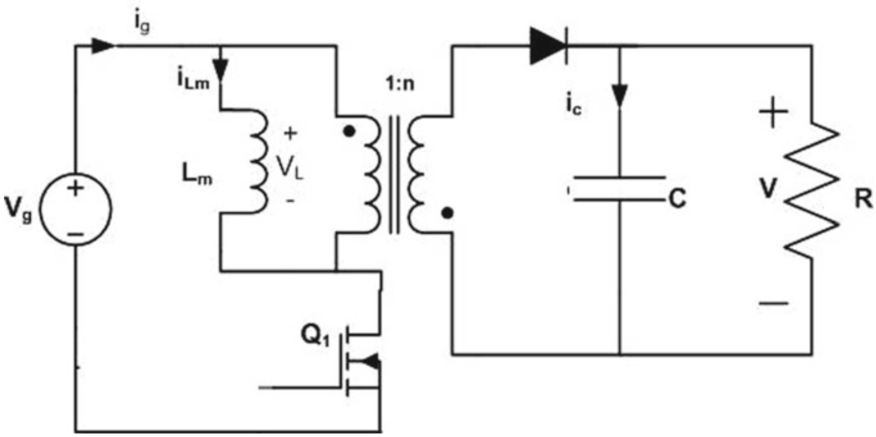


Fig. 1 Flyback converter circuit diagram

3 Peak Current Mode Control

The current mode control is a commonly used method to control DC output of the switched mode power supplies [2]. The peak current through the inductor or switch is controlled in a peak current mode control. The current mode control involves the two feedback loops. Inner loop is a current loop, and outer loop is voltage loop [3]. Figure 2 shows the circuit of flyback converter with peak current mode control.

The fixed frequency clock signal is given to the switch to close it initially, with switch closed the inductor current starts to increase. The error signal is generated by the outer voltage loop by comparing DC output voltage of converter and the required reference voltage. The compensator circuit gives the control signal v_C, and it is compared with the sensed inductor current. When peak current through the inductor reaches the control signal level, at that instant, the turning OFF of switch takes place and inductor current starts to decrease. Figure 3 shows the wave form of current through the inductor $i_{L(t)}$ with slope m_1 during switch closed position, m_2 during switch open position, control signal v_C, and gating signal generated for switch.

Current mode control method has a problem of subharmonic oscillation for the duty cycle exceeding the 50%. To overcome this problem, additional compensating

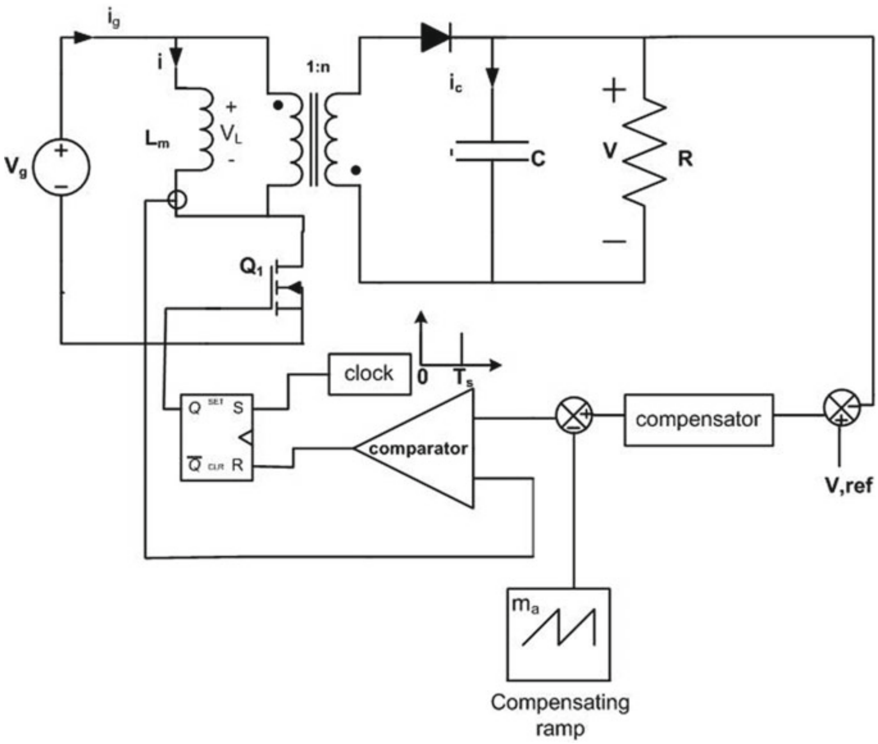
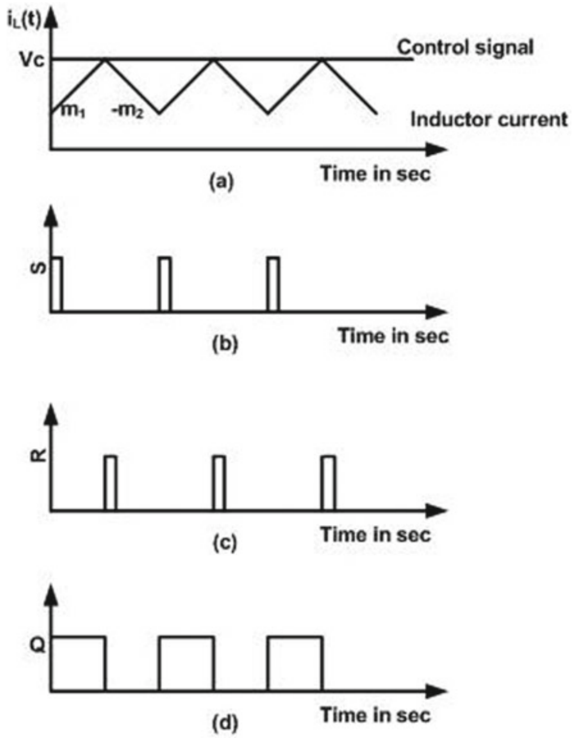


Fig. 2 Flyback converter with peak current mode control

Fig. 3 **a** Inductor current and control voltage, **b** Initial clock set signal to turn on the switch, **c** reset signal to rest the latch, **d** PWM signal given to the switch



ramp signal is added to the control signal v_C. Figure 4 shows the inductor current waveform with subharmonic oscillation. To overcome this problem, additional ramp signal is added to the control signal V_C. Figure 5 shows the ramp signal with slope m_a. The slope chosen for the compensating ramp signal is ½ of m_2, to achieve a stable control.

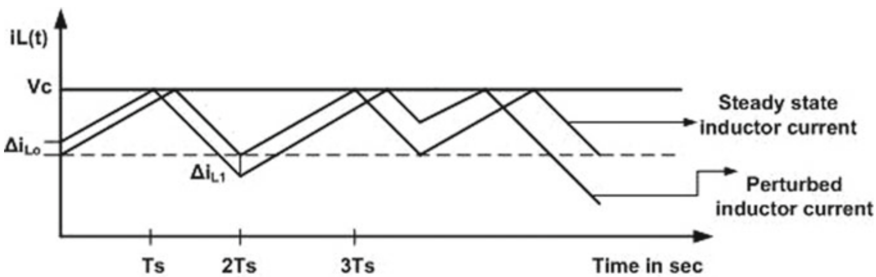


Fig. 4 Inductor current waveform with subharmonic oscillation

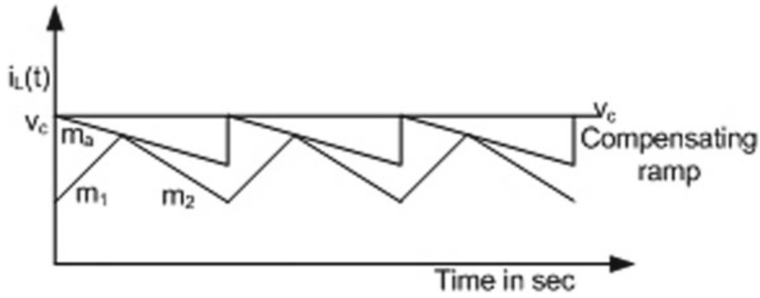


Fig. 5 Compensating ramp signal to suppress the subharmonic oscillation

4 State Space Model of Flyback Converter

The flyback converter equivalent circuit with non-ideal condition, during the switch closed is shown in Fig. 6. For the state space model, the current through the inductor $i_L(t)$ and voltage across the capacitor $v_C(t)$ are considered as state variables. For the interval when switch is closed, the differential equations are given by,

$$L\frac{\mathrm{d}i_L(t)}{\mathrm{d}t} = v_g(t) \tag{2}$$

$$C\frac{\mathrm{d}v_C(t)}{\mathrm{d}t} = \frac{-v_C(t)}{(R + R_C)} \tag{3}$$

$$v(t) = \frac{R}{(R + R_C)}v_C(t) \tag{4}$$

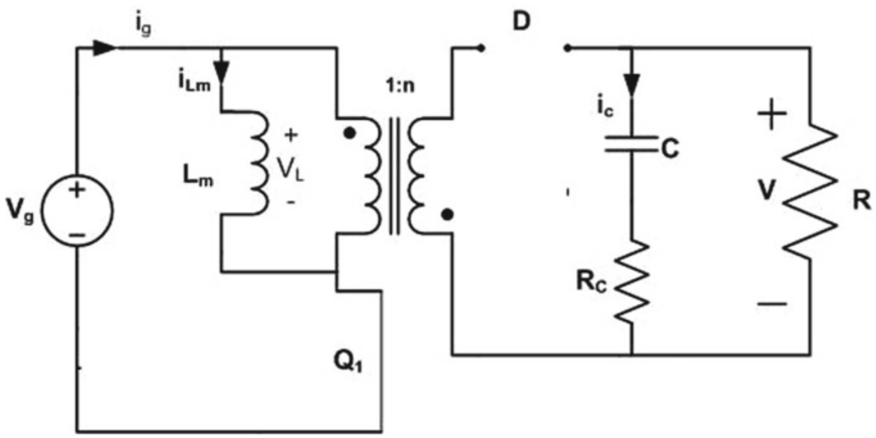


Fig. 6 Flyback converter circuit diagram with switch closed

The representation of the converter in state space model is given by

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dv_C(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{(R+R_C)C} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_g \tag{5}$$

$$v(t) = \begin{bmatrix} 0 & \frac{R}{(R+R_C)} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} \tag{6}$$

Figure 7 shows the flyback converter circuit with switch open. The equations of current though the inductor and voltage across the capacitor are given by

$$L\frac{di_L(t)}{dt} = -\frac{1}{n}\left[\frac{R}{(R+R_C)}v_C(t) + \frac{RR_C}{n(R+R_C)}i_L(t)\right] \tag{7}$$

$$C\frac{dv_C}{dt} = -\frac{1}{(R+R_C)n}v_C(t) + \frac{R}{n(R+R_C)}i_L(t) \tag{8}$$

$$v(t) = \frac{R}{(R+R_C)}v_C(t) + \frac{RR_C}{(R+R_C)n}i_L(t) \tag{9}$$

The state space representation of Eq. (7) to (9) is given by

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dv_C(t)}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-RR_C}{n^2(R+R_C)L} & \frac{-R}{n(R+R_C)L} \\ \frac{R}{n(R+R_C)C} & \frac{-1}{(R+R_C)C} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_g \tag{10}$$

$$v(t) = \begin{bmatrix} \frac{RR_C}{n(R+R_C)} & \frac{R}{(R+R_C)} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} \tag{11}$$

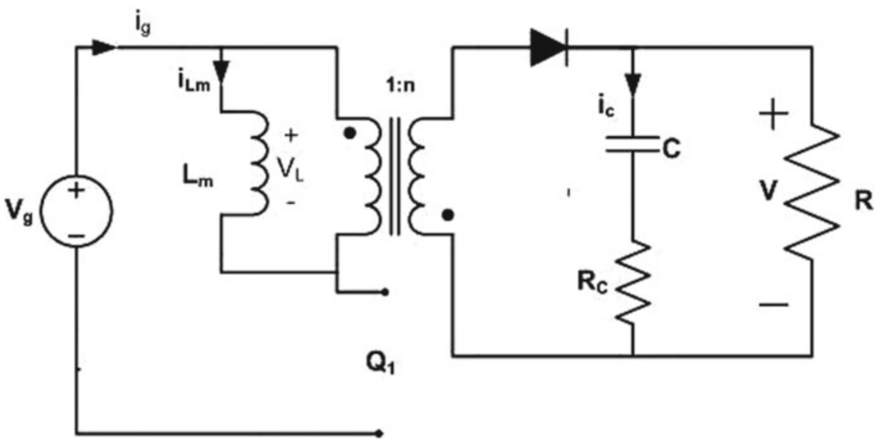


Fig. 7 Flyback converter circuit diagram with switch open

The average current through inductor and voltage across the capacitor is obtained by averaging the subintervals for a switching period.

$$L\frac{\mathrm{d}i_L(t)}{\mathrm{d}t} = v_g(t)\mathrm{d}(t) - \frac{1}{n}\left[\frac{R}{(R+R_C)}v_C(t) + \frac{RR_C}{n(R+R_C)}i_L(t)\right]\mathrm{d}'(t) \tag{12}$$

$$C\frac{\mathrm{d}v_C(t)}{\mathrm{d}t} = \frac{-v_C(t)}{(R+R_C)} + \frac{R}{n(R+R_C)}i_L(t)\mathrm{d}'(t) \tag{13}$$

In order to analyze the dynamic behavior of a converter and to achieve a small signal model, the perturbation is introduced in the input $v_g(t)$ and duty cycle d(t),

$$v_g(t) = V_g + \hat{v}_g(t)$$

$$\mathrm{d}(t) = D + \hat{\mathrm{d}}(t) \tag{14}$$

In response to input perturbation, the current through the inductor, voltage across the capacitor, and output voltage are also perturbed.

Transfer function of power stage is obtained as

$$H_{\mathrm{open}}(s) = G_o \times f_p \times f_h \tag{15}$$

$$f_p = \frac{\left(1+\frac{s}{w_{\mathrm{ESRz}}}\right)\left(1-\frac{s}{w_{\mathrm{RHPz}}}\right)}{\left(1+\frac{s}{w_{p_1}}\right)} \tag{16}$$

$$f_h = \frac{1}{\left(1+\frac{s}{w_{p2}Q_p}+\frac{s^2}{w_{p2}^2}\right)} \tag{17}$$

G_o is the open-loop gain of the power stage. The capacitor ESR zero w_{ESRz}, converter right half plane zero w_{RHPz} is given in Eqs. (18) and (19)

$$w_{\mathrm{ESRz}} = \frac{1}{R_{\mathrm{ESR}} \times C} \tag{18}$$

$$w_{\mathrm{RHPz}} = \frac{R \times (1-D)^2 \times n^2}{L \times D} \tag{19}$$

The damping factor Q_P is given by

$$Q_P = \frac{1}{\Pi \times [m_C \times (1-D) - 0.5]]} \tag{20}$$

$$m_C = 1 + \frac{m_a}{m_1} \tag{21}$$

m_C is the slope compensation factor, m_a is the slope of compensating ramp.

The frequency response of the power stage which has gain of 16 dB is shown in Fig. 8. Converter has a zero due to capacitor ESR at $f_{ESRz} = 2.17$ kHz a right half plane zero at $f_{RHPz} = 23.38$ kHz.

The closed-loop bode plot is shown in Fig. 9. In the compensation loop, a pole is placed at a frequency of 2.17 kHz to cancel the ESR zero of converter. For good phase margin, a compensator zero is placed at 584.5 Hz.

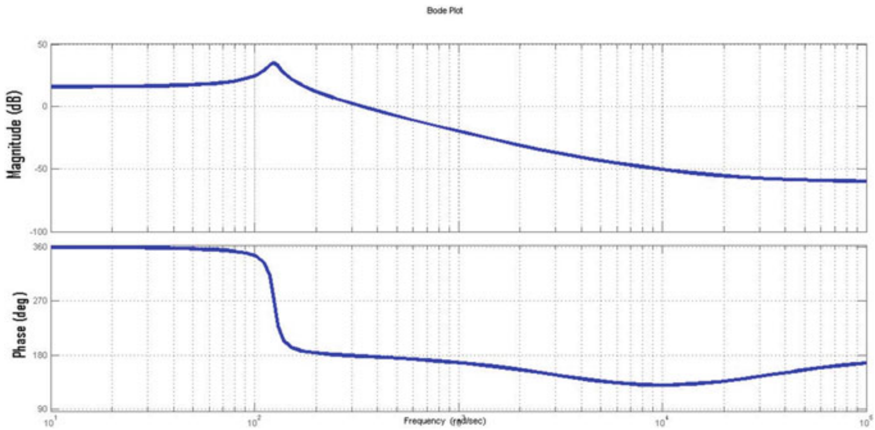


Fig. 8 Open-loop bode plot of converter

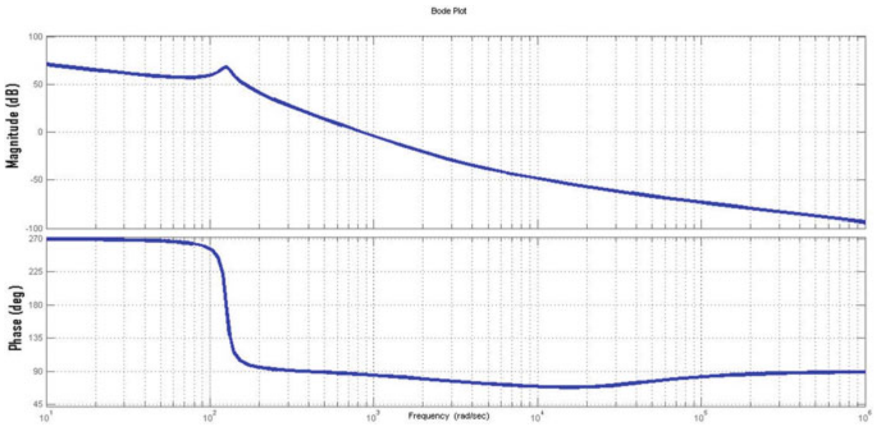


Fig. 9 Closed-loop bode plot of converter

5 Performance Comparision of PID Controller and Artificail Neural Netwok

Artificial neural network has a capability to meet the requirement of various environments which are not linear always.

A neural network block which works on the backpropagation model is used. A general backpropagation neural network model has three layers that is input, output, and middle layer as shown in Fig. 10.

The multi-layer feed forward network has to be trained with different set of examples or data, to obtain a required network behavior. The training process involves tuning the value of biases of the network and weights of the network. Mean square error(mse) is the default network function.

5.1 Neural Network(NN) Predictive Controller

NN predictive controller predicts the future plant performance by using the neural network model of nonlinear plant. The control input is then calculated by the controller to optimize the plant performance. Generally, a neural network model uses previous plant output and input to predict the future output [4].

Table 1 gives the parameter details of the neural network.

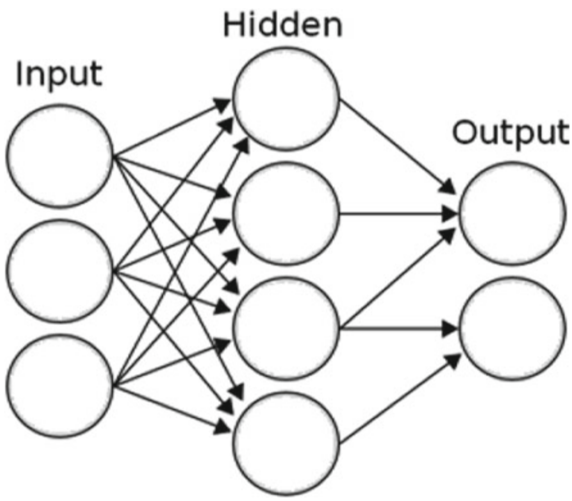


Fig. 10 Feed forward neural network layer

Table1 NN predictive controller parameter

Parameters	Values	Description	Value
Size of hidden layers	4	Cost horizon (N_2)	7
Training epochs	200	Control horizon (N_u)	2
Training function	'trainlm'	Control weighting factor (ρ)	0.005
Training samples	1000	Search parameter (α)	0.001

Table 2 Design specification

Parameter	Value
Switching frequency	40 kHz
Input voltage	325 V
Output voltage	30 V
Output Current	8A

5.2 *Simulation Results*

A flyback converter is simulated in MATLAB/simulink to analyze the performance of PID controller and the NN predictive controller. The converter design parameters are given in Table 2.

Figure 11 shows the output voltage of flyback converter which is simulated in with a PID controller. It is observed that the settling time of the output is about 4 ms.

The circuit is simulated by replacing the traditional PID controller with a NN predictive controller the network trained for the different input and output values. Figure 12 shows the output voltage of the converter with the NN predictive controller it observed that the settling time for the output is about 3 ms.

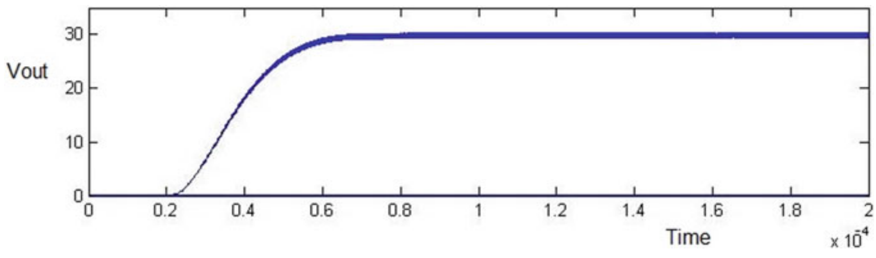


Fig. 11 Flyback converter output with a PI controller

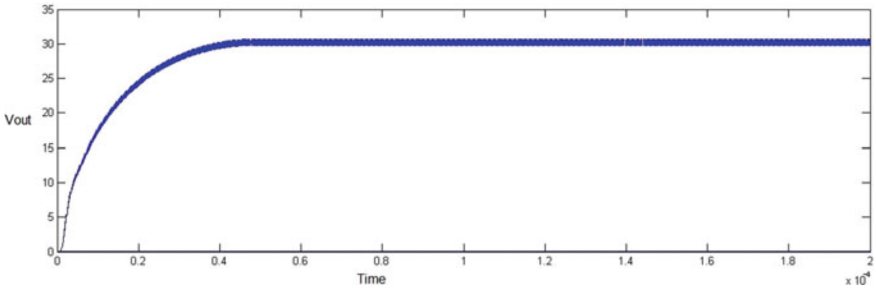


Fig. 12 Flyback converter output with a NN predictive controller

6 Conclusion

The flyback converter is described with peak current mode control, and modeling of flyback converter is explained by the state space model. Closed-loop simulation of converter is done in MATLAB/Simulink with PID controller and NN predictive controller. The result obtained through NN predictive controller is well accepted than the PID controller.

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