A Novel Loss Estimation Technique for Power Converters

K.LAVANYA, B.UMAMAHESWARI, S.K.PATNAIK
Department of Electrical and Electronics Engineering
Anna University
Chennai-600025
INDIA

Abstract: - This paper presents a feasible loss model to Buck converter using Matlab/Simulink. The process of energy conversion within the converter leads to power losses. The power loss modeling using small signal model and an algorithm for loss estimation is proposed which ensures fast convergence without the need for any a priori knowledge of the converter loss related parameters.

Key-Words: - Algorithm, Loss estimation, Simulation, Modeling

1 Introduction

The applications of power electronic devices are extended every year due to the development of the devices. Many efforts are done to obtain fast switching devices with a minimum drive power requirement and to reduce the on state voltage. A key parameter for all those elements is the power losses in the on state and the off state. Whether the design goals are to minimize the size, the losses or a combination of them, calculation of power losses in the power devices is important in converter design. Therefore it is important to model the losses in the power semiconductor devices with the highest accuracy and with a number of changeable parameters.

One approach to determine the losses is to estimate the circuit by the use of device models [3]-[4]. Dependent on the level of the models the accuracy can be different and in many cases if longer simulation runs have to be done, determination of the losses can be very time consuming. An alternative way is to characterize the devices in their different operating states and then model each kind of losses from the characterization. Common for this method is that it describes the losses as a function of load current. Different parameters are extracted from a lot of measurements. For an AC drive power losses are estimated in terms of flux [1].

This paper will present a model of the losses in a buck converter, which takes into account voltage level and current. This paper presents a technique to calculate losses in converters using any type of pulse width modulation strategy or switch without the need of building the complete prototypes for all topologies.

2 System model -Buck Converter

DC-DC buck converter system with non-idealities is shown in Fig.1.The non-idealities considered are the source resistance R1, the passive switch ON state and OFF state drop V_d, parasitic resistances R2, R3 due to inductor and capacitor respectively. The input to the converter is Vs and the output is connected to a DC load R.

2.1 Small Signal Model

The state space representation of the given model is given by:

$$\frac{dx(t)}{dt} = Ax + Bu + Eu_1 \qquad (1)$$

$$y(t) = Cx + Du \qquad (2)$$

The vector x is the state of the system, A is the constant n*n system matrix, B is the constant n*m input matrix, C is the constant p*n output matrix, D is a constant p*m matrix and u and u1 are inputs and y is the output of the system [2][5].

For the sake of simplicity all the elements considered are ideal.

The state variables are:

$x(1) = i$; Converter inductor current

$x(2) = v_c$; Converter capacitor voltage

In this work, buck converter working in continuous current conduction mode is considered.

The state equations are written for both ON and OFF states with the following definitions:

$$x = \begin{pmatrix} i & v_c \end{pmatrix} \qquad (3)$$

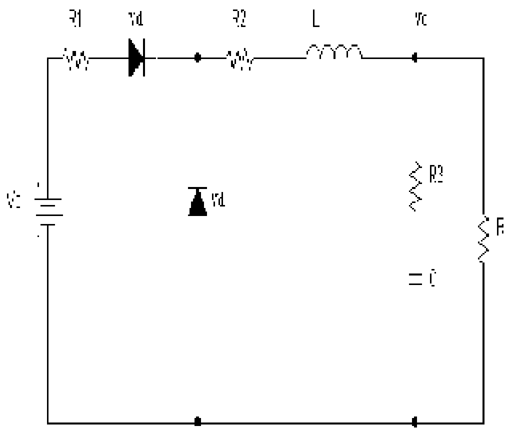

Fig.1.Buck converter with Non-idealities

$$u = v_s \tag{4}$$

$$y = v_0 \tag{5}$$

$$u_1 = v_d \tag{6}$$

The state space equations during ON state are:

$$\frac{dx(t)}{dt} = A_1 x + B_1 u + E_1 u_1 \tag{7}$$

$$y(t) = C_1 x \tag{8}$$

Where

$$A_1 = \begin{pmatrix} \frac{R*R3}{(R+R3)L} & \frac{-R}{(R+R3)L} \\ \frac{1}{C} + \frac{R3}{C(R+R3)} & \frac{-1}{C(R+R3)} \end{pmatrix} \tag{9}$$

$$B_1 = \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix} \tag{10}$$

$$E_1 = \begin{pmatrix} \frac{-1}{L} \\ 0 \end{pmatrix} \tag{11}$$

$$C_1 = \begin{pmatrix} \frac{-R*R3}{R+R3} & \frac{R}{R+R3} \end{pmatrix} \tag{12}$$

The state space equations during OFF state are:

$$\frac{dx(t)}{dt} = A_2 x + B_2 u + E_2 u_1 \tag{13}$$

$$y(t) = C_2 x \tag{14}$$

Where

$A_2=A_1$ (15)

$B_2=0$ (16)

$C_2=C_1$ (17)

$E_2=E_1$ (18)

The converter alternates between the two-switched states at high frequency. To represent the converter through a single equivalent dynamic representation, valid for both the ON and OFF state the following steps are done.

$A = A_1D + A_2$ (1-D) (19)

$B = B_1D + B_2$ (1-D) (20)

$E = E_1D + E_2$ (1-D) (21)

$C = C_1D + C_2$ (1-D) (22)

Where D is the duty cycle.

Hence the state space averaged representation becomes

$$\frac{dx(t)}{dt} = A\,x + Bu + E\,u_1 \tag{23}$$

$$y = Cx \tag{24}$$

To study the small signal behavior, the time varying system described in equation (23) and (24) can be linearized using perturbation technique. We may now consider that the inputs d and V_s are varying around their quiescent operating points D and V_s respectively.

$$d = D + \hat{d}; \frac{\hat{d}}{D} << 1 \tag{25}$$

$$v_s = V_s + \hat{v}_s; \frac{\hat{v}_s}{V_s} << 1 \tag{26}$$

$$v_d = V_d + \hat{v}_d; \frac{\hat{v}_d}{V_d} << 1 \tag{27}$$

These time varying inputs in d and Vs will result in perturbations in the dynamic variables x $\left(X + \hat{x}\right)$ and Vo $\left(V_o + \hat{v}_o\right)$.

When the perturbations in d and Vs are small, the effect of the nonlinear terms will be small on the overall response and hence may be neglected. The small signal model in its final form is given below.

The dc model:

$$0 = AX + BV_s + EV_d \tag{28}$$

Vo=CX (29)

Using the equations (28), (29), (30), (31) (current through inductor, I and output voltage, Vo) the losses in the converter are estimated using the following technique described in the forth coming section.

The ac model:

$$\frac{d\hat{x}}{dt} = A\hat{x} + B\hat{v}_s + E\hat{v}_d + [(A_1 - A_2)X$$

$$+ (B_1 - B_2)V_s + (E_1 - E_2)V_d]\hat{d} \quad (30)$$

$$\hat{v}_o = C\hat{x} + (C_1 - C_2)X \quad (31)$$

3 Power Loss Modeling

Let the current through the source resistance be for d*T_s seconds. Similarly the current through the switch is for d*Ts seconds. Hence the power loss due to the source resistance is R1*d*i^2, the conduction loss due to the switches is V_d*I (during ON state the conduction loss in the passive switch is V_d*d*I and during the OFF state the conduction loss in the switch is V_d*(1-d)*i.). The loss due to the parasitic resistance of inductor is i^2 *R2 and due to parasitic resistance of capacitor is R3*(i-Vo^2/R)^2. The output power is a measure of Vo^2. Hence the input power to the converter is given by the following equation:

$$P_{in}(t) = R1 * d * i^2 + V_d * i + R2 * i^2$$

$$+ R3\left(i - \frac{Vo}{R}\right)^2 + \frac{Vo^2}{R} \quad (32)$$

Rearranging and grouping together we get

$$P_{in}(t) = adi^2 + bi + ci^2 + eV_0^2 + f\,iV_o \quad (33)$$

Where a = R1, b = V, c = R2 + R3, e = 1/R + R_3 / R^2 and f = -2*R3/R. For power loss modeling, parameters a, b, c, e, and f must be accurately known. When the power input measurement is available, exact Pout is needed in order to acquire correct power loss value.

The input power P_{in} and the internal variables are tracked. The acquired data are further correlated and the parameters (a, b, c, e, f) that provide the best fit according to (33) are derived. The measurement errors, and the approximations made in deriving (32), along with a potentially insufficient excitation brought in by the input signals are all in favor of using additional input information. This means acquiring P_{in} samples > 5 sets, leading to redundant set of M equations. The above problem is resolved using Pseudo inverse of rectangular matrix P_{M*5} giving, Wg = | a_g ,b_g, c_g, e_g, f_g $|^T$ as an approximate solution of the equation PW = Y, such that the value of ||PW – Y|| is minimum.Fig.2.

The proposed identification procedure is illustrated in Fig.2. The inputs to the algorithm are the samples of di^2 , i , i^2 , V_o^2 , iV_o and $P_{IN.}$ As the high frequency components do not contribute to the W = |a, b, c, e, f$|^T$ identification, the input signals and the input power P_{IN} are averaged within Q_t intervals, outputting Y ,A_n ,B_n ,C_n ,E_n ,F_n each T= Q_t time units. The averaging is implemented as the sum of Q consecutive T- spaced samples of each signal

$$\int_{nT}^{(n+1)T} Pin(t)dt = a\int_{nT}^{(n+1)T} d(t) * i^2(t)dt +$$

$$b\int_{nT}^{(n+1)T} i(t)dt + c\int_{nT}^{(n+1)T} i^2(t)dt$$

$$+ e\int_{nT}^{(n+1)T} v_0^{\,2}(t)dt$$

$$+ f\int_{nT}^{(n+1)T} v_o(t)i(t)dt \quad (34)$$

The above equation is given as

$$Y = a\,A_N + bB_N + c\,C_N + e\,E_N + f\,F_N \quad (35)$$

The choice of Q becomes crucial for the identifier to operate perfectly. A sequence of M changeless values of Y .... F_N makes the matrix P^TP singular and the desired W_g values are inaccessible. Hence, the averaging interval T = Q_t should allow most of the input disturbance energy related to the speed error fluctuations to pass into matrix P, providing in such a way sufficient excitation for the W_g identification.

P (M*5) matrix is created from M successive values of A_N,B_N,C_N,E_N,F_N. Y is a vector of size M*1. The credibility of W_g , obtained from the PINV block, relies on the excitation energy contained in the input signals. Hence, in the absence of any input disturbance the matrix P becomes deficient and the W_g values obtained from P should be discarded.

The indication of matrix P getting near to being singular or rank deficient is its smallest singular value. [1]. Laborious evaluation of 5*5 matrix eigen values is avoided by considering det (P^TP) already available as an intermediate result of the matrix P^TP inversion in the block PINV in Fig 3. Finally, the P-matrix spectral norm and the confidence in W_g are measured by W_w = det $(P^TP)^{0.2}$.

The possibility of eventual long-term operation with all the drive variables at constant value prevents the parameters in W_g from being directly used by the loss function in (33). The identification mechanism given in Fig.3 therefore tracks the difference ΔW between the stored W_e integrator output and the acquired W_g .

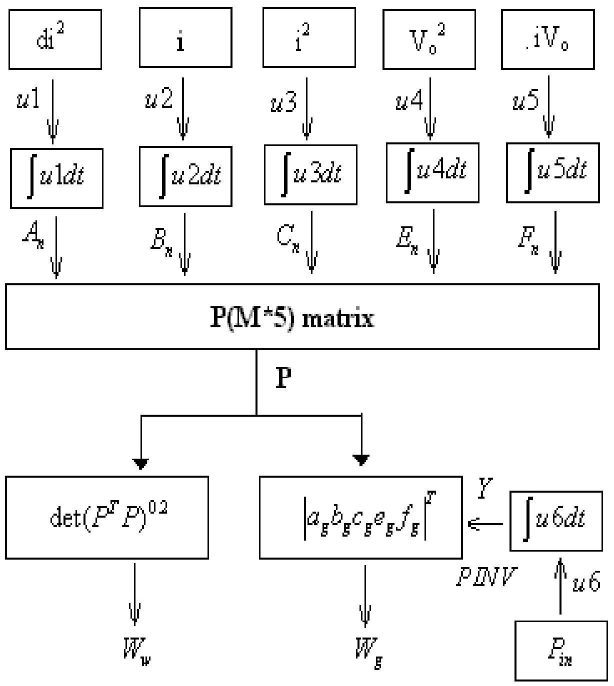

Fig 2 Formulation of Loss function

Whenever the "weight" signal W_W exceeds minimum value (min in Fig.3), indicating a satisfactory amount of energy in P matrix and a sufficient reliability of W_g parameters and the convergence of the W_e output toward the W_g input .The value of G_{MAX} limits the maximum rate of W_e change.

4 Results

Using the circuit in Fig.1, the buck converter was simulated at a constant input voltage with the following parameter values.

V_s= 24 V R1 = 0.01 Ω R2= 0.1Ω R3 = 1Ω R=10 Ω L = 0.1 H C = 0.01 F duty cycle = 0.8

4.1 Open loop response

Fig.4 shows the output voltage and current response under open loop control with step change. With these values at each instant the losses in inductor and capacitor due to parasitic resistances is calculated. Fig 4 shows these anticipated losses.

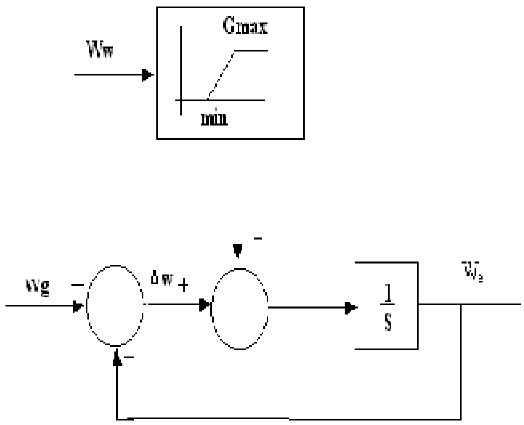

Fig. 3 Identification of Parameters.

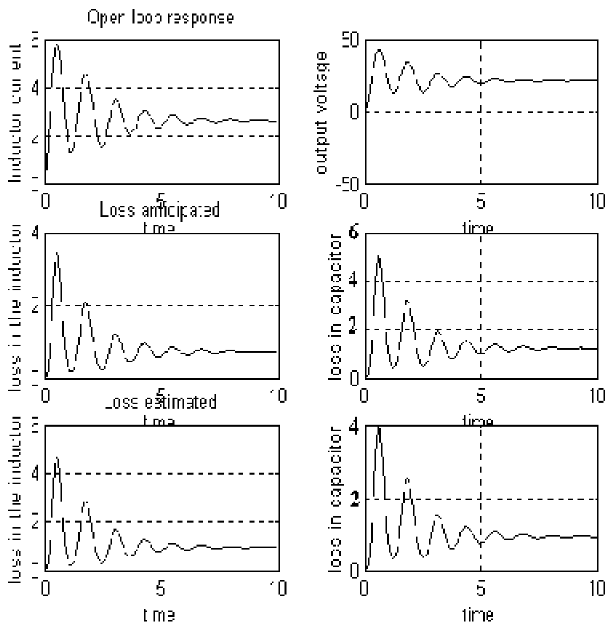

Fig.4 Open loop response, losses anticipated and losses estimated

4.2 Parameter identification and losses estimated

Loss function parameters as in (35) are identified and are listed in Table.1. Fig.4 shows the losses that are estimated.

Table.1

	Parameters used	Parameters estimated
R	10 Ω	9.8 Ω
R1	0.01 Ω	0.03 Ω
R2	0.1 Ω	0.12 Ω
R3	1Ω	1.07 Ω

5 Conclusion

Using Matlab/Simulink the small signal model of the buck converter is realized. With the simulated current and output voltage, the parameters in the circuit are identified and the losses are estimated. The above-discussed technique can be used to find the parameters involved in any circuit without any prior knowledge of the system considered.

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