

The Generalized Switched Inductor Model (GSIM): Accounting or Conduction Losses

Isaac Zafrany¹

¹Technical Support
Avant! Corporation
11 Galgaley Haplada St.
P. O. Box 12086
Herzeliya 46733
ISRAEL

Tel: +972-9-954-8555; Fax: +972-9-647-2949;
Email: Isaac_zafraany@avanticorp.com;
Website: <http://www.avanticorp.com>

Sam Ben-Yaakov*

*Power Electronics Laboratory
Department of Electrical and Computer
Engineering
Ben-Gurion University of the Negev
P. O. Box 653, Beer-Sheva 84105
ISRAEL

Tel: +972-8-646-1561; Fax: +972-8-647-2949;
Email: sby@ee.bgu.ac.il;
Website: <http://www.ee.bgu.ac.il/~pel>

Abstract - The method of average modeling and simulation of PWM converters was extended to include conduction losses. The method covers losses due to the inductor's resistance and due to the voltage drops across the switch and the diode. The same model is applicable to both CCM and DCM operations, and the switching from one to the other is automatic. The large-signal model is SPICE compatible and as such can be used to run DC (steady state), TRAN (large signal, time domain) and AC (small signal, frequency domain) analyses.

I. INTRODUCTION

As previously shown [1-6], classical PWM converters share a common, topology independent switching module: a switched inductor (Fig. 1a). Although normally realized by a switch and a steering diode, the switching action with ideal diode can be described by a toggle switch which alternately connects one end of the inductor to two terminals b and c (Figs. 1a, b). A Generic Switched Inductor Model (GSIM) which includes three dependent current sources (Fig. 1c) was used to describe the interaction of the switched inductor module with the interface circuitry. The dependent sources of the (GSIM) represent the average terminal currents of the switched inductor assembly [1-6].

The GSIM models described earlier did not accurately take into account conduction losses. These affect not only the efficiency but can also

change the large and small signal transfer functions. The objective of this study was to expand the GSIM methodology to include conduction losses due to the inductor's resistance, the voltage drops across the switch and diode.

II. THE BASIC GSIM WITH NO LOSSES

The GSIM topology-independent equivalent circuit is developed by considering the average voltage across the inductor V_L . Examination of the switched inductor assembly (Figs. 1b,c) reveals that V_L is a function of the voltage across the terminals $V_{(a,b)}$, $V_{(a,c)}$ and the time that the switch is in the ON (T_{ON}) and OFF (T_{OFF}) positions:

$$E_L \equiv V_L = \frac{V_{(a,b)} T_{on} + V_{(a,c)} T_{off}}{T_s} = V_{(a,b)} D_{on} + V_{(a,c)} D_{off} \quad (1)$$

where T_s is the period of the switching cycle, $D_{on} = T_{on}/T_s$, $D_{off} = T_{off}/T_s$.

The average voltage impressed on the inductor will develop the corresponding average current. Once the current is available, the dependent current sources of the GSIM model (Fig. 1c) can be readily defined by considering the way by which the current is split between the terminals. Since the current of terminal (a) is identical to the inductor current ($I_{L,av}$) the dependent current source G_a can be defined as:

* Corresponding author

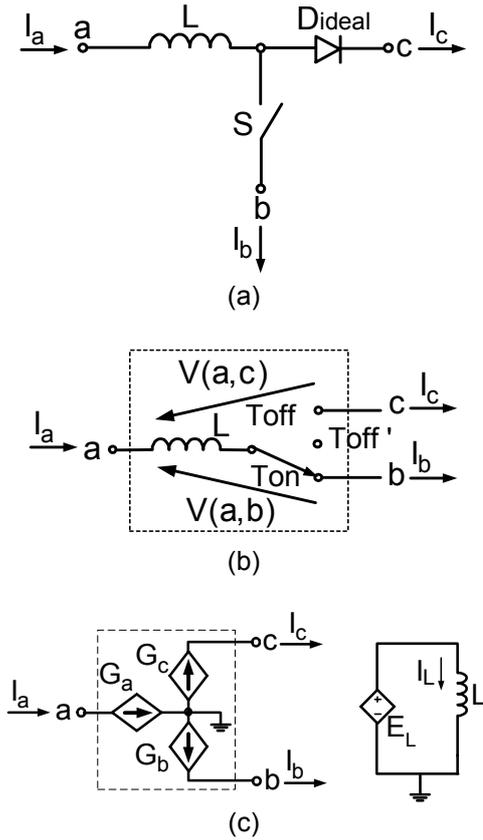


Fig.1. The average simulation method. (a) Switched inductor in PWM topologies. (b) Switched inductor assembly. (c) The Generic Switched Inductor Model (GSIM) [1-6].

$$G_a \equiv I_{Lav} \quad (2)$$

The current is then divided between terminals (b) and (c) (Figs. 1b,c) according to the fraction of time the inductor is connected to them, namely:

$$G_b \equiv \frac{I_{Lav} D_{on}}{D_{on} + D_{off}} \quad (3)$$

$$G_c \equiv \frac{I_{Lav} D_{off}}{D_{on} + D_{off}} \quad (4)$$

where in case of continuous conduction mode (CCM) (Fig. 2a):

$$(D_{on} + D_{off}) = 1 \quad (5)$$

and therefore:

$$D_{off} = 1 - D_{on} \quad (6)$$

In the case of discontinuous conduction mode (DCM): $D_{off} < 1 - D_{on}$. From geometrical consideration [2-4] the expression for D_{off} will be:

$$D_{off} = \frac{2I_{Lav} L f_s}{V_{(a,b)} D_{on}} - D_{on} \quad (7)$$

For the case of DCM the dependent current sources G_b and G_c (eqs. 3,4) are normalized by $(D_{on} + D_{off})$ in order to obtain the correct average current during the conduction intervals of the inductor: T_{on} and T_{off} [2-4].

The GSIM model can be made to automatically follow CCM-DCM changes by selecting D_{off} according to the rule:

$$D_{off} = \min \left\{ (1 - D_{on}), \left(\frac{2I_{Lav} L f_s}{V_{(a,b)} D_{on}} - D_{on} \right) \right\} \quad (8)$$

where $f_s = 1/T_s$ - switching frequency

In SPICE implementation of the GSIM, analog behavioral dependent sources are used to emulate E_L , G_a , G_b and G_c . Further, since SPICE recognizes time dependent variables which are either voltage or currents, D_{on} and D_{off} are coded into voltage. The minimum function (8) is recognized as a valid expression by most modern circuit simulators. Consequently, the simulation model will automatically follow a CCM to DCM change by selecting the correct D_{off} for each case. Another important feature of the GSIM is that it can be used as-is to run DC (steady state), TRAN (large signal, time domain) and AC (small signal, frequency domain) analyses. The latter is due to the fact that the GSIM is formulated as SPICE compatible large-signal model that is automatically linearized by the simulator before running the AC analysis. No further derivations are needed beyond the formulation of the large signal model.

III. THE GSIM WITH LOSSES

The circuit of Fig. 2a represents the problem on hand. It shows that the basic switched inductor assembly includes additional elements: the resistance of the inductor, the voltage drop of the transistor and the voltage drop across the diode. These effects can be taken into account by adding the additional voltage drops to the original port's voltages (a' , b' , c' in Fig 2a). However, care should be taken to account for the fact that the voltage drops are, in general,

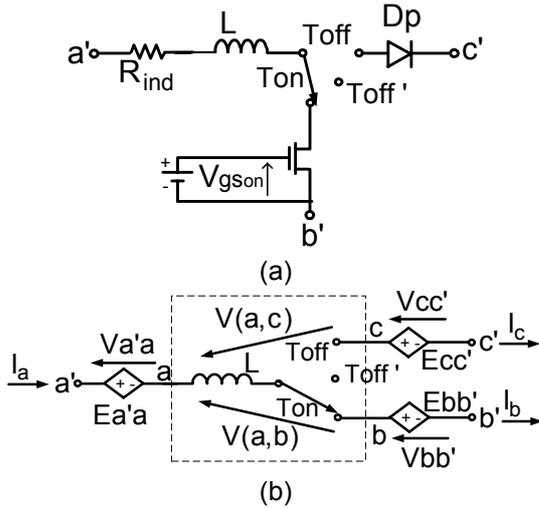


Fig. 2. Proposed modeling steps. (a) Switched inductor in PWM topologies with conduction losses. (b) Generalized model of switched inductor assembly.

not a function of the average current that is passing through a given port, but rather to the average current during the time that the inductor is connected to a given port. For example, the model should take into account the fact that when the inductor is connected to the transistor (Fig. 2a), the relevant voltage drop is a function of the average voltage drop across the transistor during the T_{on} time. This fine detail is especially important in DCM that may be characterized by a high current during T_{on} but having a low average current (when computed over T_s). It follows then that additional dependent sources: $E_{a'a}$, $E_{bb'}$ and $E_{cc'}$ (Fig 2b) that account for the parasitic voltage drops need to be formulated in term of the added voltage seen by the inductor when connected to a given port. Under these conditions, the average voltage across the inductor (V_L) will be:

$$V_L = \{V(a', b') - V(a'a) - V(bb')\} D_{on} + \{V(a', c') - V(a'a) - V(c', c)\} D_{off} \quad (9)$$

The method used to derive the expressions for $E_{a'a}$, $E_{bb'}$ and $E_{cc'}$ is explained with reference to Fig. 3. Here we distinguish between the average inductor current (I_{Lav}), which is averaged over T_{on} , and I_{Ls} , the average current during the conducting interval $T_{on} + T_{off}$ (Fig. 3). From basic geometrical considerations we find:

$$I_{Ls} = \frac{I_{Lav}}{D_{on} + D_{off}} \quad (10)$$

In the private case of CCM:

$$I_{Ls} = I_{Lav} \quad (11)$$

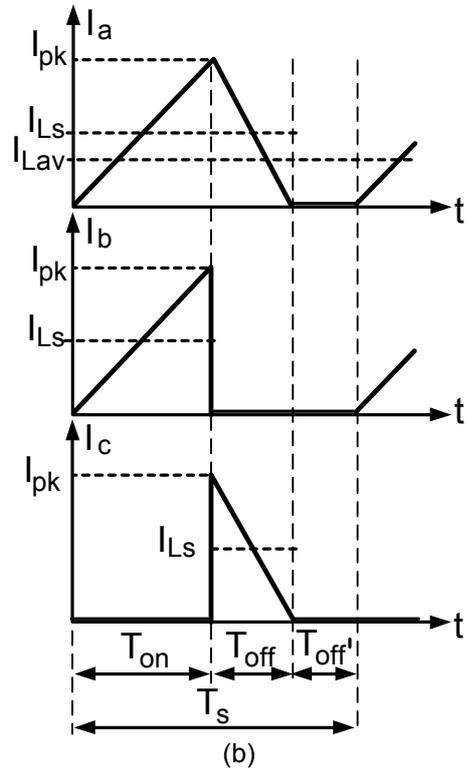
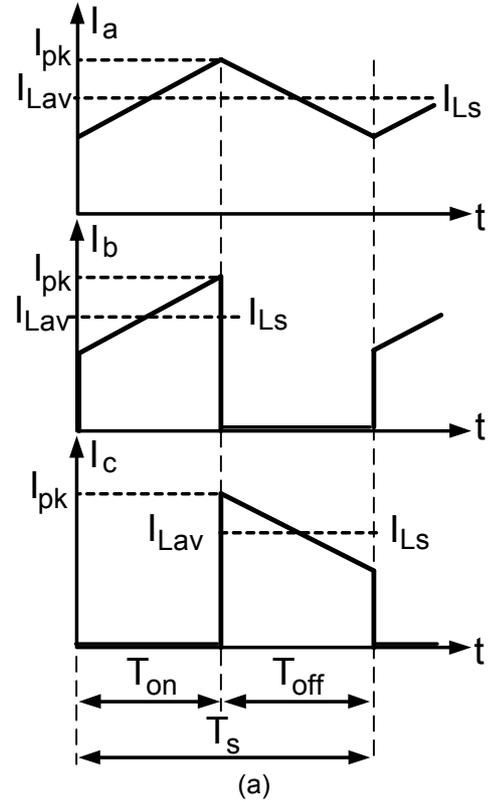


Fig. 3. Waveforms of terminal currents of the switched inductor assembly: (a) under CCM, (b) under DCM.

Base on the above we can now define dependent voltage sources that will emulate the parasitic voltage drops:

$$E_{a'a} \equiv V_{a'a} = I_{Ls} * R_{ind} \quad (12)$$

$$E_{bb'} \equiv V_{bb'} = V(\text{Switch_Model})@I_{Ls} \quad (13)$$

$$E_{cc'} \equiv V_{cc'} = V(\text{Diode_Model})@I_{Ls} \quad (14)$$

where $V(\text{Switch_Model})@I_{Ls}$ and $V(\text{Diode_Model})@I_{Ls}$ are the actual voltage drops across the transistor and diode respectively when the current I_{Ls} is passing through them.

These voltage sources account for the real voltage drops that are caused by the actual current flowing through the parasitic elements: inductor's resistance, transistor and diode. By this method we can expand the generalized model (Fig. 1c) to include the effect of conduction losses. The approach takes into account the physical characteristics of the elements by applying the SPICE models of the actual switch (MOSFET, IGBT etc.) and diode and by calculating the voltage drops for each instance of the simulation. In the absent of SPICE model, one can use linear models to take into account the resistances and voltage offset (if any) of the elements. It should be noted that except for the added voltage sources $E_{a'a}$, $E_{bb'}$ and $E_{cc'}$, the model is identical to the original GSIM (Fig. 1c).

IV. SPICE IMPLEMENTATION

The proposed generalized model can be used to develop input files for general purpose electronic circuit simulator which includes algebraic behavioral models. To simulate a given topology, the model has to be placed in the corresponding orientation.

The proposed model is demonstrated by considering a Boost converter with practical parasitic losses R_{ind} , D and S (Fig. 4a). The power stage is reduced to SPICE-compatible circuit (Fig. 4b) by applying the generalized model (Fig. 2b). The dependent voltage sources $E_{a'a}$, $E_{bb'}$ and $E_{cc'}$ duplicate the voltage drops V_{Rind} , V_{SWon} and V_D , respectively. These voltage drops are generated on 'the fly' during the simulation by passing the I_{Ls} current (calculated each instance) via the models of the diode and switch. Consequently, the voltage drops represent the actual voltage that the inductor will see as it connects to the corresponding elements. The definition of the dependent

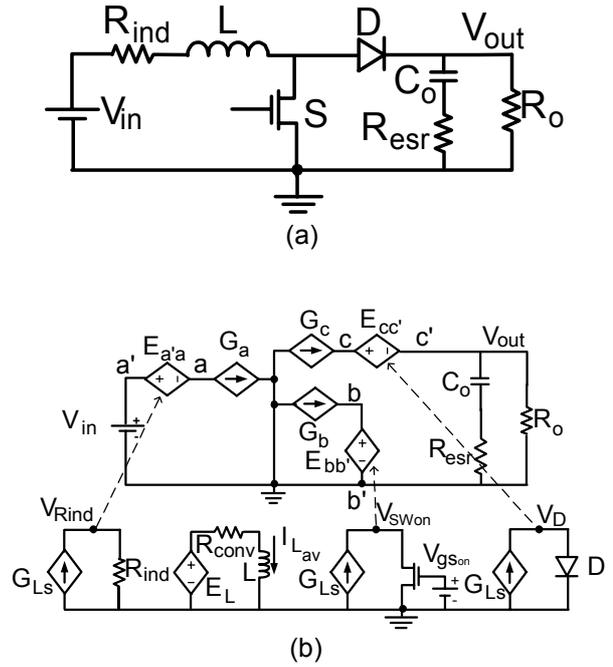


Fig. 4. Simulation circuit. (a) Benchmark circuit used to demonstrate the proposed simulation approach. (b) SPICE compatible average model for benchmark circuit. See text for definition of behavioral dependent sources.

sources are as given above. R_{conv} is a small resistor placed to prevent a short at DC (when the simulator shorts the inductor during the evaluation of the bias point). Missing in Fig. 4b is the voltage junctions that represent D_{on} and D_{off} [5,6]. D_{on} is the primary drive that can be generated by an independent voltage source (for open loop simulation) or a function of the output voltage of the error amplifier for close loop simulation [2-4]. Simulation can be carried out for voltage mode control or current mode control (average or peak) by applying the proper Duty Cycle Generator (DCG) [5, 6].

V. SIMULATION RESULTS

The proposed generalized model (Fig. 4b) was verified against a time domain (cycle-by-cycle) simulation of the complete circuit. The parameters of the converter were as follows: $V_{in}=10V$, $D_{on}=0.25$, $R_{ind}=0.08\Omega$, $L=75\mu H$, practical diode MUR405 (from Orcad Version 9 library), $C_o=220\mu F$, $R_{esr}=0.07\Omega$ and switching frequency $f_s=100KHz$. In these runs, the transistor model was replaced by a resistor

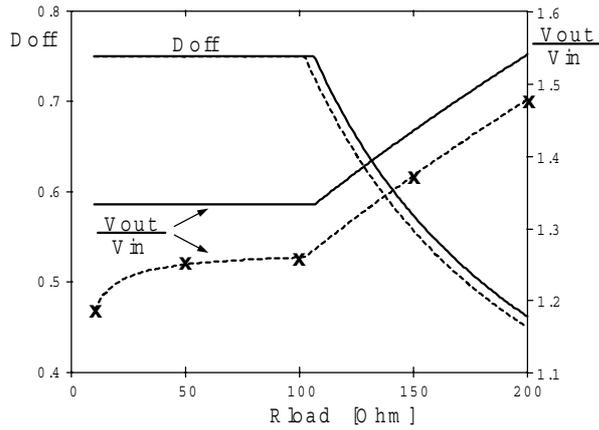


Fig. 5. DC transfer function and D_{off} of lossless converter (solid line) and lossy converter (dashed line) verified against cycle-by-cycle simulation results (crosses).

($R_{SWon} = 1\Omega$) rather than a SPICE model as shown in Fig. 4b. This demonstrates the versatility of the model that can either apply full SPICE models or piecewise linear models.

The solid line in Fig. 5 shows the DC transfer function V_{out}/V_{in} and D_{off} as a function of the value of the load resistance R_{load} - under continuous and discontinuous operating conditions of the ideal converter. For the converter with conduction losses, a very good agreement between the proposed generalized model (Fig. 5, dashed line) and the cycle-by-cycle simulation results (depicted by X) is observed over the whole load range.

The open-loop small-signal transfer functions between duty cycle and output voltage $V_{out}/V_d(f)$ (Fig. 6) were obtained by running two sets of simulations: for DCM and CCM. The resulting Bode plots of $V_{out}/V_d(f)$ and phase under deep DCM condition ($R_{load} = 200\Omega$,) are shown in Fig. 6a, and under CCM condition ($R_{load} = 10\Omega$) - in Fig. 6b. The solid lines in Fig. 6 represent the transfer functions of the lossless converter and the dashed lines are for the converter with parasitic losses. Crosses and circles mark the cycle-by-cycle simulation results, which were obtained by Star-Hspice (Avant! Corp.). Excellent agreement is observed between the simulation results obtained by the proposed generalized model (lines) and the cycle-by-cycle simulation results over most of the frequency range. The discrepancy at high frequency reflects the inaccuracy of the average modeling method when the frequency of the modulated signal approaches the switching frequency.

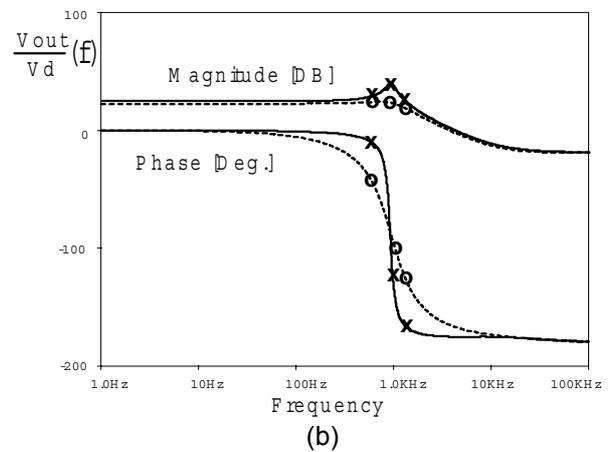
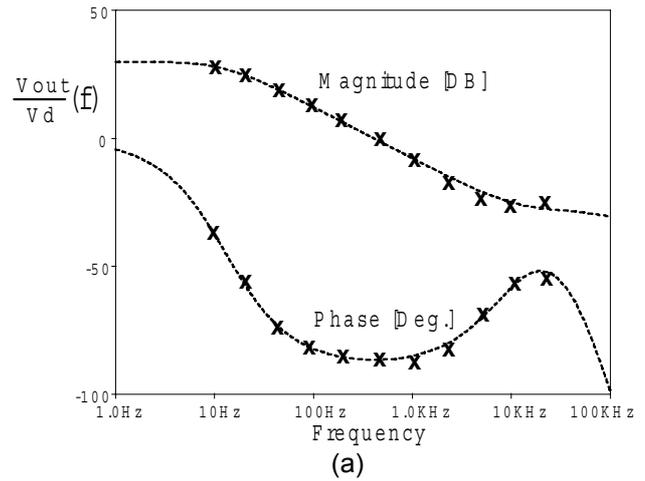


Fig. 6. Small signal output-voltage to duty-cycle transfer function of Boost converter (Fig. 4) under DCM (a) and CCM (b). Solid lines: ideal converter. Dashed lines: lossy converter. Discrete points (crosses and circles): results of cycle-by-cycle simulation.

VI. CONCLUSIONS

The modified GSIM methodology presented here can be used to estimate conduction losses, large signal transfer function and the real small signal transfer functions that take into account the damping effect of the losses. The method provides an estimate of the power dissipation of the inductor, switch and diode caused by conduction losses. By taking the ratio of output to input power the efficiency (associated with conduction losses) can be also easily obtained. These could help to optimize the design of switch mode systems.

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