01 Aug 2004

A Method of Including Switching Loss in Electro-Thermal Simulations

Jonathan W. Kimball
Missouri University of Science and Technology, kimballjw@mst.edu

A Method of Including Switching Loss in Electro-Thermal Simulations

Jonathan W. Kimball, *Member*

Grainger Center for Electric Machinery and Electromechanics
University of Illinois at Urbana-Champaign
1406 W. Green St., Urbana, IL 61801 USA

Abstract – **Often, power electronics systems are simulated with ideal switching elements, perhaps augmented with conduction loss models. A behavioral model is proposed that also includes switching loss and is independent of switching frequency. Therefore, it is suitable for variable frequency control methods, including hysteresis, delta modulation, and random PWM. Models have been realized in Dymola using voltage-controlled voltage sources, current sources, logic, and additional ideal switches. Thermal ports are included to facilitate electro-thermal simulation. A method for parameter extraction is demonstrated using experimental data from standard PWM.**

I. INTRODUCTION

Models used in power electronics simulation are typically either extremely complex or simple conduction loss models. Neither type is directly suitable for electro-thermal simulation. A model of moderate complexity is derived to include switching loss in addition to conduction loss in an IGBT switching pole.

Most models previously published are fundamentally physics-based. A comprehensive review [1] of these models is available, although new models are still being developed. Physics-based models are useful for highly detailed power electronics design, such as gate drive design, but are inappropriate in system-level studies. There are also a few behavioral models that have been published. In [2], a model is built in Simulink with a parallel capacitor to model switching behavior. A more complex system developed in [3] attempts to model each voltage and current transition in a switching event. Similar to [2], the method in [4] uses a nonlinear capacitor to model switching behavior more accurately. The intent of the models in [2]-[4] is to study voltage transients such as occur on motor cabling. Each of these methods relies on detailed information about switching transients, perhaps measured by an oscilloscope. Unfortunately, such measurements are useful for voltage transient studies, but are notoriously unreliable as power measurements due to limited dynamic range and unknown synchronism between current and voltage measurements.

The proposed method simplifies the rise and fall of voltage and current at each switching event. The model addresses only power loss and its effect on slowly-changing currents and voltages. These effects can be found in simulation using square pulses to replace the complex, near-triangular power pulse. The resulting model is inherently faster to simulate than the previously proposed models. Parameters are obtained from dc voltage, dc current, and calorimetry, eliminating most or all of the issues related to the use of an oscilloscope.

II. MODEL DERIVATION

We will consider only a "buck" switch pole, shown in Fig. 1. The derivation for a "boost" pole, in which the controlled switch and diode are swapped, is equivalent with logic and polarity inversions. All non-isolated converters, and many isolated ones, contain one of these two basic switch poles.

The switch pole is defined by a voltage port (input voltage in a buck converter) and a current port (output current in a buck converter). It receives a logic signal that determines the state of the active switch. The diode is on when its current is positive, and is off when its voltage is negative.

Consider the idealized waveforms of Fig. 2. The characteristics of a typical IGBT and corresponding soft fast free-wheeling diode (FWD) are shown. Switching losses are significant in the IGBT, since its terminal voltage is high while commutating the current. Switching losses are low but not zero in the FWD due to reverse recovery current. Some manufacturers cite E_{rec} for their IGBT/FWD modules, particularly those of high current and voltage ratings, to account for this loss mechanism.

The waveforms shown in Fig. 2 are complicated for a simulation to track. There are multiple dv/dt and di/dt slopes related to various capacitances in the two devices. Most

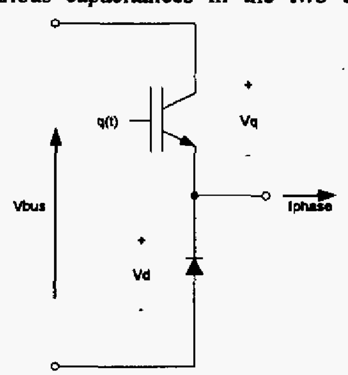

Figure 1: Buck-Derived Switch Pole

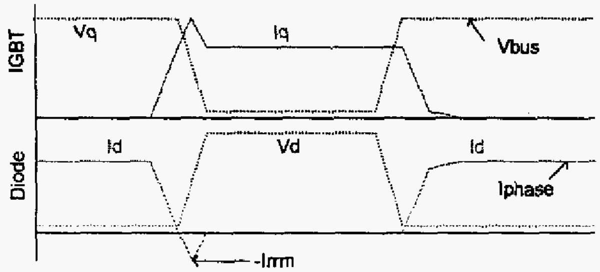

Figure 2: Idealized Switching Waveforms

troubling for electro-thermal simulation is tail current, the residual current after most of the current commutates from the IGBT to the FWD. Although only a small percentage of the main terminal current, this condition can add up to a significant amount of energy due to high voltage across the IGBT. Additionally, tracking all of these transients requires a simulation time step much shorter than the switching period. For example, a typical IGBT switching event is complete within 1 μs, so a reasonable time step might be 10 ns. Compare this with a typical switching period of 50-500 μs, and it becomes clear that the simulation will bog down at every switching event, greatly extending simulation time.

A preferred model is one that does not have any slopes, but instead is composed of steps. Some simulation programs struggle with such a model, but the better ones, such as Dymola and ACSL, can handle a step change in anything but a state variable with little simulation overhead.

First, we assume that IGBT switching energy varies linearly with current. This is not strictly true, but is a reasonable approximation for many technologies. Then the energy dissipated at each switching instant is:

$$E = kV_{bus}I_{phase}t_{sw} \tag{1}$$

Ordinarily, one would have two energies, E_{on} and E_{off}, and t_{sw} would be different for each (t_{on} and t_{off}). The parameter k is a proportionality constant. Essentially, the rest of the expression represents a square wave whose value is equal to the peak power dissipation. It is common to use a square wave to represent a half-sine or triangular pulse of power in thermal calculations [5]. The requirement is that the maximum value of the square wave is equal to 70% of the actual peak power, and the total energy is equal. This requirement is met by setting $k=0.7$ and calculating t_{sw} not from waveforms, but from energy equivalence.

Given the form of (1), it is straightforward to define a model. At each switching instant, instead of simply turning the IGBT on or off fully, insert a voltage-controlled voltage source (VCVS) in series with the IGBT. The VCVS is controlled by Vbus with a proportionality of $k=0.7$. The timing is controlled by a monostable one-shot programmed for the relevant t_{sw}.

The above method takes care of E_{off} in an IGBT and a portion of E_{on}. The model must take into account the reverse-recovery phenomenon, which leads to E_{rec} and the remainder of E_{on}. E_{rec} can be given by:

$$E_{rec} = \frac{kI_{rrm}V_{bus}t_{rr}}{2} \tag{2}$$

The factor of ½ results from the transitioning of the terminal voltage during reverse recovery. Here, t_{rr} is calculated from energy balance again, rather than being measured from waveforms. The same amount of energy adds to E_{on}, so a complete form is:

$$E_{on} = kV_{bus}I_{phase}t_{on} + \frac{kI_{rrm}V_{bus}t_{rr}}{2} \tag{3}$$

This additional factor accounts for much of the nonlinearity of switching energy. I_{rrm} is largely independent of phase current, depending instead on diode construction and applied voltage and di/dt.

Equations (2) and (3) imply a model composed of a switched current source of magnitude kI_{rrm} turned on for time t_{rr}. For electro-thermal simulation, half of the losses are apportioned to the IGBT, half to the FWD.

To make the model complete, conduction losses must be considered. Modern IGBTs and, to a lesser extent, FWDs can be modeled accurately as a voltage source plus a resistance. Most simulation software cannot handle a model of a diode that includes infinite resistance in the off-state, so a large resistance (~10^6 Ω) is used.

Idealized waveforms of the model are shown in Fig. 3. A high-level Dymola model is shown in Fig. 4. A complete library is available [6] that includes buck, boost, half-bridge, and six-pack configurations along with useful building blocks. An excerpt, the underlying text of Fig. 4, is given in the Appendix.

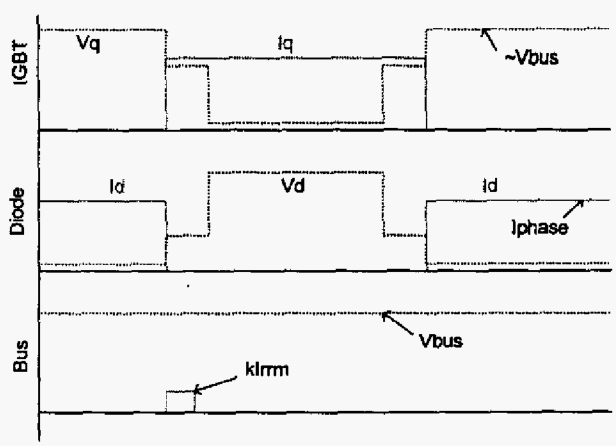

Figure 3: Model Waveforms

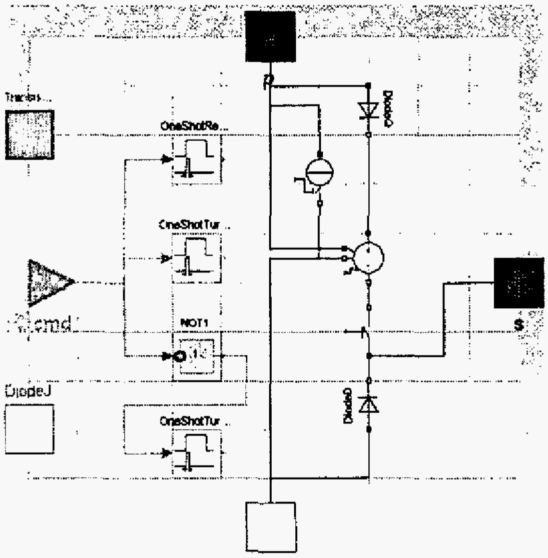

Figure 4: Dymola Model (Some Connections in Text)

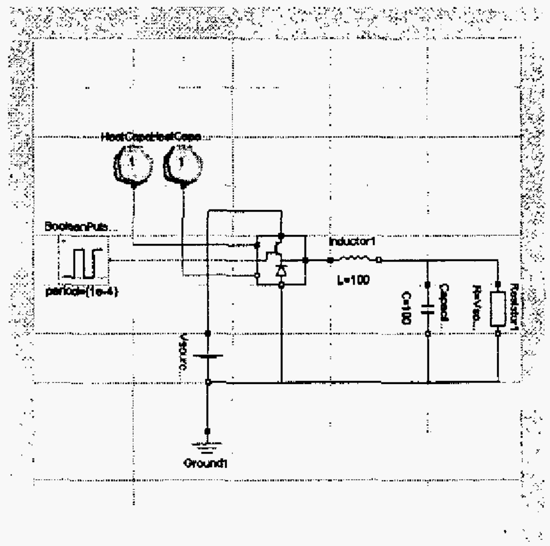

Figure 5: Buck Converter for Validation Study

III. ANALYTICAL VALIDATION

As a first check, the model shown in Fig. 4 was inserted in a complete buck converter, shown in Fig. 5, and simulated. For this circuit, operating at fixed frequency f_{sw} and duty cycle D, power dissipation in the IGBT and FWD can be found analytically:

$$\begin{aligned} P_{Q1} &= D\cdot\left(V_{on,Q}+R_{on,Q}I_{out}\right)\cdot I_{out}+\ldots \\ &\quad \left(E_{on}\left(I_{out},V_{in}\right)+E_{off}\left(I_{out},V_{in}\right)\right)\cdot f_{sw} \\ P_{D1} &= \left(1-D\right)\cdot\left(V_{on,D}+R_{on,D}I_{out}\right)\cdot I_{out}+\ldots \\ &\quad E_{rec}\left(I_{out},V_{in}\right)\cdot f_{sw} \end{aligned} \tag{4}$$

Since the load is effectively a constant current source (100 H connected to an RC pair) and the input is a constant voltage source, the energy terms are all constant. Conservation of energy dictates:

$$V_{out}I_{out}+P_{Q1}+P_{D1}=V_{in}I_{in} \tag{5}$$

where all quantities are the dc values (averaging out any ripple or pulsation). The input current is the IGBT current:

$$\begin{aligned} I_{in} &= DI_{out}+kI_{rrm}t_{rr}f_{sw} \\ t_{rr} &= \frac{2E_{rec}\left(I_{rated},V_{rated}\right)}{kI_{rrm}V_{rated}} \end{aligned} \tag{6}$$

So the expected average V_{out} is:

$$V_{out}=\frac{1}{I_{out}}\left(V_{in}\cdot\left(DI_{out}+kI_{rrm}t_{rr}f_{sw}\right)-P_{Q1}-P_{D1}\right) \tag{7}$$

For given values of k, D, f_{sw}, and device parameters, V_{out} can be determined analytically and compared against simulation results. See Tables 1 and 2. The simulation error is well within expected limits due to finite resolution.

Some thought must be given to the value of D. The command coming into the model has some duty cycle D_0. The IGBT turns on immediately through a VCVS. The IGBT turns off slowly, extending the falling edge by t_{off}, again conducting through a VCVS. The net result is that:

$$D=D_0+t_{off}f_{sw} \tag{8}$$

This compensation factor has been applied to the results in Table 2. It is not insignificant; neglecting this effect results in error on the order of 1%, much larger than the observed simulation error.

IV. EXPERIMENTAL VALIDATION

To validate the models created, a simple buck converter was built and tested. A calorimetric method was used to

Table 1: Simulation Parameters

$V_{on,Q}$	1.0 V	E_{rec}	1 μJ	I_{rrm}	2 A
$R_{on,Q}$	0.1 Ω	E_{on}	1 mJ	V_{in}	400 V
$V_{on,D}$	0.7 V	E_{off}	1 mJ	I_{out}	10 A
$R_{on,D}$	0.1 Ω	I_{rated}	10 A	D_0	0.5
k	0.7	V_{rated}	400 V	f_{sw}	10 kHz

Table 2: Simulation Results

Variable	Analytical	Dymola	Error
V_{out}	197.5785481	197.5730286	-0.0028%
I_{in}	5.035764286	5.035627365	0.0027%
P_{Q1}	30.07142857	30.07070732	0.0024%
P_{D1}	8.449285714	8.449525833	-0.0028%

measure losses in the switching pole [7],[8]. To reduce the bus capacitor losses, high-quality polpropylene film capacitors from Solen were used. All other losses were excluded from the measurement.

A number of operating points were tested and a model was fit to the data. In contrast to the analytical validation given above, current ripple is important in a real converter. The circuit was operated at low enough frequencies that under certain load conditions, the inductor current was just barely continuous. Considering ripple, conduction losses are given by:

$$
\begin{aligned}
&I_{phase} \in \left[I_o - \tfrac{1}{2}\Delta I, I_o + \tfrac{1}{2}\Delta I \right] \\
&P_{cond,Q} = V_{on,Q} I_o D + R_{on,Q} D \left(I_o^2 + \tfrac{1}{12}(\Delta I)^2 \right) \\
&P_{cond,D} = V_{on,D} I_o (1-D) + R_{on,D} (1-D) \left(I_o^2 + \tfrac{1}{12}(\Delta I)^2 \right)
\end{aligned}
\tag{9}
$$

Clearly, if ΔI is small, the formulas of the previous section can be used, but if ΔI is large, the ripple can have a significant effect on the resistive loss term. Similarly, current ripple affects switching loss:

$$
\begin{aligned}
&E_{on,Q} = kV_{bus} t_{on} \left(I_o - \tfrac{1}{2}\Delta I \right) + \tfrac{1}{2} k V_{bus} I_{rrm} t_{rr} \\
&E_{off,Q} = kV_{bus} t_{off} \left(I_o + \tfrac{1}{2}\Delta I \right) \\
&E_{rec,D} = \tfrac{1}{2} k V_{bus} I_{rrm} t_{rr}
\end{aligned}
\tag{10}
$$

Again, current ripple can significantly affect the relative contributions of turn-on and turn-off losses. Switching power is simply the sum of the relevant energy terms multiplied by the switching frequency.

Measuring efficiency of a converter above 90% is an extremely challenging instrumentation problem. Two sets of data were obtained, voltage and current on the input and output ports and temperature data. Using the most naïve approach:

$$P_{loss} = V_{in} I_{in} - V_{out} I_{out} \tag{11}$$

This formula overestimates the power loss. When trying to fit the data with the above model, switching times of approximately 1 μs are found. The tests were performed near room temperature, and voltage rise and fall times were on the order of 100 ns, so that the data derived from (11) are considered suspect.

Calorimetry is considered to be the most effective method for measuring power dissipation in a highly efficient converter. The resulting model fit gives a worst-case error of approximately 15%. Results are shown in Table 3. Switching frequency is 8 kHz and duty cycle is 50%. Due to instrument failure, we were unable to verify the simulation using an alternative control method such as delta modulation or hysteresis control. The author is actively investigating a more accurate form of power dissipation measurement to reduce the model error. Once effective power dissipation measurement can be shown, this modeling method will be applied to a number of control schemes.

Table 3: Model Fit to Experimental Data

Output Current	Measured Dissipation	Modeled Dissipation	Error
2.065	2.917	3.259	11.7%
3.053	5.033	4.981	-1.02%
5.046	10.272	8.783	-14.5%
7.046	13.704	13.047	-4.79%

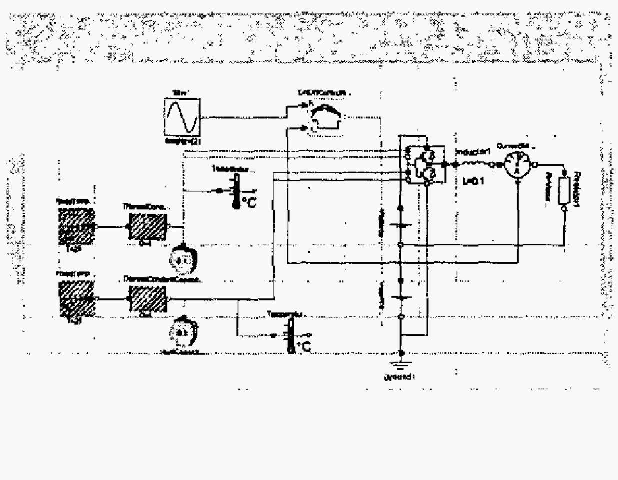

Figure 6: Full Simulation with Hysteresis Current Control

V. Example Simulation

This model can be used effectively for variable frequency systems. The circuit of Fig. 6 was simulated using hysteresis current control. Fig. 7 shows the resulting inductor current and two temperatures. For convenience, the junctions of an IGBT and its anti-parallel diode were tied together, as if the circuit was built using IGBT/FWD co-packs. For a half bridge, there are then two temperatures corresponding to each hypothetical package. The thermal time constant was intentionally shortened to demonstrate the dynamic effects.

As expected, with low-frequency (2 Hz) sinusoidal current, junction temperatures evolve with the same frequency. The hysteresis band is set large to exaggerate the switching action. The effective switching frequency varies from approximately 370 Hz near the current peaks to approximately 500 Hz near the current zero-crossings.

VI. Conclusion

A new model has been developed that accounts for switching losses in IGBTs and diodes. This model has been

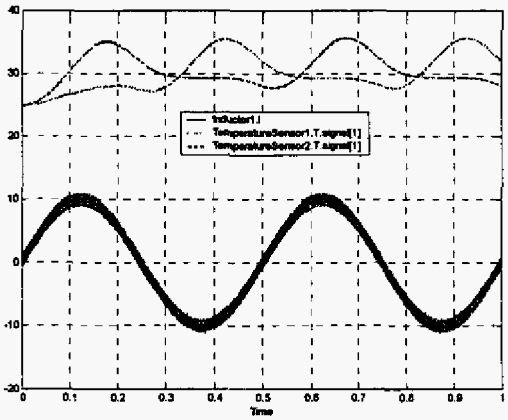

Figure 7: Simulation Results for Circuit of Fig. 6

verified analytically and experimentally and can be derived from calorimetric measurements.

This model was verified with dc loads, but the derivation made no assumptions about voltage and current beyond the switching event. This model can be used in virtually any system, so long as current and voltage is well-behaved during the switching event, including hard-switched inverters.

The only fundamental limitation at this point is the polarity of the current. In IGBT/FWD systems, typical of motor drives and other high voltage, high current converters, pairs of devices can be identified that correspond to buck or boost switch poles. In these pairs, current is always nonnegative (buck) or nonpositive (boost). This characteristic has been used in dissecting the switching waveforms. Further work is necessary to extend this modeling method to MOSFET inverters, in which current is bipolar in each device, or MOSFET synchronous buck or boost converters, in which one device is composed of a controlled switch plus a diode. Switching becomes much more complicated and depends in part on timing of the gate commands.

This model can be a powerful tool for simulating IGBT-based motor drives under transient conditions. Because of its frequency independence, this model can also be used to determine power dissipation in drives based on direct torque control (DTC) or other hysteresis or delta-modulation based techniques, or variable frequency methods such as random PWM or certain space vector modulation implementations. It can also predict other performance measurements such as current ripple or effective switching frequency

The model presented is only directly applicable at a single temperature, and can be used as-is with experimental data at a relevant temperature like 125°C. Alternatively, since this model was developed with thermal ports, a model of the thermal management system can be added, and all parameters can be found as functions of temperature. A model that includes temperature effects would allow more exact analysis of design margins and would show some of the unusual phenomena that occur during overloads. However, due to the complicated nature of the temperature dependence and the large amount of data required, it is probably best to characterize devices at a worst-case temperature and design accordingly.

VII. Acknowledgements

The author would like to thank Yongxiang Chen for assistance in obtaining and analyzing the experimental data. This work was supported by the Grainger Center for Electric Machinery and Electromechanics.

VIII. References

[1] K. Sheng, B.W. Williams, S.J. Finney, "A review of IGBT models," *IEEE Trans. Power Elec.*, vol. 15, pp. 1250-1266, Nov. 2000.

[2] C.A. Murphy, P.T. Krein, "High level Simulink switch model for investigating capacitive effects," in *Comp. Power Elec. (COMPEL)*, 2000, pp. 241-246.

[3] F. Charfi, M.B. Messaoud, B. Francois, K. Al-Haddad, F. Sellami, "Two novel modeling methodologies for IGBT transistor," in *Conf. Ind. Elec. Soc. (IECON)*, 2002, pp. 550-554.

[4] J.L. Tichenor, S.D. Sudhoff, J.L. Drewniak, "Behavioral IGBT modeling for predicting high frequency effects in motor drives," *IEEE Trans. Power Elec.*, vol. 15, pp. 354-360, Mar. 2000.

[5] ON Semiconductor, AN569, "Transient thermal resistance – general data and its use," pp. 4-5.

[6] J. Kimball, "Dymola Switch Models with Inverter Application," July 2004, http://power.ece.uiuc.edu/Kimball/SwitchModels/Inverter.html.

[7] E. Ritchie, J.K. Pedersen, F. Blaabjerg, P. Hansen, "Calorimetric measuring systems," *IEEE Industry Applications Magazine*, vol. 10, May-June 2004, pp. 70-78.

[8] D.J. Patterson, "An efficiency optimized controller for a brushless DC machine, and loss measurement using a simple calorimetric technique," in *Rec. Power Elec. Spec. Conf. (PESC)*, 1995, pp. 22-27.

APPENDIX: MODELICA CODE FOR FIGURE 4

```
model Switching "Buck switch modeled with conduction and switching losses"
  parameter Modelica.SIunits.Voltage VonQ=1 "On-State Voltage of IGBT";
  parameter Modelica.SIunits.Resistance RonQ=0.1
    "On-State Resistance of IGBT";
  parameter Modelica.SIunits.Voltage VonD=0.7 "On-State Voltage of FWD";
  parameter Modelica.SIunits.Resistance RonD=0.1 "On-State Resistance of FWD";

  parameter Real k=0.7 "Multiplier on Peak Power";
  parameter Modelica.SIunits.Energy Err=1e-6 "Reverse Recovery Energy";
  parameter Modelica.SIunits.Energy Eon=1e-3 "Turn-On Energy";
  parameter Modelica.SIunits.Energy Eoff=1e-3 "Turn-Off Energy";
  parameter Modelica.SIunits.Current Irated=10
    "Rated Current for Energy Parameters";
  parameter Modelica.SIunits.Voltage Vrated=400
    "Rated Voltage for Energy Parameters";
  parameter Modelica.SIunits.Current Irrm=2 "Reverse Recovery Peak Current";

  Modelica.SIunits.Power PQ "Power Dissipated in Controlled Switch";
  Modelica.SIunits.Power PD "Power Dissipated in Free-Wheeling Diode";

  Modelica.Electrical.Analog.Interfaces.PositivePin p "Positive Bus"
    annotation (extent=[-10, 90; 10, 110]);
  Modelica.Electrical.Analog.Interfaces.NegativePin n "Negative Bus"
    annotation (extent=[-10, -110; 10, -90]);
  Modelica.Electrical.Analog.Interfaces.Pin s "Switched Node"
    annotation (extent=[90, -10; 110, 10]);
  Modelica.Blocks.Interfaces.BooleanInPort cmd "Switching Command"
    annotation (extent=[-100, -10; -80, 10]);
  Inverter.SwitchedVCVS SwitchedVCVS1(k=k)
    annotation (extent=[50, 0; 30, 20], rotation=-90);
  Inverter.OneShot OneShotTurnOn(pw=(Eon - Err)/(k*Vrated*Irated))
    annotation (extent=[-40, 0; -20, 20]);
  Inverter.OneShot OneShotTurnOff(pw=Eoff/(k*Vrated*Irated))
    annotation (extent=[-40, -80; -20, -60]);
  Inverter.SwitchedCurrent SwitchedCurrent1(Ion=k*Irrm)
    annotation (extent=[10, 52; 30, 32], rotation=90);
  Inverter.OneShot OneShotReverseRecovery(pw=2*Err/(k*Irrm*Vrated))
    annotation (extent=[-40, 40; -20, 60]);
  ModelicaAdditions.Blocks.Logical.NOT NOT1
    annotation (extent=[-40, -40; -20, -20]);
  Inverter.Dlossy DiodeQ(Von=VonQ, Ron=RonQ)
    annotation (extent=[30, 60; 50, 80], rotation=270);
  annotation (
    Diagram,
    Icon(
      Rectangle(extent=[-100, 100; 100, -100]),
      Line(points=[0, 20; 0, -20; 20, -20; -20, -20; 0, -20; -20, -60; 20, -60;
             0, -20]),
      Line(points=[0, -60; 0, -100]),
      Line(points=[-88, 0; -60, 0; -60, 32; -28, 32]),
      Line(points=[0, 0; 100, 0]),
      Text(extent=[2, 58; 28, 30], string="SW"),
      Line(points=[-28, 32; -28, 62]),
      Line(points=[0, 100; 0, 74; -20, 60; -20, 72; -20, 20; -20, 32; 0, 20;
            -4, 28; -10, 20; 0, 20])),
    Documentation(info="Buck switch pole with conduction loss and switching loss, using switched
voltage & current sources to model Eon, Eoff, and Err.  Controlled switch
is ON when input is TRUE.

The controlled switch is on when commanded, plus some turn-off delay
modeled by OneShotTurnOff and an OR gate.  During turn-on and turn-off,
voltage across the switch is increased to k times the bus voltage to
model switching transient.  In addition, k times Irr conducts from
bus to bus to model commutating the diode current (reverse recovery).
"));
  Inverter.Dlossy DiodeD(
    Von=VonD,
    Ron=RonD,
```

```
      Goff=1e-10) annotation (extent=[30, -60; 50, -40], rotation=90);
    Modelica.Electrical.Analog.Ideal.IdealSwitch Q
      annotation (extent=[30, -30; 50, -10], rotation=90);
  equation
    connect(SwitchedVCVS1.ControlP, p)
      annotation (points=[30, 14; 0, 14; 0, 100], style(color=3));
    connect(SwitchedVCVS1.ControlN, n)
      annotation (points=[30, 10; 0, 10; 0, -100], style(color=3));
    connect(SwitchedCurrent1.p, p)
      annotation (points=[20, 52; 20, 72; 0, 72; 0, 100], style(color=3));
    connect(SwitchedCurrent1.n, n)
      annotation (points=[20, 32; 20, 10; 0, 10; 0, -100], style(color=3));
    Q.control.signal[1] = not ((cmd.signal[1]) or (OneShotTurnOff.outPort.
      signal[1]));
    SwitchedCurrent1.TurnOn.signal[1] = (s.i < 0) and (OneShotReverseRecovery.
      outPort.signal[1]);
    SwitchedVCVS1.TurnOn.signal[1] = (OneShotTurnOff.outPort.signal[1]) or (
      OneShotTurnOn.outPort.signal[1]);

    PQ = DiodeQ.i*(DiodeQ.p.v - SwitchedVCVS1.n.v) + 0.5*SwitchedCurrent1.i*
      SwitchedCurrent1.v;
    PD = DiodeD.i*DiodeD.v + 0.5*SwitchedCurrent1.i*SwitchedCurrent1.v;

    connect(cmd, OneShotTurnOn.inPort)
      annotation (points=[-90, 0; -60, 0; -60, 10; -42, 10], style(color=5));
    connect(cmd, OneShotReverseRecovery.inPort)
      annotation (points=[-90, 0; -60, 0; -60, 50; -42, 50], style(color=5));
    connect(NOT1.inPort, cmd)
      annotation (points=[-42, -30; -60, -30; -60, 0; -90, 0], style(color=5));
    connect(NOT1.outPort, OneShotTurnOff.inPort) annotation (points=[-19, -30;
          -10, -30; -10, -50; -60, -50; -60, -70; -42, -70], style(color=5));
    connect(DiodeQ.p, p)
      annotation (points=[40, 80; 0, 80; 0, 100], style(color=3));
    connect(DiodeQ.n, SwitchedVCVS1.p)
      annotation (points=[40, 60; 40, 20], style(color=3));
    connect(DiodeD.p, n)
      annotation (points=[40, -60; 40, -80; 0, -80; 0, -100], style(color=3));
    connect(Q.p, DiodeD.n)
      annotation (points=[40, -30; 40, -40], style(color=3));
    connect(Q.n, SwitchedVCVS1.n)
      annotation (points=[40, -10; 40, 0], style(color=3));
    connect(Q.p, s)
      annotation (points=[40, -30; 60, -30; 60, 0; 100, 0], style(color=3));
  end Switching;

  model SwitchingThermal "Buck Switch with Total Loss Model with Thermal Ports"

    extends Inverter.Buck.Switching;

    Modelica.Thermal.HeatTransfer.Interfaces.HeatPort_a TransistorJ
      "Thermal Port for Transistor" annotation (extent=[-110, 50; -90, 70]);
    Modelica.Thermal.HeatTransfer.Interfaces.HeatPort_b DiodeJ
      "Thermal Port for Diode" annotation (extent=[-110, -70; -90, -50]);
    annotation (
      Icon,
      Documentation(info="Buck.Switching with added thermal ports.  Q_dot at each port reflects
associated device's power dissipation."),
      Diagram);
  equation

    TransistorJ.Q_dot = -PQ;
    DiodeJ.Q_dot = -PD;

  end SwitchingThermal;
```