

Applicable Method for Average Switching Loss Calculation in Power Electronic Converters

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Abstract

Accurate calculation of the conduction and switching losses of a power electronic converter is required to achieve the efficiency of the converter. Such calculation is useful for computing the junction temperature of the switches. A few models for calculating the switching energy losses during switching transitions for the given values of switch voltage and current have been developed. In this study, these models are comprehensively reviewed and investigated for the first time for ease of comparison among them. These models are used for calculating the average amount of switching power losses. However, some points and details should be considered in utilizing these models when the switch current or voltage presents time variant and alternative quantity. Therefore, an applicable technique is proposed to use these models under the above-mentioned conditions. An optimal switching loss model and the presented technique are used to establish a new and fast method for obtaining the average switching power losses in any type of power electronic converters. The accuracy of the proposed method is evaluated by comprehensive simulation studies and experimental results.

Keywords: Analytical loss model, Conduction loss calculation model, Power electronic converter loss, Switching loss model

I. INTRODUCTION

Power electronic converters play an important role in the electric power industry because of their applications, such as integrating the distributed energy units into the grid [1], improving the power quality of the grid [2], and driving the electric motors. Electrical power loss is an important concern of power electronic converters. Converter losses usually involve the power losses of the magnetic devices and those of the semiconductor switches. Switching losses include the switching, conduction, and negligible off-state losses.

Switching losses are dominant losses at high switching frequencies and depend on four factors [3]: 1) switch voltage, 2) switch current, 3) switching frequency, and 4) rising and falling times of the switch voltage and current. Switching losses are more difficult to calculate than conduction losses [4]. The difficulty is attributed to the small amount of the turn-on and turn-off transition times, and the estimation of switch waveforms during transition times to provide the accurate model of the switch.

Calculating the conduction and switching losses of a power electronic converter is useful for 1) calculating the junction temperature of the switches for designing the heat sink, and 2)

obtaining the efficiency of the converter. Efficiency is an important characteristic of power electronic converters and is thus used as an evaluation criterion for five types of DC/AC converters in [5], for two types of AC/AC converters in [6], and for photovoltaic inverters in [7].

The switching losses of the converters can be calculated using three methods [8], [9]: 1) utilizing experimental switching waveforms acquired by constructing the laboratory prototype, 2) utilizing simulation models obtained using the switch datasheet and its electrical and thermal models, and 3) utilizing analytical models.

Unlike the analytical methods, simulation-based methods require calculating the switching energy losses for all the turn-on and turn-off transitions. In analytical methods for sinusoidal output current, the average switching power loss is calculated using some information, such as switch characteristics, output displacement factor, amplitude of the output current, and modulation index. Simulation-based methods exhibit more computational burden than analytical methods, but they can be implemented for all kinds of converters and output currents. An analytical model for a given power converter can be derived using two elements [10]: 1) the conduction and switching loss model for each turn-on and turn-off transitions, and 2) the operating principle of the converter. Several converters that use analytical models for computing switching losses are listed in Table I.

A few semiconductor manufacturers have provided online or

TABLE I
SEVERAL CONVERTERS USING ANALYTICAL MODELS FOR SWITCHING LOSS CALCULATION

Converter type	Corresponding references
Matrix Z-source converter (MZC)	[10]
Very sparse matrix converter (VSMC)	[13], [14]
Conventional matrix converter (CMC)	[14]
Sparse matrix converter (SMC)	[14]
Modular multilevel converter (MMC)	[15], [16]
Two-level converter	[17]
Three-level neutral point clamped converter (NPC)	[17]
Three-level and four-level flying capacitor converter (FC)	[17]
Ladder multilevel converter	[18]

offline software tools (e.g., [11], [12]) for calculating the average losses and junction temperature of power switches using loss calculation models. However, these software tools are applicable only for limited types of converters.

The switching loss calculation models used in the methods above are expressed as Eqs. (1)–(10) in this study. These models can calculate the switching energy losses during turn-on and turn-off transitions for the given values of switch voltage and current. In existing simulation-based methods, these models are required to calculate the average value of switching power losses. However, using these models for alternative switch current or voltage requires additional points and details to be considered. Therefore, an applicable technique is proposed in this study to use these models under the said conditions. This technique is composed of two main steps. The first step samples the switch voltage and current properly, and the second step generates the appropriate square signals. The average number of square signals will be equal to the average switching power losses.

The switching loss models are comprehensively reviewed in the following section for ease of selection of an appropriate model.

The switching energy losses of a power switch such as a transistor can be calculated by the following equations [3].

$$E_{sw,off} = \int_{t_{off}} i(t) \cdot v(t) \cdot dt \quad (1)$$

$$E_{sw,on} = \int_{t_{on}} i(t) \cdot v(t) \cdot dt \quad (2)$$

In the equations above, $i(t)$ is the current passing through the switch; $v(t)$ is the voltage across the switch; $E_{sw,on}$ and $E_{sw,off}$ are the switching energy losses of the switch which are calculated during its turn-on transition time t_{on} and turn-off transition time t_{off} , respectively. The above-mentioned method is limited by its need of a precise model of the switch to accurately estimate the waveforms of the switch voltage and current during turn-on and turn-off transitions. Such a precise model is presented in [8] for SiC MOSFETs but requires bulky calculations and detailed parameters of the transistor. The method is also computationally demanding and time consuming [15]. According to [8] and [9], this drawback occurs owing to the minimum values of the

falling and rising times of the transistor current and voltage, thereby resulting in an extremely small simulation step time (approximately in nanosecond range).

The problems above can be resolved by finding appropriate equations as the solutions to the integrals in Eqs. (1) and (2) instead of solving the integrals by numerical methods. After solving Eqs. (1) and (2) using simplified approximations, an analytical expression is obtained for switching losses of a transistor as Eq. (3) for the resistive load [18], and as Eq. (4) for the inductive load [19].

$$E_{sw,x} = \frac{1}{6} \cdot V_{CC,x} \cdot I_{C,x} \cdot t_x \quad (3)$$

$$E_{sw,x} = \frac{1}{2} \cdot V_{CC,x} \cdot I_{C,x} \cdot t_x \quad (4)$$

In the equations above, “x” can be replaced with “on” or “off” and indicates that the parameter is related to the turn-on or turn-off transition of the switch. $V_{CC,x}$ is the off-state voltage of the transistor, and $I_{C,x}$ is the on-state current of the transistor; these components are switched when the transistor is turned on or off. For the inductive load, transition time t_x depends on the rising and falling times of the switch voltage which are not given in the switch datasheets.

Curve fitting methods and experimental loss curves of the switch are usually used to derive appropriate equations for switching loss calculation. Using curve fitting, the dependency of the switching energy loss of an IGBT, $E_{sw,x}$, on the switch voltage $V_{CC,x}$ and switch current $I_{C,x}$ is provided by a fourth degree polynomial in [10].

$$E_{sw,x} = k_{1,x} V_{CC,x} I_{C,x} + k_{2,x} V_{CC,x} I_{C,x}^2 + k_{3,x} V_{CC,x}^2 I_{C,x} + k_{4,x} V_{CC,x}^2 I_{C,x}^2 + k_{5,x} V_{CC,x}^2 I_{C,x}^2 \quad (5)$$

In the equation above, $k_{1,x}$, $k_{2,x}$, ..., $k_{5,x}$ are the fitting constants, and “x” can be replaced with “on” or “off.” Such an equation can also be used to calculate the diode turn-off losses. According to [10], the values of $k_{1,x}$ are the greatest among the presented values for fitting constants.

In [15], [17], and [20], the switching losses are estimated by Eq. (6) using curve fitting methods. The switching losses are related to a quadratic polynomial in the switch current $I_{C,x}$ and are linearly related to the switch voltage $V_{CC,x}$.

$$E_{sw,x} = (a_x I_{C,x}^2 + b_x I_{C,x} + c_x) \times \frac{V_{CC,x}}{V_{CC,x}^*} \quad (6)$$

In the equation above, $V_{CC,x}^*$ is the switch voltage used to acquire the experimental switching loss curves, and “x” can be replaced with “on” or “off.” In the said works, the values of the fitting constant a_x are approximately 10^{-4} to 10^{-3} times smaller than the values of b_x and c_x .

In [5] and [21], the switching losses are expressed as Eq. (7) with a linear relationship to $(I_{C,x})^{B_x}$. In [22], this equation is improved as Eq. (8). In the equation, the switching loss is dependent on the switch voltage $V_{CC,x}$ in addition to the switch

current $I_{C,x}$.

$$E_{sw,x} = A_x \cdot (I_{C,x})^{B_x} \quad (7)$$

$$E_{sw,x} = A'_x \cdot (I_{C,x})^{B_x} \cdot \frac{V_{CC,x}}{V_{CC,x}^*} \quad (8)$$

In the equations above, A_x , A'_x , and B_x are the fitting constants and “ x ” can be replaced with “*on*” or “*off*.” Switching loss curves are plotted on log-log scales in [23] to obtain the values of the fitting constants in Eq. (7). In the said works, the values of B_x are approximately equal to 1 for IGBTs.

From the properties of Eqs. (5)–(8), the following conclusions can be obtained. The turn-on and turn-off switching losses of the IGBTs present a nearly linear relationship with the switch current and voltage as stated in [9]. This linear relationship is clearly demonstrated in [24] and [25] as follows.

$$E_{sw,off} = E_{sw,off}^* \cdot \frac{V_{CC,off}}{V_{CC,off}^*} \cdot \frac{I_{C,off}}{I_{C,off}^*} \quad (9)$$

$$E_{sw,on} = E_{sw,on}^* \cdot \frac{V_{CC,on}}{V_{CC,on}^*} \cdot \frac{I_{C,on}}{I_{C,on}^*}, \quad (10)$$

In the equations above, $E_{sw,on}^*$ and $E_{sw,off}^*$ are the experimentally measured values for the switching energy losses of the transistor during its turn-on and turn-off transitions, respectively. They are available in the transistor datasheets for the given $V_{CC,x}^*$ and $I_{C,x}^* \cdot V_{CC,x}^*$ is the measured off-state voltage of the transistor, and $I_{C,x}^*$ is the measured on-state current of the transistor; these components are switched during the transition time. $E_{sw,on}$ and $E_{sw,off}$ are the switching energy losses of the transistor; these losses are calculated for the intended switched off-state voltage V_{CC} and switched on-state current I_C .

The switching losses vary depending on the gate impedance, parasitic circuit elements [8], and snubber characteristics. However, this linear approximation provides a good accuracy, particularly near the test point of the manufacturer ($V_{CC,x}^*$ and $I_{C,x}^*$) and the snubber condition [4], [25].

The switching loss models are comprehensively reviewed in this study to ease the selection of the appropriate loss model. The study mainly contributes by establishing an applicable technique for calculating the average value of switching power losses using switching loss models. This technique can be utilized in any type of converters and has the following advantages. 1) This technique is useful for alternative switch current or voltage. 2) This technique can be implemented easily using the basic blocks of programs such as MATLAB/SIMULINK. 3) This technique samples the switch voltage and current properly. 4) This technique uses a simple and creative approach for saving and averaging the switching losses.

In the following sections of the paper, the proposed method for obtaining the average value of switching power losses is

described first. Then, the conduction loss models for calculating the total loss of the converter are investigated. Finally, the accuracy of the proposed method is evaluated by simulation and experimental results.

II. NEW METHOD FOR CALCULATING AVERAGE SWITCHING POWER LOSSES

In this section, a new method for calculating the average switching power losses of a transistor with an antiparallel diode is proposed and described in detail. In the proposed method, switching losses are considered without dependency on the junction temperature. This method is composed of three parts: 1) selecting a proper switching loss model, 2) sampling the switch voltage and current correctly, and 3) generating appropriate square signals. These parts are described below.

Using Eqs. (1) and (2) for calculating switching losses is computationally demanding, time consuming, and requires a precise model of the switches. These drawbacks can be overcome by utilizing curve-fitting methods to obtain switching loss models. In the current study, Eqs. (9) and (10) are selected as switching loss calculation models because of their less computational burden. The parameter values of these models are easily obtained via the transistor datasheets.

The average amount of the switching power losses of a switch $\overline{P_{sw}}$ can be calculated as Eq. (11) by considering constant amounts for $V_{CC,x}$ and $I_{C,x}$ in Eqs. (9) and (10). In this equation, f_{sw} is the switching frequency. Such a condition can occur in the DC–DC converters.

$$\overline{P_{sw}} = f_{sw} \cdot (E_{sw,on} + E_{sw,off}) \quad (11)$$

However, Eq. (11) is inapplicable for an inverter because of the variable and periodic feature of $I_{C,x}$ in each switch of the inverter [23]. $I_{C,x}$ in Eqs. (9) and (10) is substituted with the absolute average value of switch current $|I_{ave}|$ to solve the said problem in [16], and Eq. (11) is modified as

$$\overline{P_{sw}} = (E_{sw,off}^* + E_{sw,on}^*) \cdot \frac{V_{CC}}{V_{CC}^*} \cdot \frac{|I_{ave}|}{I_C^*} \cdot f_w \quad (12)$$

In the equation above, $V_{CC,x}^*$, $I_{C,x}^*$, and $V_{CC,x}$ are substituted with the constant values of V_{CC}^* , I_C^* , and V_{CC} , respectively.

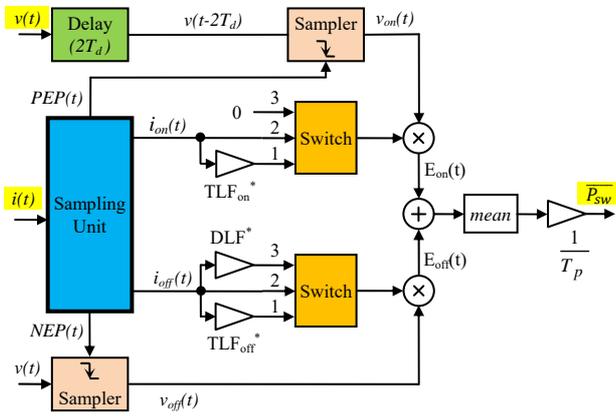


Fig. 1. Block diagram of the proposed method for calculating the average switching power losses in a transistor and its antiparallel diode.

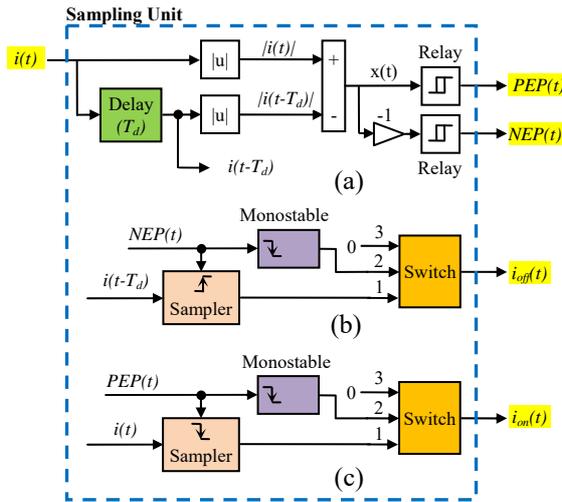


Fig. 2. Details of the “Sampling Unit” block of Fig. 1: (a) generating $PEP(t)$ and $NEP(t)$, (b) generating $i_{off}(t)$, and (c) generating $i_{on}(t)$.

According to Eq. (12), the average switching loss of a power switch exhibits a linear relationship with the average amount of its current. This equation is a special case of the proposed method in the current study and will malfunction under the following two conditions: 1) when the switching frequency varies during the simulation as in the hysteresis switching technique; 2) when the switching frequency is extremely low such that the switch current varies considerably during the on-state interval of the switch.

In the present study, an appropriate technique based on the switching loss models as in Eq. (9) and (10) is proposed to deal with the above-mentioned problems. This method is used to calculate the average value of switching power losses of a transistor and its antiparallel diode, and the alternative current. This method can be implemented easily in simulation environments and is described in Fig. 1 and Fig. 2 in the form of a block diagram. Each of the curve fitting equations described in the previous section can be utilized in this method instead of Eqs. (9) and (10).

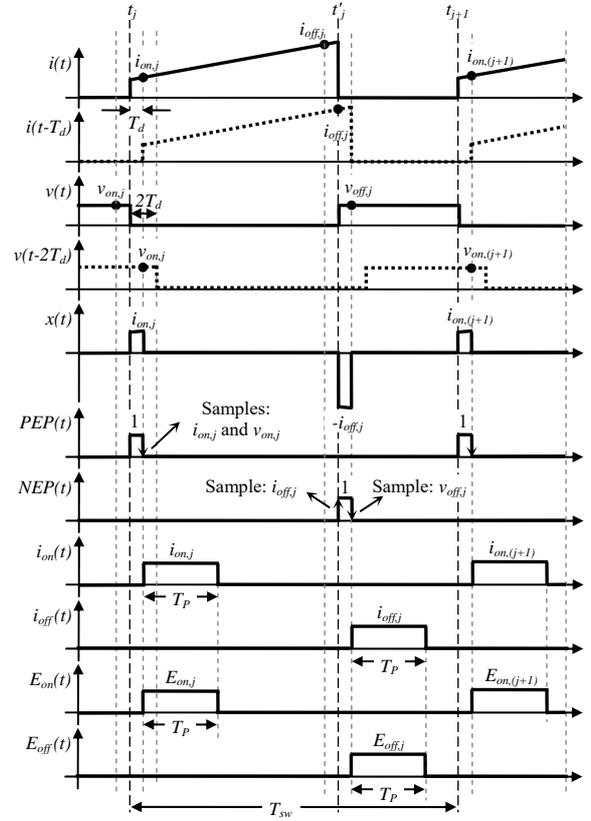


Fig. 3. Generated signals in the proposed method for calculating the average switching power losses in a switch when $i(t) \geq 0$.

In Fig. 1, the switch current $i(t)$ and its voltage $v(t)$ are the input variables of the proposed method. The positive value of $i(t)$ indicates that the current passes through the transistor whereas the negative value means that the current passes through the antiparallel diode.

If $f_{sw} = 1/T_{sw}$ represents the switching frequency, and $f = 1/T$ represents the main frequency of the switch current, then $n = T/T_{sw}$ will be the number of the switching operations during a period of the switch current. For the j^{th} switching operation of n ones, $i(t)$ and $v(t)$ along with some other waveforms are shown in Fig. 3. These waveforms are used to describe the operation of the proposed method.

The current and voltage of the switch used in Eqs. (9) and (10) are measured instances before or after turn-on and turn-off transitions when they have a stable value. As shown in Fig. 3, the value of the switch current right after t_j , $i_{on,j} = i(t_j + T_d)$, when the switch is turned on at t_j is sampled. Moreover, the value of the switch voltage right before t_j , $v_{on,j} = v(t_j - T_d)$, is sampled. Then, these samples are used in Eq. (10) for calculating $E_{sw,on}$.

On the contrary, when the switch is turned off at t'_j , the value of the switch current right before t'_j , $i_{off,j} = i(t'_j - T_d)$, and the value of the switch voltage right after t'_j , $v_{off,j} = v(t'_j + T_d)$, are sampled and used in Eq. (9) for calculating $E_{sw,off}$.

As shown in Fig. 3, the negative and positive edges of control signals $PEP(t)$ and $NEP(t)$ are used for obtaining $i_{on,j}$, $i_{off,j}$, $v_{on,j}$, and $v_{off,j}$. The signals $i(t)$ and $v(t - 2T_d)$ are sampled as $i_{on,j}$ and $v_{on,j}$ respectively, when the edge of $PEP(t)$ is negative. The signal

$i(t-T_d)$ is sampled as $i_{off,j}$ when the edge of $NEP(t)$ is positive whereas the signal $v(t)$ is sampled as $v_{off,j}$ when the edge of $NEP(t)$ is negative. The sampler blocks in Fig. 1 and Fig. 2 perform the above-mentioned process using control signals $PEP(t)$ and $NEP(t)$.

The generating process of $PEP(t)$, a square pulse at the positive edge of $|i(t)|$, and $NEP(t)$, a square pulse at the negative edge of $|i(t)|$, with the pulse width of T_d is described in Fig. 2(a). In this figure, the ‘‘Relay’’ blocks present a Schmitt trigger characteristic [26] and can be presented as Eq. (13).

$$PEP(t) = \begin{cases} 1 & x(t) > k_U \\ 0 & x(t) < k_L \end{cases} ; \quad (13)$$

In the equation above, $x(t)$ is the input signal, $PEP(t)$ is the output signal, k_U is the lower limit, and k_L is the upper limit of the block. $x(t)$, $PEP(t)$, and $NEP(t)$ are shown in Fig. 3.

As shown in Fig. 3, the square pulse $i_{on}(t)$ with the pulse width of T_p and the amplitude of $i_{on,j}$ is generated when the edge of $PEP(t)$ is negative. Moreover, the square pulse $i_{off}(t)$ with the pulse width of T_p and the amplitude of $i_{off,j}$ is generated when the edge of $NEP(t)$ is negative. The signals $i_{on}(t)$ and $i_{off}(t)$ are generated in Fig. 2(b, c) using ‘‘Monostable’’ [26] and ‘‘Switch’’ blocks. In the Monostable block, one square pulse with pulse width of T_p and amplitude of 1 is generated for each negative edge of input signal. The large value of T_p will improve the accuracy of the proposed method, but its maximum value is limited to T_{sw} . The Switch block in Fig. 2(b, c) is a conditional block and works as follows. For the positive values of the applied signal to input 2, the output of the block is connected to input 3; for other values of input 2, the output is connected to input 1. In this case, the Switch block acts as a multiplier of low computational burden.

In Fig. 1, the Switch blocks are used to distinguish the transistor current from its antiparallel diode current. As mentioned previously, the positive value of $i_{on}(t)$ indicates that the current passes through the transistor. In calculating $E_{sw,on}$ by Eq. (10), $i_{on}(t)$ is first multiplied by the constant number TLF_{on}^* and then by the switch sampled off-state voltage $v_{on}(t)$. TLF_{on}^* is the transistor turn-on switching loss factor and is defined by Eq. (14). In this equation, V_{CC}^* and I_C^* are constant values that are used instead of $V_{CC,on}^*$ and $I_{C,on}^*$, respectively, in Eq. (10). By contrast, the negative amount of $i_{on}(t)$ means that the current passes through the antiparallel diode. As shown in Fig. 1, the turn-on switching loss of the diode is zero because it is usually ignored [4], [9], [10]. The resulted signal is denoted as $E_{on}(t)$ in Fig. 1. Thus, $E_{on,j}$, the amplitude of the j^{th} pulse of $E_{on}(t)$ in Fig. 3, is equal to $TLF_{on}^* \cdot v_{on,j} \cdot i_{on,j}$. In this way, $E_{on,j}$ indicates the turn-on switching energy losses of the switch for the j^{th} turn-on transition during T , a period of the fundamental component of the switch current. As mentioned previously, the number of the switching operations during the period T is equal to n . As a result, the average turn-on switching power loss of the device

$\overline{P_{sw,on}}$ is obtained by Eq. (15). In this equation, function $\mathbf{mean}(x)$ calculates the average value of variable x during T .

$$TLF_{on}^* = \frac{E_{sw,on}^*}{V_{CC}^* \cdot I_C^*} \quad (14)$$

$$\begin{aligned} \overline{P_{sw,on}} &= \frac{1}{T} (E_{on,1} + \dots E_{on,j} + \dots E_{on,n}) \\ &= \frac{1}{T_p} \cdot \mathbf{mean}(E_{on}(t)) \end{aligned} \quad (15)$$

In Fig. 1, $E_{off}(t)$ is obtained by multiplying $i_{off}(t)$ by suitable factors, such as the method of obtaining $E_{on}(t)$ from $i_{on}(t)$. In calculating $E_{sw,off}$ by Eq. (9), $i_{off}(t)$ is first multiplied by TLF_{off}^* when it passes through the transistor and then multiplied by DLF^* when it passes through the antiparallel diode. Next, it is multiplied by switch sampled off-state voltage $v_{off}(t)$. The constants TLF_{off}^* and DLF^* are the transistor and diode turn-off switching loss factors, respectively, and are defined as follows.

$$TLF_{off}^* = \frac{E_{sw,off}^*}{V_{CC}^* \cdot I_C^*}, \quad DLF^* = \frac{-E_{rr}^*}{V_{CC}^* \cdot I_D^*} \quad (16)$$

In the equation above, V_{CC}^* and I_C^* are the constant values that are used instead of $V_{CC,off}^*$ and $I_{C,off}^*$, respectively, in Eq. (9). Moreover, E_{rr}^* represents the antiparallel diode reverse recovery energy losses which are measured experimentally during the diode turn-off transition. E_{rr}^* is available in the switch datasheet for the specified V_{CC}^* and I_D^* , V_{CC}^* is the switched off-state voltage of the diode, and I_D^* is its switched on-state current.

As a result, $E_{off,j}$, the amplitude of the j^{th} pulse of $E_{off}(t)$ in Fig. 3, is equal to $TLF_{off}^* \cdot v_{off,j} \cdot i_{off,j}$ or $DLF^* \cdot v_{off,j} \cdot i_{off,j}$. $E_{off,j}$ indicates the turn-off switching energy losses of the switch for the j^{th} turn-off transition during the period T . Thus, the average turn-off switching power losses of the switch $\overline{P_{sw,off}}$ can be obtained as follows.

$$\begin{aligned} \overline{P_{sw,off}} &= \frac{1}{T} (E_{off,1} + \dots E_{off,j} + \dots E_{off,n}) \\ &= \frac{1}{T_p} \cdot \mathbf{mean}(E_{off}(t)) \end{aligned} \quad (17)$$

Using Eqs. (15) and (17), the average switching power loss of each switch, $\overline{P_{sw}}$, is calculated by Eq. (18). This equation is implemented in Fig. 1.

$$\overline{P_{sw}} = \overline{P_{sw,on}} + \overline{P_{sw,off}} = \frac{1}{T_p} \cdot \mathbf{mean}(E_{on}(t) + E_{off}(t)) \quad (18)$$

In Fig. 1, the coefficient $1/T_p$ can be eliminated by modifying the loss factors as Eq. (19). This simplification will reduce the computational burden of the proposed method.

$$\begin{aligned}
 TLF_{on}^{**} &= \frac{1}{T_p} \cdot TLF_{on}^* \quad , \quad TLF_{off}^{**} = \frac{1}{T_p} \cdot TLF_{off}^* \\
 DLF^{**} &= \frac{1}{T_p} \cdot DLF^*
 \end{aligned} \quad (19)$$

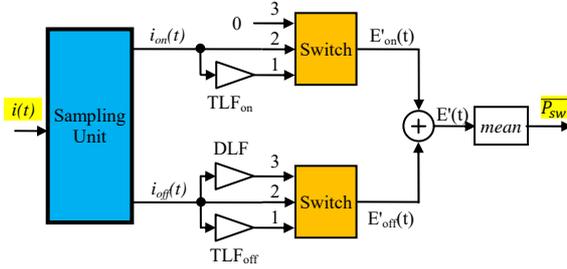


Fig. 4. Simplified block diagram of the proposed method in Fig. 1 when the switch-off state voltage is constant and predefined.

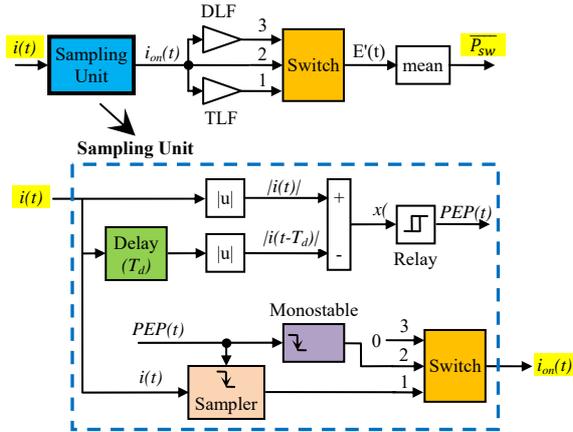


Fig. 5. Simplified block diagram of the proposed method in Fig. 4 when the switching frequency is high.

The switch off-state voltage is usually constant and equal to DC link voltage; thus, measuring and sampling of this voltage can be eliminated in Fig. 1. In this state, the proposed method in Fig. 1 can be simplified as shown in Fig. 4. TLF_{on} , TLF_{off} , and DLF in Fig. 4 are defined using Eq. (20), which is obtained from Eq. (19). In Eq. (20), V_{CC} is the constant and predefined switch off-state voltage.

$$\begin{aligned}
 TLF_{on} &= \frac{V_{CC} \cdot E_{sw,on}^*}{T_p \cdot V_{CC}^* \cdot I_C^*} \quad , \quad TLF_{off} = \frac{V_{CC} \cdot E_{sw,off}^*}{T_p \cdot V_{CC}^* \cdot I_C^*} \\
 DLF &= -\frac{V_{CC} \cdot E_{rr}^*}{T_p \cdot V_{CC}^* \cdot I_D^*}
 \end{aligned} \quad (20)$$

When the switching frequency is high and the switch is on, switch current cannot change considerably. Therefore, in this state, the current $i_{on,j}$ in Fig. 3 can be approximately equal to $i_{off,j}$. For high switching frequency and specified switch off-state voltage, the proposed method in Fig. 4 can be simplified as shown in Fig. 5. TLF in this figure is defined as follows.

$$TLF = \frac{V_{CC} \cdot (E_{sw,on}^* + E_{sw,off}^*)}{T_p \cdot V_{CC}^* \cdot I_C^*} \quad (21)$$

III. CALCULATING CONDUCTION AND TOTAL

LOSSES

If the value of rising and falling times of the switch current and voltage is set to be zero, then the switching losses will also be zero. In this case, the switching losses include only the conduction (on-mode) and off-mode losses. The switching losses in the off mode are negligible compared with the conduction losses; thus, the average conduction power losses of the switch $\overline{P_{on}}$ can be calculated as follows.

$$\overline{P_{sw}} = 0 \Rightarrow \overline{P_{on}} = \frac{1}{T} \int_{t_0}^{t_0+T} i(t) \times v(t) \times dt \quad (22)$$

In the equation above, $i(t)$ and $v(t)$ are the current and voltage of the switch, $\overline{P_{sw}}$ denotes the average switching losses, and T is the period of the switch current.

The amount of $\overline{P_{on}}$ is affected significantly by the voltage drop across the switch in the conduction mode. Meanwhile, this voltage is affected considerably by the switch current. Therefore, the correct voltage drop is calculated by modeling the switch in conduction mode using a DC voltage source and a resistor in series. In this model, the voltage source represents the device threshold voltage V_T , and the resistor indicates the resistance of the switch in the conduction mode R_{on} . This model is used in [15]–[17], [20], and [25]. The forward on-state voltage of the switch $v_{on}(t)$ is represented as follows.

$$v_{on}(t) = V_T + R_{on} \cdot i(t) \quad (23)$$

By substituting the equation above in Eq. (22), the following equation for calculating $\overline{P_{on}}$ is obtained [25].

$$\overline{P_{on}} = V_T \cdot |I_{ave}| + R_{on} \cdot I_{rms}^2 \quad (24)$$

In the equation above, I_{ave} and I_{rms} are the average and rms value of the switch current $i_C(t)$, respectively.

In [5] and [21], $v_{on}(t)$ is represented as Eq. (25) by utilizing curve fitting methods. In this equation, V_0 , A , and B are the fitting constants. In [17] and [16], an analytical model is derived for calculating the average conduction losses for some of the converters.

$$v_{on}(t) = V_0 + A \cdot i(t)^B \quad (25)$$

In this study, Eq. (22) and (23) are used to calculate the average conduction losses.

A. Average Total Power Loss

The calculation of $\overline{P_{sw}}$ and $\overline{P_{on}}$ is described in the previous sections. By utilizing them, the average total power losses of the semiconductor switch, $\overline{P_{tot}}$, is calculated as follows.

$$\overline{P_{tot}} = \overline{P_{sw}} + \overline{P_{on}} + \overline{P_{off}} \approx \overline{P_{sw}} + \overline{P_{on}} \quad (26)$$

The congruence of the calculated power losses with the experimental results is attributed to the accuracy of the parameter values of the switching loss model. The parameters of a switch used in the selected switching loss models are summarized in Table II with their values for some IGBTs when the junction temperature is high. These parameters are easily

obtained via the datasheets. Switches S1 and S2 of this table are produced by the SEMIKRON company, and switch S3 is produced by the FUJI ELECTRIC company.

B. Dependency of Switching Losses on the Junction Temperature

The methods for calculating the conduction and switching losses of the power switches can be classified into two categories: 1) the methods that consider the dependency of the switch characteristic on the junction temperature, and 2) the methods that ignore such assumption and use the constant characteristics of the switches obtained for the maximum junction temperature. The latter methods can be implemented readily and can accurately calculate the losses, whereas the former methods are computationally demanding.

In [27], a five-step iterative process is used to consider the junction temperature effects on the switching losses. In [16], only the conduction losses of the switch are related to the junction temperature. The dependency of the losses on the temperature is investigated extensively in [20] by relating the conduction and switching losses to the temperature.

In [20], the losses of the semiconductor switches are increased by only 10% through increasing the heat sink temperature from 30 °C to 100 °C. This result shows that the parameters of the power switch can be obtained for the maximum junction temperature and can be used to calculate the losses as in [6]. Therefore, this method is acceptable because the error in the calculated losses is within the acceptable range when the temperature effect on the losses is neglected. A converter, which is designed for the worst conditions (switch parameters in the maximum junction temperature), will also operate correctly for other allowed conditions (switch parameters in the minimum junction temperature).

IV. SIMULATION RESULTS

The proposed method for calculating the average switching and conduction power losses of power switch is implemented in the MATLAB/SIMULINK software as shown in Fig. 6. The “switching power loss calculation” block is described in Fig. 1 and is implemented in the SIMULINK environment as shown in the appendix (Fig. 15). Moreover, the “conduction power loss calculation” block operates based on Eq. (22). Eq. (23) is implemented in the IGBT model for generating the switch on-state voltage $v_{on}(t)$.

A. Evaluating the Operation of the Proposed Method

The proposed method is used to calculate the average power losses of a single-phase inverter for evaluating its performance. As shown in Fig. 7, the inverter is composed of an H-bridge and an LC filter and is used to connect a DC source to the AC load. The characteristics of the inverter and the load are summarized in Table III.

Considering the amount of 50 kHz for the upper limit of the switching frequency, the maximum value of T_p will be equal to 20 μ s in simulations. The duration of the voltage or current

oscillations after switching is one of the parameters that affect the value of T_d . In the simulations in this study, T_d is set to 2 μ s.

TABLE II
PARAMETERS OF IGBTs USED FOR COMPUTING SWITCHING LOSSES WHEN THE JUNCTION TEMPERATURE IS HIGH
($V_n=600$ V, $V_{ce}^*=300$ V, $I_c^*=I_D^*=I_n$)

Name	Part Num.	I_n (A)	Transistor (IGBT)		Antiparallel diode			
			E_{on}^* , E_{off}^* (mj)	V_T (v)	R_{on} (m Ω)	V_T (v)	R_{on} (m Ω)	E_{rr}^* (mj)
S1	SKiiP 28GH066V1	100	3.4, 3.5	1	9	0.9	6	3.3
S2	SK50GBB0 66ET	50	2.2, 1.7	0.8	17	0.9	12	0.7
S3	2MBI100V A-060-50	100	5, 4	0.8	12	0.8	6	2.1

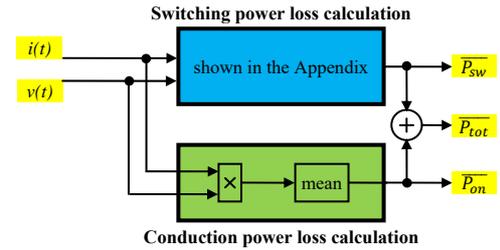


Fig. 6. Proposed method in the MATLAB/SIMULINK environment for calculating the average losses of power switch.

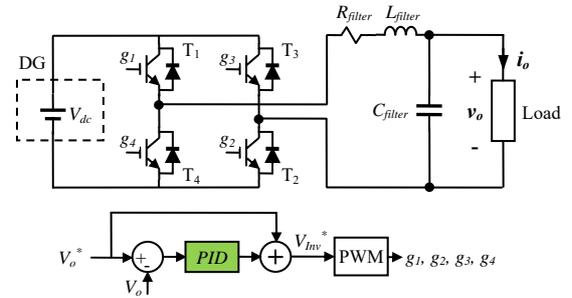


Fig. 7. Single-phase voltage source inverter used for connecting a DC source to the AC load.

TABLE III
CHARACTERISTICS OF THE SINGLE-PHASE INVERTER WITH THE NOMINAL CURRENT OF 50 A

Parameter	Value	Parameter	Value
V_o^*	220 V(rms)/50 Hz	V_{dc}	544 V
P_{Load} , Q_{Load}	7.5 kW, 5.6 kVAR	P	18
R_{filter} , L_{filter}	2.6 m Ω , 2.6 mH	PID controller	$I = 5400$
C_{filter}	100 μ F		$D = 0.001$
			$N = 30000$

As shown in Fig. 8, each square pulse of $i_{on}(t)$ is generated the moment the switch is turned on as described previously in Fig. 3. Each pulse is generated with the pulse width of T_p and with the amplitude that is equal to the switch current right after the turn-on transition.

The signal $i_{off}(t)$ in Fig. 8 is similar to that in Fig. 3. In other words, each square pulse of $i_{off}(t)$ is generated at the turn-off moment of the switch. Furthermore, the duration of each pulse is equal to T_p , and its amplitude is equal to the switch current

right before the turn-off transition.

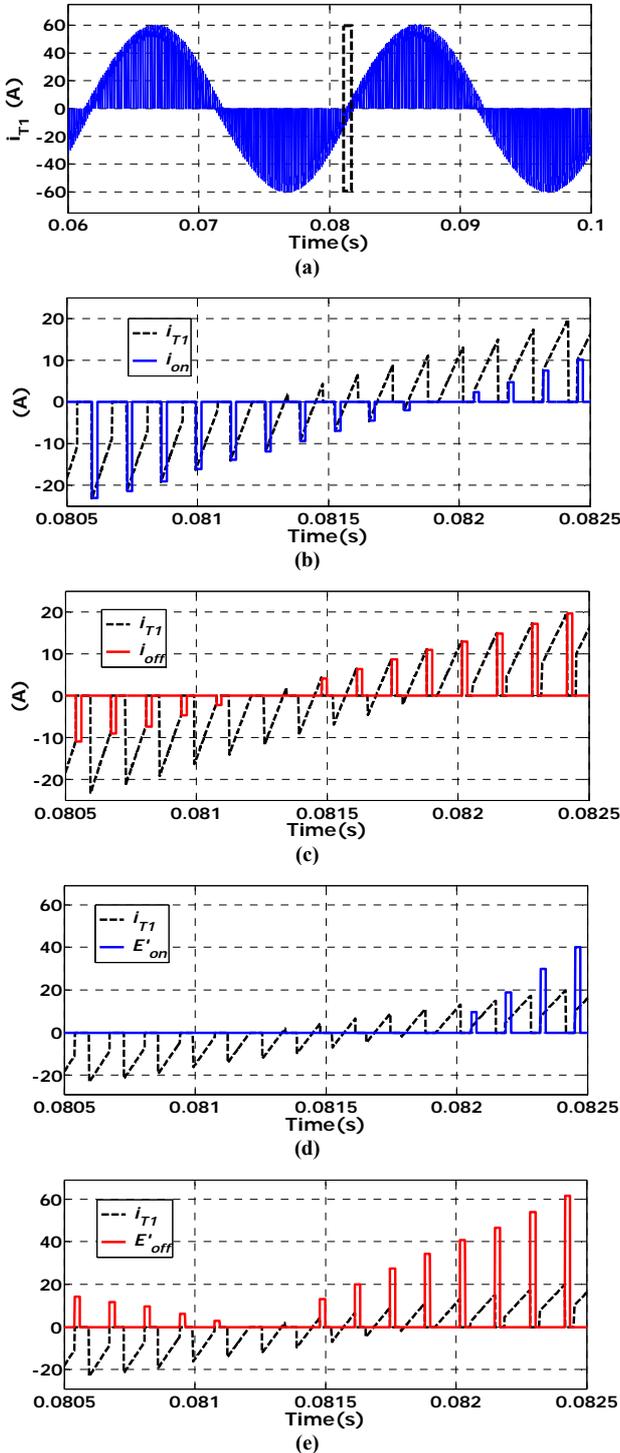


Fig. 8. Number of waveforms in the proposed method in Fig. 4 used for calculating the average switching loss of switch T_1 in Fig. 7: (a) switch current (i_{T1}), (b) i_{T1} and square current at turn-on time (i_{on}), (c) i_{T1} and square current at turn-off time (i_{off}), (d) i_{T1} and square switching loss at turn-on time (E'_{on}), and (e) i_{T1} and square switching loss at turn-off time (E'_{off}).

In Fig. 7, the off-state voltage of the switches is constant and is equal to V_{dc} . Therefore, the simplified form of the proposed method in Fig. 4 is used to calculate the switching power losses.

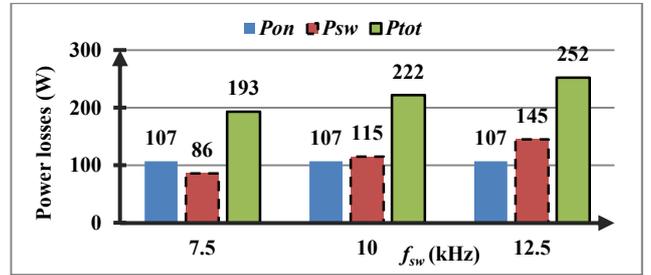


Fig. 9. Power losses of the described inverter in Table III when constructed by switch S2 for some switching frequencies.

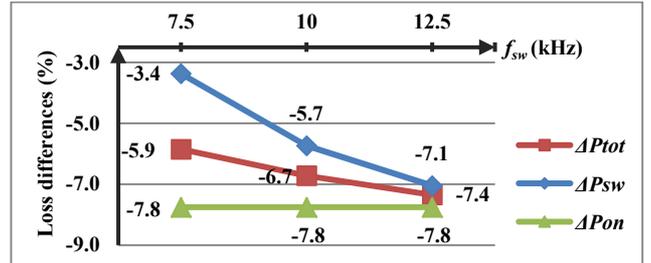


Fig. 10. Relative differences between the losses by the proposed method and the SemiSel software versus some switching frequencies f_{sw} .

Switch S2 in Table II is suitable for constructing the intended inverter with the nominal current of 50 A. Using the characteristics of S2 and value of V_{dc} from Table III, the amount of the loss factors TLF_{on} , TLF_{off} , and DLF in Fig. 4 are obtained by Eq. (20) as $TLF_{on} \approx 3.9893$, $TLF_{off} \approx 3.1371$, and $DLF \approx -1.3056$.

Using the adjusted proposed method, the losses of the inverter are calculated and shown in Fig. 9. In this figure, P_{on} , P_{sw} , and P_{tot} are the average amount of the conduction, switching, and total power losses of the inverter, respectively.

B. Evaluating the Accuracy of the Calculated Losses

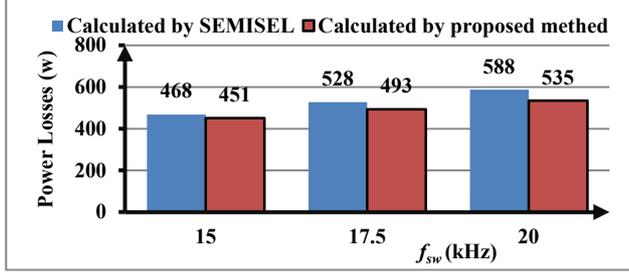
1) *Using the IGBT Loss Simulator Programs:* The accuracy of the calculated losses can be evaluated by comparing them with the losses obtained via loss simulator programs under the same conditions. These programs are provided by the manufacturers of power electronic devices. For example, Semisel-Simulation Software V4.1.2 [11] and FUJI IGBT Simulator V6 [12] are two loss simulator programs presented by the SEMIKRON and FUJI ELECTRIC companies, respectively. These programs can calculate the losses of the single- and three-phase inverters designed by the transistors of the associated companies.

For the described inverter in Table III, the relative differences between the losses by the proposed method and SemiSel software are calculated by Eq. (27). The results of these calculations for some switching frequencies are shown in Fig. 10. As discussed in part B of Section III, the comparison is conducted under the worst conditions. In other words, the parameter values of S2 in Table II are obtained in the high junction temperature. The thermal parameters in the SEMISEL software are adjusted to ensure high junction temperature.

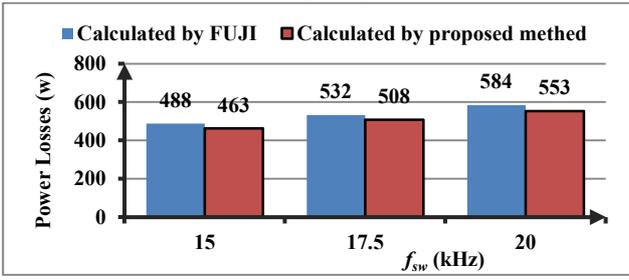
TABLE IV

CHARACTERISTICS OF THE SINGLE-PHASE INVERTER WITH THE NOMINAL CURRENT OF 100 A

Parameter	Value	Parameter	Value
V_o^*	220 V(rms)/50 Hz	V_{dc}	400 V
P_{Loads} Q_{Load}	12.5 kW, 9.3 kVAR	$P = 14$	
$R_{filters}$ L_{filter}	1 mΩ, 1 mH	PID controller	$I = 8700$ $D = 0.001$ $N = 43000$
C_{filter}	100 μF		



(a) Designed by S1



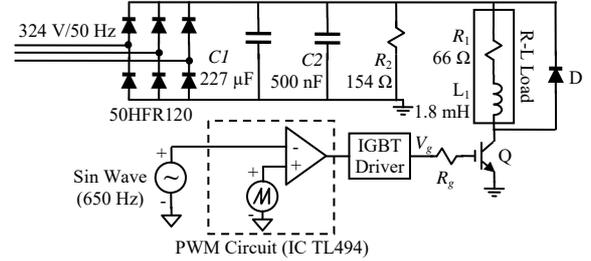
(b) Designed by S3

Fig. 11. Total power losses of the described inverter in Table IV for some switching frequencies.

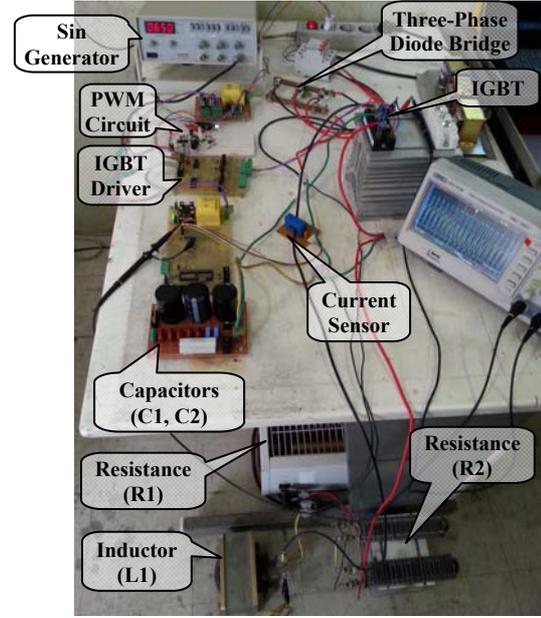
$$\Delta P_{tot} = 100 \times \frac{P_{tot}^{Proposed\ method} - P_{tot}^{Semisel}}{P_{tot}^{Semisel}} \quad (27)$$

In the equation above, P_{tot} is the total power loss of the inverter. This parameter can be substituted by the switching power loss P_{sw} and conduction power loss P_{on} to obtain ΔP_{sw} and ΔP_{on} , respectively. The losses obtained by the proposed method are slightly smaller than the losses by the Semisel software; however, the differences are acceptable.

The characteristics of the intended inverter are changed as shown in Table IV. Switches S1 and S3 in Table II are suitable for constructing this new inverter with the nominal current of 100 A. The average power losses of this inverter are shown in Fig. 11 versus some switching frequencies for two designs: 1) the inverter by SEMIKRON IGBT (i.e., S1) and 2) the inverter by FUJI IGBT (i.e., S3). For these designs, the inverter losses in the worst conditions are calculated by two methods: 1) the proposed method in this study and 2) the associated loss simulation software tools (Semisel-Simulation and FUJI IGBT Simulator). As shown in Fig. 11, the power losses by the proposed method show an acceptable congruence with the power losses by the associated loss simulator software tools.



(a)



(b)

Fig. 12. Proper electrical circuit for evaluating the proposed method experimentally (a) and its laboratory prototype (b).

2) *Using the Experimental Results:* The accuracy of the proposed method can also be evaluated using the experimental results. Thus, the proposed electrical circuit in Fig. 12(a) is constructed and used to obtain the experimental data. The constructed laboratory prototype is shown in Fig. 12(b). As shown in Fig. 12(a), the switch voltage is provided by a three-phase diode-bridge rectifier. Thus, the switch voltage remains approximately constant over time with the value of 550 V as shown in Fig. 13(a).

The alternative load current in Fig. 12(a) will cause the switch current to be an alternative. Therefore, an alternative current with a frequency of 650 Hz flows in the R-L load as shown in Fig. 13(a). This current is generated using the pulse-width modulation (PWM) technique as shown in Fig. 13(a). The triangular and sinusoidal waveforms used in the PWM technique are shown in Fig. 13(b). An oscilloscope (GPS 1072B) with a memory length of 20480 points and sample rate of 12.5 MSa/s is used to measure and save the switch voltage and current waveforms. Considering the limited memory length, the frequency of load current should be increased to 650 Hz to decrease the time and gather all the current samples in one period.

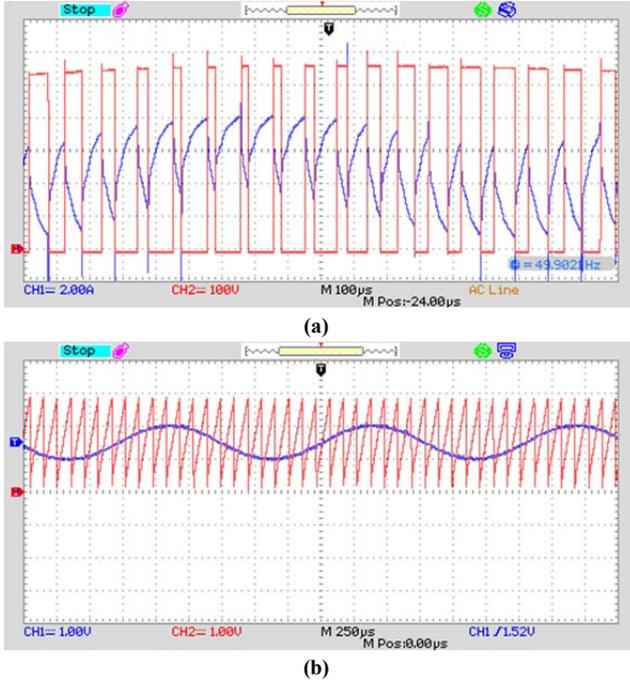


Fig. 13. Waveforms obtained from the laboratory prototype: (a) the IGBT voltage (square waveform) and load current, and (b) triangular and sinusoidal waveforms used for generating alternative switch current by PWM.

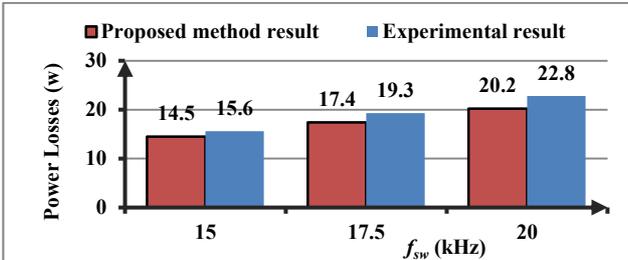


Fig. 14. Average total power losses of the IGBT of the constructed laboratory prototype for some switching frequencies.

TABLE V
MEASURED PARAMETERS OF THE IGBT USED IN LABORATORY PROTOTYPE FOR THE LOW JUNCTION TEMPERATURE
($V_n = 1200$ V, $I_n = 75$ A, $V_{cc} = 600$ V, $I_C = I_D = I_n$)

Part Num.	Transistor (IGBT)			Antiparallel diode		
	E_{on}^*, E_{off}^* (mj)	V_T (v)	R_{on} (m Ω)	V_T (v)	R_{on} (m Ω)	E_{rr}^* (mj)
SKM75GB12T4	2.6, 15.5	0.8	17.4	0.96	21	4.3

The measured and saved waveforms of the switch voltage and current are used to measure the total power losses of the switch. The used switch is an IGBT from the products of the SEMIKRON company. The average power losses of the transistor of the constructed prototype are measured for some switching frequencies and are demonstrated in Fig. 14.

The parameters of the loss models of the IGBT used are summarized in Table V. The values of the parameters are measured in the laboratory for the low junction temperature and the characteristics of the IGBT driver used ($V_g = \pm 15$ V, and $R_g = 10 \Omega$). These values are used in the proposed method, and the average total power losses of the IGBT of the laboratory prototype are calculated in the simulation environment. The calculated losses and the measured losses for some switching frequencies are shown in Fig. 14. The calculated losses present an acceptable congruence with the measured losses. Therefore, the proposed method is operating correctly.

V. CONCLUSION

In this study, switching loss calculation models are comprehensively reviewed for the first time. Accordingly, a proper loss model with less computational burden is selected. The study mainly contributes by establishing an applicable technique for obtaining the average switching power loss by utilizing switching loss models. This technique works properly when the switch current or voltage is an alternative. In addition, the technique can be implemented easily using the basic blocks of programs such as MATLAB/SIMULINK and can sample the switch voltage and current properly.

The performance of the proposed method is evaluated by the simulation and experimental results. In the simulation environment, the proposed method is used to obtain the average switching power losses of a single-phase inverter. For various types of IGBTs, the inverter losses are calculated using the proposed method and compared with the losses by loss simulator tools. The similar values of the compared losses confirm the accuracy of the proposed method.

APPENDIX

An implementation of Fig. 1 in the MATLAB/SIMULINK software environment is shown in Fig. 15.

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