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Modeling of Power Losses in High-Power Motor Drives

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ABSTRACT

The efficiency of the system decreases with increasing switching frequency in high-power density industrial driving applications. In order to increase the system efficiency, reliability, and power quality in a high-power drive system, power losses are becoming more crucial to calculate precisely in the industrial drive. In this study, the switching and conduction losses in a 370 kW industrial motor driver with 1000V DC bus voltage are calculated with the information obtained from the datasheets and modeled in detail for three different insulated-gate bipolar transistor (IGBT)/diode modules on the MATLAB/Simulink environment. Thanks to the obtained model, the losses can be optimized for different switching frequencies, and the performance of the system in terms of losses and efficiency can be examined in the case of using different IGBT/diode modules.

***Index Terms*—**Diode conduction losses, high-power motor drives, IGBT conduction losses, IGBT switching losses

I. INTRODUCTION

Motor drivers, which have become an essential feature in several industrial applications today, are used in power electronic circuits to adjust the amplitude and frequency of the voltage applied to the motor as required by processing the voltage taken from any direct voltage source. In recent years, advances in semiconductor power switches have opened up new possibilities in static power converter systems and industrial motor drive systems [1].

Insulated-gate bipolar transistor (IGBT) switches, which can switch under high voltage and current, are used in high-power industrial motor drivers [2]. Industrial motor drivers are powered by a direct-current (DC) bus and produce a sinusoidal output voltage with adjustable amplitude and frequency. To obtain a sinusoidal output voltage, the semiconductor switches have to be controlled at certain given intervals according to the chosen modulation strategy. Due to the nature of the switching action, a perfect sinusoidal voltage can never be produced at the driver out, and hence the waveform of the output voltage contains harmonics. The quality of the voltage at the driver's output is not very significant due to the high-power IGBT's limited switching frequency, resulting in a high-harmonic supply voltage and current [3]. Although the increase in switching frequency improves the quality of voltage and current, it is not preferred due to the increase in switching losses. In addition, harmonics at the output of the driver generate additional losses in the motors, causing a decrease in efficiency and torque ripple.

In high-power drive systems, additional L filter is connected to the endpoint to reduce the harmonics that occur at the output voltage. Despite its simplicity, the L filter reduces system performance and increases the volume of the driving system due to losses in non-ideal conditions. The additional losses based on harmonics can be reduced by increasing switching frequencies. On the other side, high switching frequencies increase the switching losses in semiconductor devices due to frequent switching [4]. Thus, designing low-loss drive systems has become mandatory to reduce both the additional machine losses caused by the harmonic component of the current at the driver output and the losses caused by high switching frequencies [5]. Moreover, since inverters operate at high frequencies, the IGBT's high-power loss damages devices and the inverter. Hence, it is critical to accurately and quickly determine power losses and to find ways to reduce them [6]. For instance, while in [7, 8] zero voltage and zero current topologies were

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being developed to decrease the losses in IGBT/diode modules, in [9, 10], closed-form solutions for decreasing switching and conduction losses were proposed to be used. In [11], an algorithm that aims to reduce the switching losses in active power filters with a new modulation strategy was suggested.

In [12, 13], the researchers aimed to design different IGBT/diode modules with low loss. Therefore, it is becoming compulsory not only to select proper switching devices according to power ratios [14] but also to design the systems in line with the performance of each component [15].

In this paper, the switching and conduction losses of IGBT/diode modules used in high-power motor drivers are calculated using only the datasheet parameters. In Section II, the mathematical base of losses is given by classifying IGBT/diode module losses in the motor driver. In Section III, switching and conduction losses in modules were modeled with MATLAB/Simulink. In Section IV, the losses of a 370 kW industrial induction motor driver with 1000V DC bus voltage and 690V/40 Hz output voltage are calculated using a mathematical base. In Section V, the study's findings were also interpreted and the success of the developed model was discussed.

II. INSULATED-GATE BIPOLAR TRANSISTOR LOSSES

The losses in an industrial motor driver are determined by power losses in IGBT/diode modules. These losses are composed of dynamic losses (on and off) and static losses (on-state and off-state) [16]. Within this paper, the losses in the modules are classified into three categories:

1. switching losses ($P_{sw,IGBT}$);
2. conduction losses ($P_{con,IGBT}$); and
3. reverse recovery losses on freewheeling diode ($P_{con,FWD}$).

A. Switching Losses

The switching power loss, which occurs during the switching states, is proportional to the square of the switching frequency. While the switch is conducting, the current on the switching device increases, and the voltage drop decreases. While the switch is cut off, on the contrary, the current on the switching element decreases, and the voltage drop increases [17]. Because of certain time requirements for switching in an IGBT, a significant amount of energy is consumed by the switching element, and therefore switching losses occur at the switching moment [5, 6]. In an IGBT with a freewheeling diode (FWD), switching losses are categorized into three groups:

1. IGBT turn on energy losses (E_{on});
2. IGBT turn off energy losses (E_{off}); and
3. FWD reverse recovery losses (E_{rr})

The power losses are expressed the total of IGBT and freewheeling diode power losses in (1).

$$P_{sw} = P_{sw,IGBT} + P_{SW,FWD} \quad (1)$$

Total switching loss in one period declared as the sum of , and energy losses including switching frequency is given in (2).

$$P_{sw} = \left(E_{on} + E_{off} + E_{rr}\right).f_{sw} \quad (2)$$

B. Conduction Losses

During the conduction period, the switching devices do not conduct as if they were ideal switches, which have zero on-state resistance and zero voltage drop [5]. While the IGBT is on state, there is always a voltage drop on the switching element and it has on state resistance. This voltage drop means there is power disruption on the switching element and occurrence of power loss [18]. Because of these non-ideal situations, conduction losses occur while the switch is turned on. In an IGBT with a freewheeling diode, conduction losses are divided into two groups.

1. IGBT conduction losses ($P_{con,IGBT}$)
2. FWD conduction losses ($P_{con,FWD}$)

The conduction losses of a switch for an IGBT/diode module are described primarily as in (3).

$$P_{con} = \left(I_{sw,RMS}\right).V_x \quad (3)$$

III. MATHEMATICAL MODELING

Fig. 1 contains information about the model developed for the paper. In this case, a MATLAB/Simulink model of the induction motor and driver is built to investigate the IGBT losses and obtain the required current values. The gate signals which are used to drive the IGBT power switches in the installed model are obtained by using space vector pulse width modulation, which is currently a commercial driving strategy of drives. Thus, the gate signals with 40 Hz output voltage and 120° phase difference in between are achieved. The information about the reference motor driver is given in Table I.

To model the losses that occur in high-power motor drivers, the current flowing from the IGBT/diode modules, as well as the voltage on the module, must be known with high accuracy to be used in calculating switching and conduction losses.

As seen in Fig. 1, in addition to IGBT switches, a freewheeling diode is used in this model to obtain the current value through the diode, which is not possible in other IGBT models. With this driver model, the current flowing and voltage drop of each switch and diode in industrial motor drivers can be obtained. The waveforms of the motor line voltage, motor line current, and the current flowing from the IGBT and diode for one period are given in Figs 2–4, respectively.

A. Modeling of Switching Loss

Switching losses occur due to non-ideal voltage and current transitions during the switching operation in an IGBT. Switching loss in a switching element is described as in (4).

MAIN POINTS

- *The switching and conduction losses that occur in a high-power industrial motor drives are classified, and the mathematical background of the losses is explained.*
- *A motor drive model was built to obtain the current flowing from the insulated-gate bipolar transistor (IGBT)/diode modules to create high-accuracy loss models using MATLAB/Simulink.*
- *Switching and conduction losses were calculated for three different IGBT/diode modules at three different switching frequencies using loss models developed using mathematical modeling principles in MATLAB/Simulink.*
- *It has been verified that the switching losses are higher than the other losses and are directly proportional to the switching frequency.*
- *It has been revealed that total drive losses are an important optimization problem that cannot be ignored in terms of the efficiency and reliability of the motor drive system.*

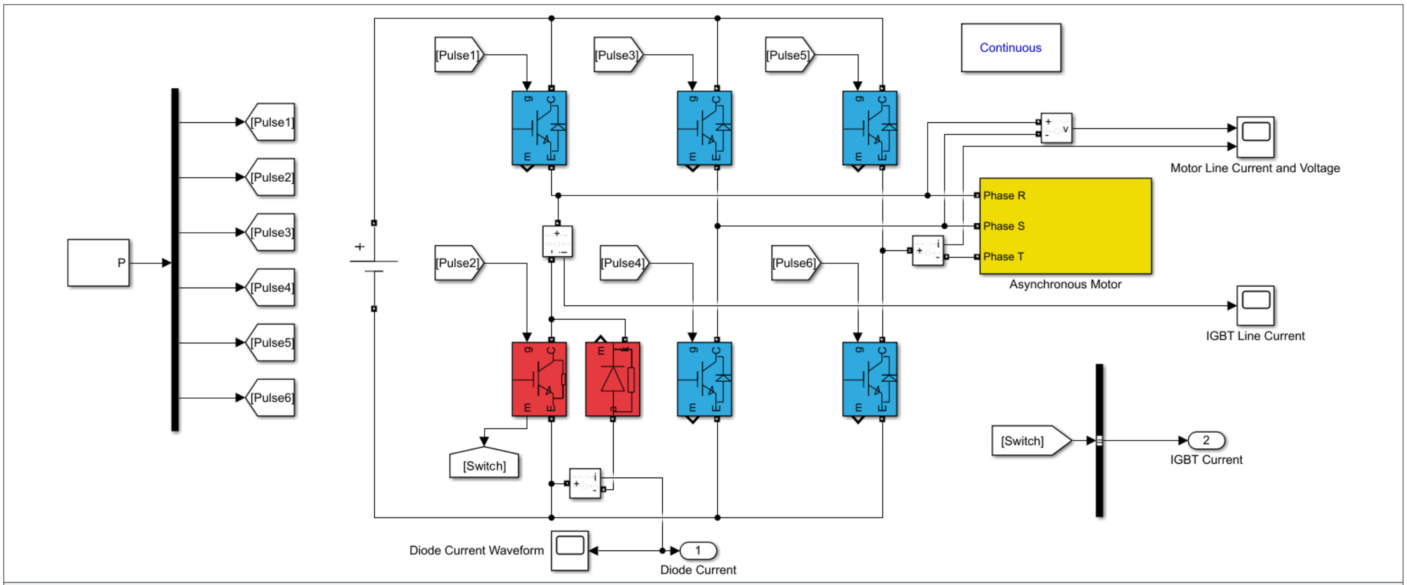

Fig. 1. MATLAB/Simulink model for an industrial motor driver.

TABLE I. NOMINAL OPERATING VALUES OF THE DRIVER

Symbol	Parameter	Value
V_{DC}	DC bus voltage	1000 V
f_o	Output voltage frequency	40 Hz
f_s	Switching frequency	1.6 – 3.2 – 4.8 kHz
P_o	Driver power	370 kW

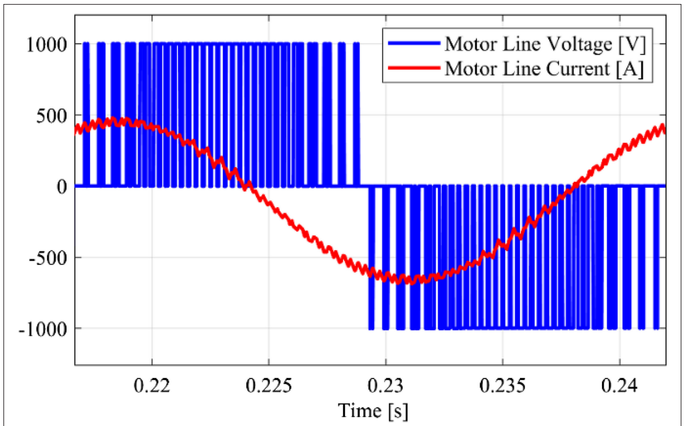

Fig. 2. Waveform of motor line voltage and current.

$$P_{sw}=\frac{1}{T_{sw}}\int_0^{T_{sw}}\left[E_{on}(t)+E_{off}(t)\right]dt \quad (4)$$

Considering switching topologies, it is observed that the reverse recovery losses on the diode also increase switching losses. Consequently, (4) can be arranged when reverse recovery losses are also included in the total energy loss as follows:

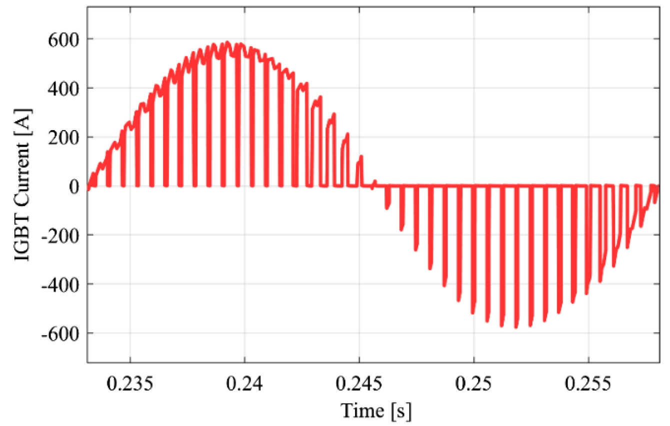

Fig. 3. Waveform of a current flowing through the insulated-gate bipolar transistor (IGBT).

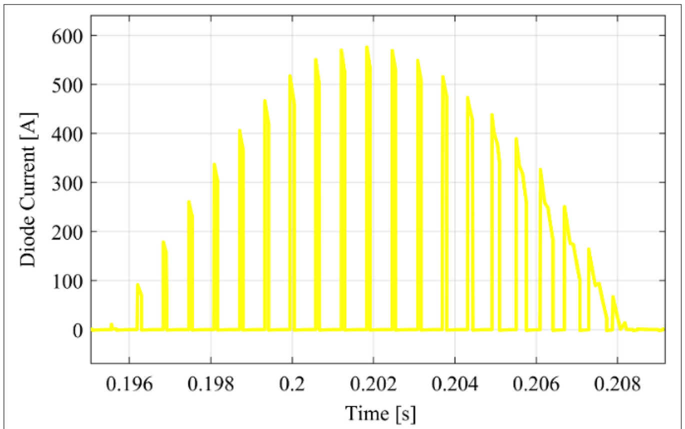

Fig. 4. Waveform of a current flowing through the diode.

$$P_{sw} = \frac{1}{T_{sw}} \int_0^{T_{sw}} \left[E_{on}(t) + E_{off}(t) + E_{rr}(t) \right] dt \tag{5}$$

The formula for calculating switching losses is given in (6).

$$P_{sw} = \left(E_{on} + E_{off} + E_{rr} \right).f_{sw} \tag{6}$$

As mentioned in (6), total switching losses are obtained by multiplying the switching frequency by the sum of IGBT turn-on, turn-off, and reverse recovery energy losses. The parameters needed for calculation can be found in the datasheet of the IGBT/diode module. In this paper, the change curves of E_{on}, E_{off}, and E_{rr} energies given in the datasheet of three different IGBT/diode modules, MIO2400-17E10 [19], FZ2400R17HP4_B29 [20], and 1MBI2400VD-170E [21], at 125°C operating condition, were used in Fig. 5.

B. Modeling of Conduction Loss

Conduction losses increase in inverters due to the harmonic content of the phase currents and the fact that they are not completely sinusoidal. The instantaneous conduction loss for a current-flowing IGBT can be calculated by (7) [19].

$$P_{con,X}(t, i_x, T_j) = R_x(T_j).i_x(t)^2 + V_x(T_j).i_x(t) \tag{7}$$

The average value of conduction losses over a period can be calculated as given in (8).

$$P_{con,X}(i_x, T_j) = \frac{1}{T_{sw}} \int_0^{T_{sw}} P_{con,X}(t, T_j) dt \tag{8}$$

The conduction losses can be expressed as given in (9), the voltage drop on the semiconductor multiplied by the current through the IGBT or diode, where the substring (*x*) symbolizes IGBT as well as FWD since the equation remains the same for each.

$$P_{con,X}(i_x, T_j) = \frac{1}{T_{sw}} \int_0^{T_{sw}} V_{CE}(t, T_j).i_x(t) dt \tag{9}$$

As the sum of the conduction losses, (10) shows the entire conduction losses at any T_j junction temperature as well as any current flowing through the device.

$$P_{con}(i_x, T_j) = P_{con,IGBT}(i_{IGBT}, T_j) + P_{con,FWD}(i_{FWD}, T_j) \tag{10}$$

The conduction losses, as seen in Fig. 6, are classified into two groups: IGBT conduction losses and diode conduction losses. In this paper, the parameters given in the datasheet of three different IGBT/diode modules, MIO2400-17E10, FZ2400R17HP4_B29, and 1MBI2400VD-170E, for 125ºC operating condition, were used. The equations for conduction loss show that the junction temperature has a direct effect on conduction loss. Therefore, the junction temperature value is directly included in the calculations. In the final step, the obtained switching and conduction losses are added together, and the total losses in an IGBT/diode module are calculated.

IV. SIMULATION RESULTS AND DISCUSSION

In this paper, the total losses on the driver were modeled and calculated at 1000V DC bus voltage, 690V/40 Hz output voltage, and 370 kW power using three different IGBT/diode modules that are commonly used in industrial drives. Switching, conduction, diode losses,

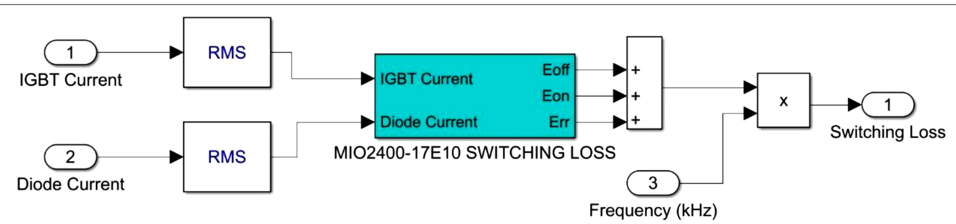

Fig. 5. Subsystem of total switching loss calculation. IGBT, insulated-gate bipolar transistor.

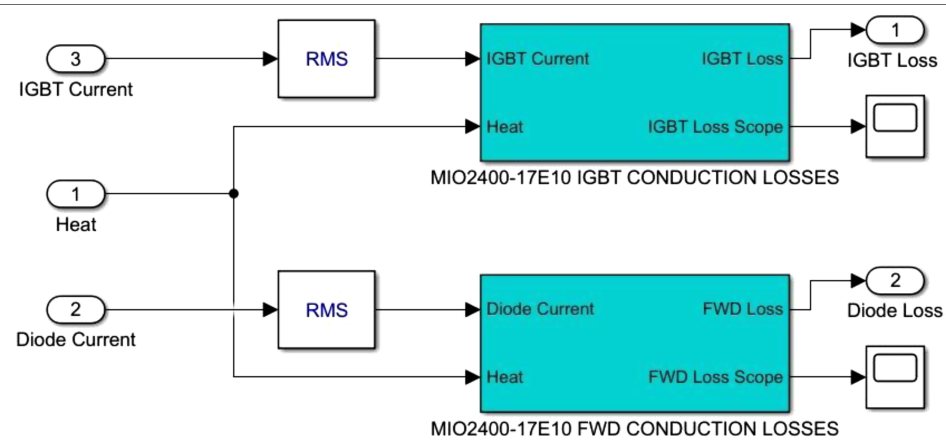

Fig. 6. Subsystem of total insulated-gate bipolar transistor (IGBT) and diode conduction loss calculation.

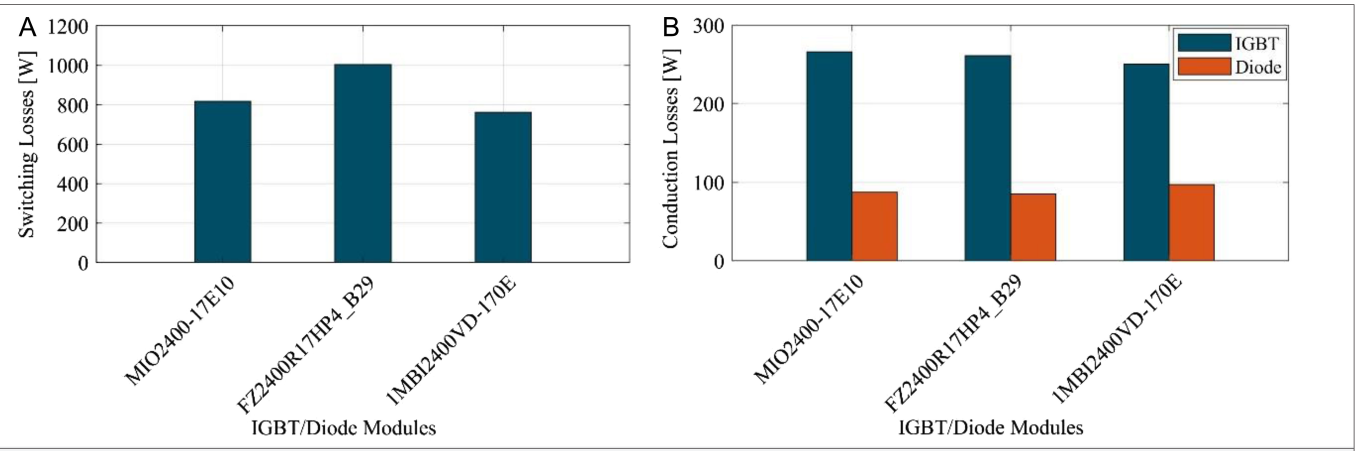

Fig. 7. Total insulated-gate bipolar transistor (IGBT)/diode (a) switching and (b) conduction losses at 1.6 kHz switching frequency.

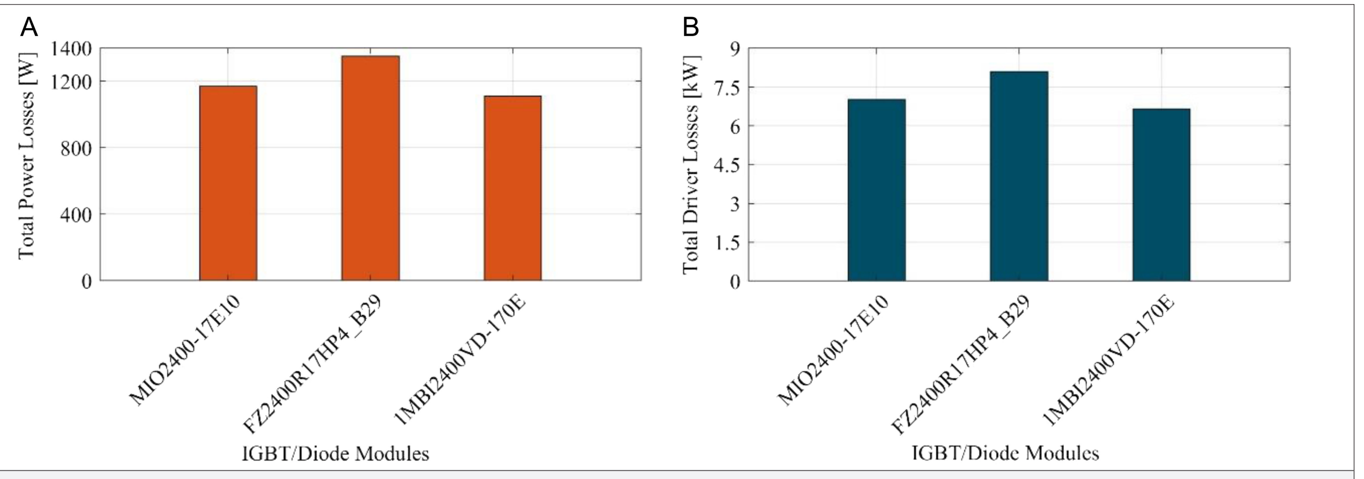

Fig. 8. Total (a) power losses of one insulated-gate bipolar transistor (IGBT)/diode and (b) the driver at 1.6 kHz switching frequency.

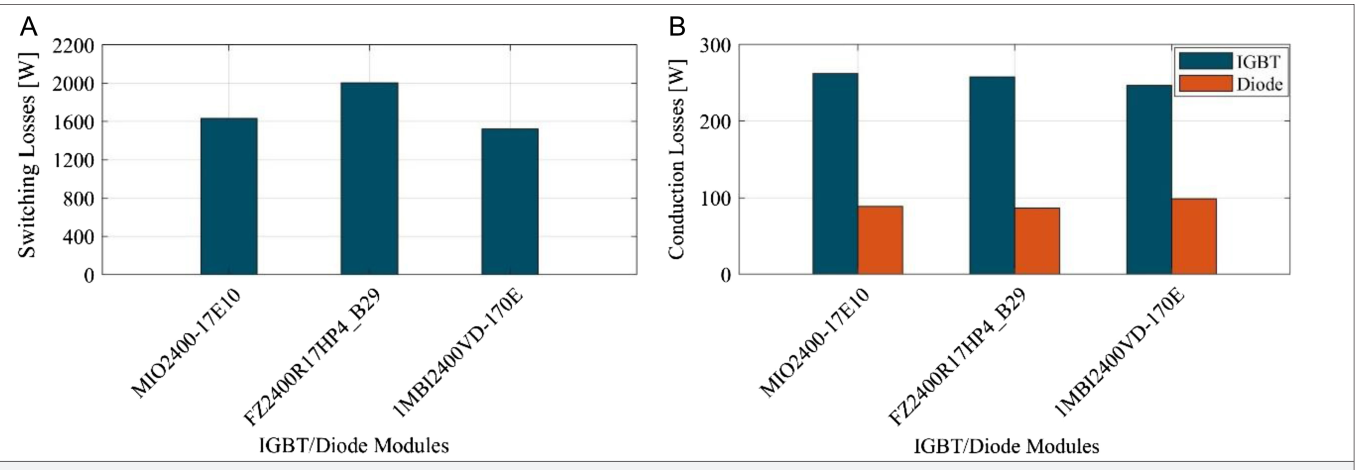

Fig. 9. Total insulated-gate bipolar transistor (IGBT)/diode (a) switching and (b) conduction losses at 3.2 kHz switching frequency.

total power losses for each IGBT/diode, and the total losses for six IGBTs/diodes in the driver system for three different modules at three different switching frequencies are shown in Figs 7–12, respectively.

The obtained loss values for three different switching frequencies are given in Table II. As it can be inferred from the results, the majority of losses in an industrial driver are switching losses.

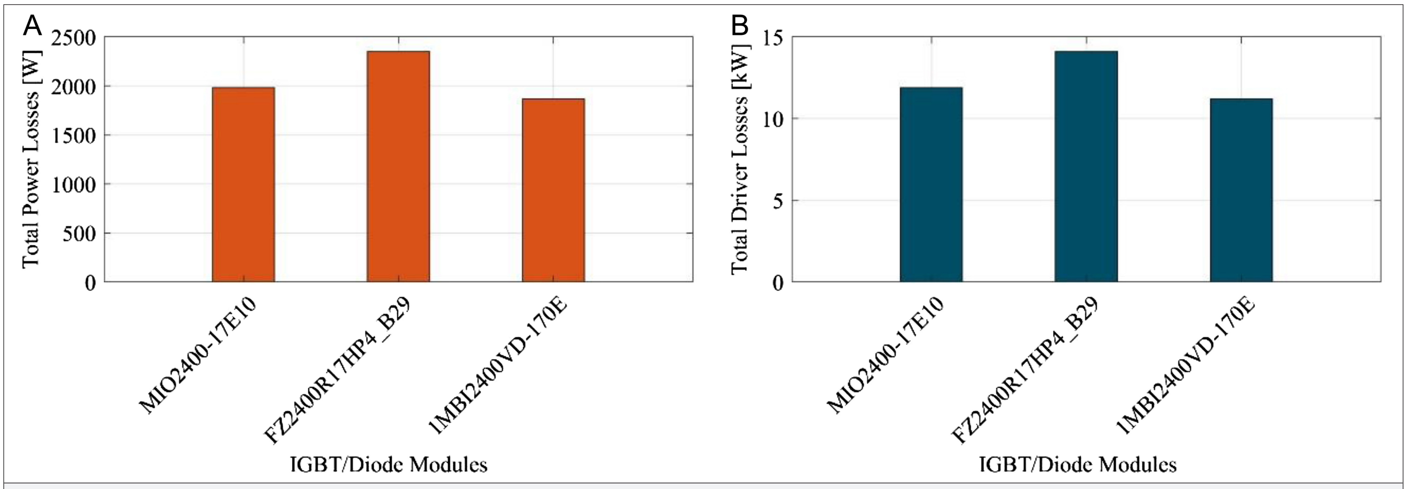

Fig. 10. Total (a) power losses of one insulated-gate bipolar transistor (IGBT)/diode and (b) the driver at 3.2 kHz switching frequency.

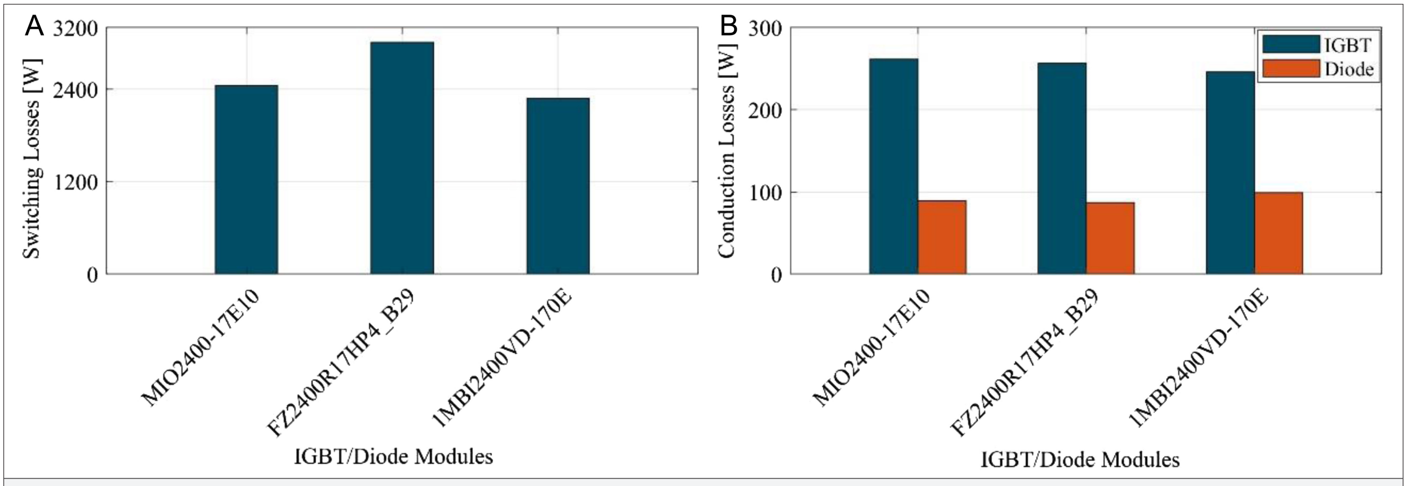

Fig. 11. Total insulated-gate bipolar transistor (IGBT)/diode (a) switching and (b) conduction losses at 4.8 kHz switching frequency.

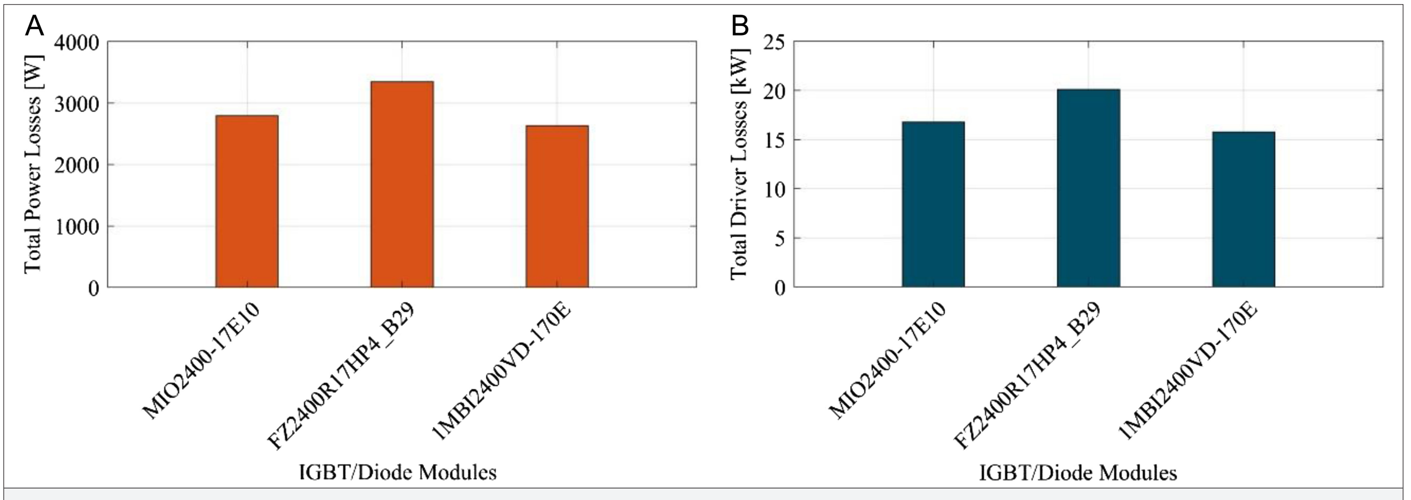

Fig. 12. Total (a) power losses of one insulated-gate bipolar transistor (IGBT)/diode and (b) the driver at 4.8 kHz switching frequency.

TABLE II. THE LOSSES ON EACH IGBT/DIODE FOR THREE DIFFERENT MODULES AT DIFFERENT SWITCHING FREQUENCIES

Modules	Loss Types	1.6 kHz	3.2 kHz	4.8 kHz
MIO2400-17E10	Switching losses	816.6 W	1632 W	2448 W
	IGBT conduction losses	265.8 W	262.4 W	261.6 W
	Diode conduction losses	87.58 W	88.84 W	89.35 W
FZ2400R17HP4_B29	Switching losses	1003 W	2004 W	3006 W
	IGBT conduction losses	260.9 W	257.6 W	256.9 W
	Diode conduction losses	85.27 W	86.67 W	87.1 W
1MBI2400VD-170E	Switching losses	762.6 W	1524 W	2286 W
	IGBT conduction losses	250.2 W	246.9 W	246.1 W
	Diode conduction losses	96.89 W	98.48 W	98.97 W

IGBT, insulated-gate bipolar transistor.

V. CONCLUSION

In high-power industrial drive systems due to the high switching currents and voltages, very high switching speeds are not possible to reach. In consequence, motor current can involve considerable harmonic components. These harmonic components enhance both driver losses and motor losses. This paper modeled the losses in a 370 kW industrial induction motor driver with a 1000V DC bus voltage and a 690V/40 Hz output voltage using MATLAB/Simulink. The total loss in IGBT and diode is calculated by using each switch and diode current values, which are obtained from the real model of a drive system. The obtained results show that the switching losses in an IGBT are greater than conduction losses, and when the total numerical result is taken into account, the IGBT losses are too large to be ignored. As a result, increasing the switching frequency not only improves the quality of the voltage applied to the motor but also significantly increases the switching losses. By this finding, it is concluded that the impact of increasing switching losses at high switching frequencies on system performance and cooling systems should be considered for the final design of high-power motor drivers.

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