TILAS: A Simple Analysis Tool for Estimating Power Losses in an IGBT-Diode Pair under Hysteresis Control in Three-Phase Inverters

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Abstract**—** Several techniques for analyzing and estimating power losses in insulated-gate bipolar transistors (IGBTs), diodes, MOSFETs, and other power electronics switching devices are known. Most of the approaches in the literature deal with periodic pulse width modulation (PWM) switching schemes. This paper presents a simple analysis tool to estimate these losses under aperiodic switching schemes, e.g. hysteresis. The tool aims to simplify such an analysis with two main measurements – the load current of a converter phase leg and the gate switching waveform of the upper IGBT of that phase. No model estimations, thermal analyses, or slow simulations are required. Consistency between results from the proposed tool and a commercially available tool designed by an IGBT manufacturer is shown. A periodic frequency is proposed to adapt available software used with periodic switching schemes to aperiodic switching schemes. Experimental tests from an inverter application are presented here.

Index Terms**—IGBT Losses, Loss Estimation Technique, Converter Losses.**

I. Introduction

Power losses in power electronics determine cooling requirements for insulated-gate bipolar transistors (IGBTs), diodes, MOSFETS, etc. The sizing and material of heat sinks, in addition to the choice of blowers, liquid cooling, heat pumps, etc. is dictated by these losses. New design and analyses tools are required for hysteretic control in three-phase inverters and controlled rectifiers. Hysteretic control is useful in power factor correction and provides flexibility in setting ripple and switching frequency through adaptive hysteresis bands. The literature includes loss-analysis tools that are useful under certain applications and conditions but not for aperiodic switching schemes.

II. Literature Review

References [1-10] assume fixed frequency under PWM operation. The approaches cannot be applied to aperiodic switching. In [1] and [2], it is assumed that the current is a sine wave while the IGBTs operate under pulse width modulation (PWM). This is an idealized case. In [3], an analytical calculation tool for power losses in both voltage-source and current-source inverters is presented using the same assumptions as [1] and [2], but also assuming switching energy linearity with the current. [4] includes a detailed analytical derivation of power-loss equations using plots of switching energies found on datasheets. On the other hand, [5] assumes a fixed switching frequency and analyzes power losses based on experimental data rather than a simple tool, while using soft switching resonant techniques. A simple procedure for estimating power losses in IGBTs under fixed-frequency techniques based on sensitive temperature measurements is presented in [6]. A useful idea in [7] is to estimate switching-loss functions through an identification procedure. The goal in [8] is to compare power losses in planar and trench-gate IGBTs under soft switching and space vector modulation.

Two important techniques for loss measurement are presented in [9]: calorimetry and another thermal approach. In [9] as well as [6-8], only IGBT losses are analyzed. [10] focuses on design considerations rather than techniques for estimating losses. A loss summation method is presented in [11], which first determines values of parasitic elements in the model then the switching energy curves. Even though the method compares well to actual measurements, the simulations are computationally intense and involve detailed knowledge of the physical structure. Computational effort is reduced in [12] by using ideal switch models and estimating junction temperatures to determine power losses. This technique suffers from measurement offsets which the authors corrected manually. [13] and [14] investigate IGBT turn-off losses to compare planar and trench IGBTs. Hardware measurements are used in [15] to determine losses through a sophisticated technique. Accuracy of 7.1% is achieved. The procedure in [16] also depends on measurements, but it estimates energy functions from these measurements by determining function coefficients.

Past work addressing simple, straightforward, and accurate analysis tools to determine IGBT and diode losses under aperiodic switching is limited. An accurate approach of estimating power losses through modeling was presented in [17] in which an IGBT-diode pair is modeled in Dymola. The developed model included both electrical and thermal characteristics, and was able to predict losses under aperiodic

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switching schemes. Another attempt was [18], which is based on curve fitting of switching energies, and takes into consideration aperiodic switching. It is applied to a motor drive.

III. PROPOSED ANALYSIS TOOL: TILAS

The proposed analysis tool, TILAS: "Tool for IGBT-diode pair Losses under Aperiodic Switching", requires only two inputs: the load current and the gate switching signal of the upper IGBT-diode module. It is independent of a complex IGBT-diode model and detailed knowledge of physical characteristics, as well as thermal measurements, and switching frequency. The switching signal need not be periodic as in the hysteretic control case studied here, and the load current does not have to be a pure sine wave. Compared to TILAS, the procedure in [18] has a smaller step size and therefore longer simulation time, non-polynomial models of the functions, dependence on rise and fall times, and incomplete comparisons with available software. Also, compared to [17], TILAS does not require the development of a complete IGBT-diode pair model. Here, IGBT and diode switching and conduction losses are estimated using TILAS, where the waveforms are taken either from simulations or hardware measurements. TILAS is developed in MATLAB® and uses data from a text file or spreadsheet containing measurements.

The application simulated is an indirect field oriented control (IFOC) of a 50 hp induction motor with hysteretic control through an ideal three-phase voltage source inverter (VSI), as shown in Figure 1. A sample phase "a" current (I) and switching signal (p) waveforms are shown in Figure 2. T_e* is the command torque in N·m., λ_{dr}* is the command rotor flux in V·s., ω_r is the rotor speed in rad/sec, and I_{abc} is the vector of the motor current. In Figure 2, a diode is labeled "D" and an IGBT is labeled "Q."

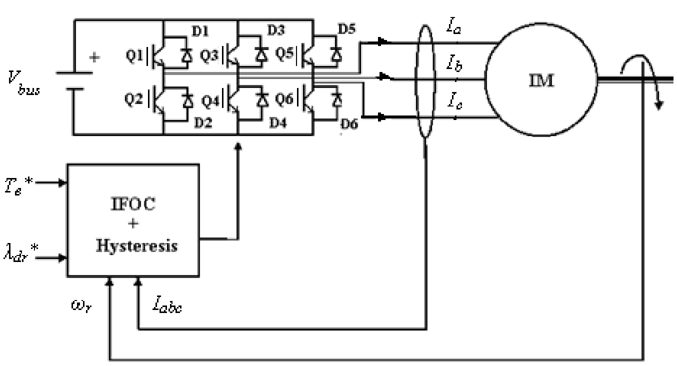

FIGURE 1: BLOCK DIAGRAM OF AN INDUCTION MOTOR CONTROLLED UNDER IFOC

TILAS uses four or five points taken from datasheet graphs to estimate switching-energy functions, the diode forward voltage, and the IGBT saturation voltage as second-order polynomials. Then, these functions are scaled depending on the dc voltage of the actual system. A window is then chosen from a steady-state measurement on which TILAS is applied. Figure 3 shows a flow chart of the logic for determining the losses. It can be summarized as examining the sign of the current and the previous and current state of the upper IGBT (Q1). The positive current convention is shown in Fig. 1. Note that cases in which the current commutates from positive to negative while the IGBT gate is high would cause a negligible switching effect, because the voltage across the IGBT or diode is low compared to V_{bus}.

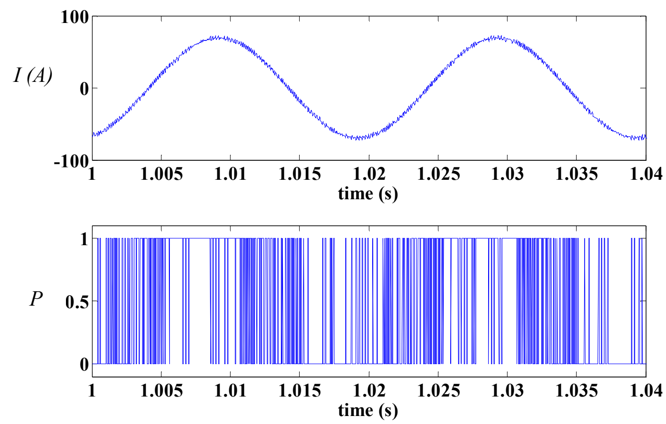

FIGURE 2: SAMPLE CURRENT AND PULSE WAVEFORMS FROM SIMULATIONS

In (1-6) and Figure 3, $E_{Q,sw}$ is the IGBT switching energy including both on ($E_{Q,on}$) and off ($E_{Q,off}$) switching energies, $E_{Q,cond}$ is the IGBT conduction, $E_{D,sw}$ is the diode turn-off energy, $E_{D,cond}$ is the diode conduction energy, $V_{ce,sat}$ is the IGBT saturation voltage, V_f is the diode forward voltage, and the "a", "m", and "n" terms are the unknowns determined using MATLAB's curve fitting function to estimate the switching energy at a current level $I(i)$ at iteration i.

$$E_{Q,on}(i)=E_{Q,on}(i-1)+a_{11}I(i)^2+a_{12}|I(i)|+a_{13}, \quad E_{Q,on}(1)=0 \tag{1}$$

$$E_{Q,off}(i)=E_{Q,ff}(i-1)+a_{21}I(i)^2+a_{22}|I(i)|+a_{23}, \quad E_{Q,off}(1)=0 \tag{2}$$

$$E_{Q,sw}(i)= E_{Q,on}(i)+ E_{Q,off}(i) \tag{3}$$

$$E_{D,sw}(i)=E_{D,sw}(i-1)+a_{31}I(i)^2+a_{32}|I(i)|+a_{33}, \; E_{D,sw}(1)=0 \tag{4}$$

$$\begin{aligned} E_{Q,cond}(i)&=E_{Q,cond}(i-1)+V_{ce,sat}(i)\times|I(i)|\times[t(i)-t(i-1)] \\ &= E_{Q,cond}(i-1)+[m_1I(i)^2+m_2|I(i)|+m_3]\times|I(i)|\times[t(i)-t(i-1)], \\ &E_{Q,cond}(1)=0 \end{aligned} \tag{5}$$

$$\begin{aligned} E_{D,cond}(i)&=E_{D,ccond}(i-1)+V_f(i)\times|I(i)|\times[t(i)-t(i-1)] \\ &= E_{D,cond}(i-1)+[n_1I(i)^2+n_2|I(i)|+n_3]\times|I(i)|\times[t(i)-t(i-1)], \\ &E_{D,cond}(1)=0 \end{aligned} \tag{6}$$

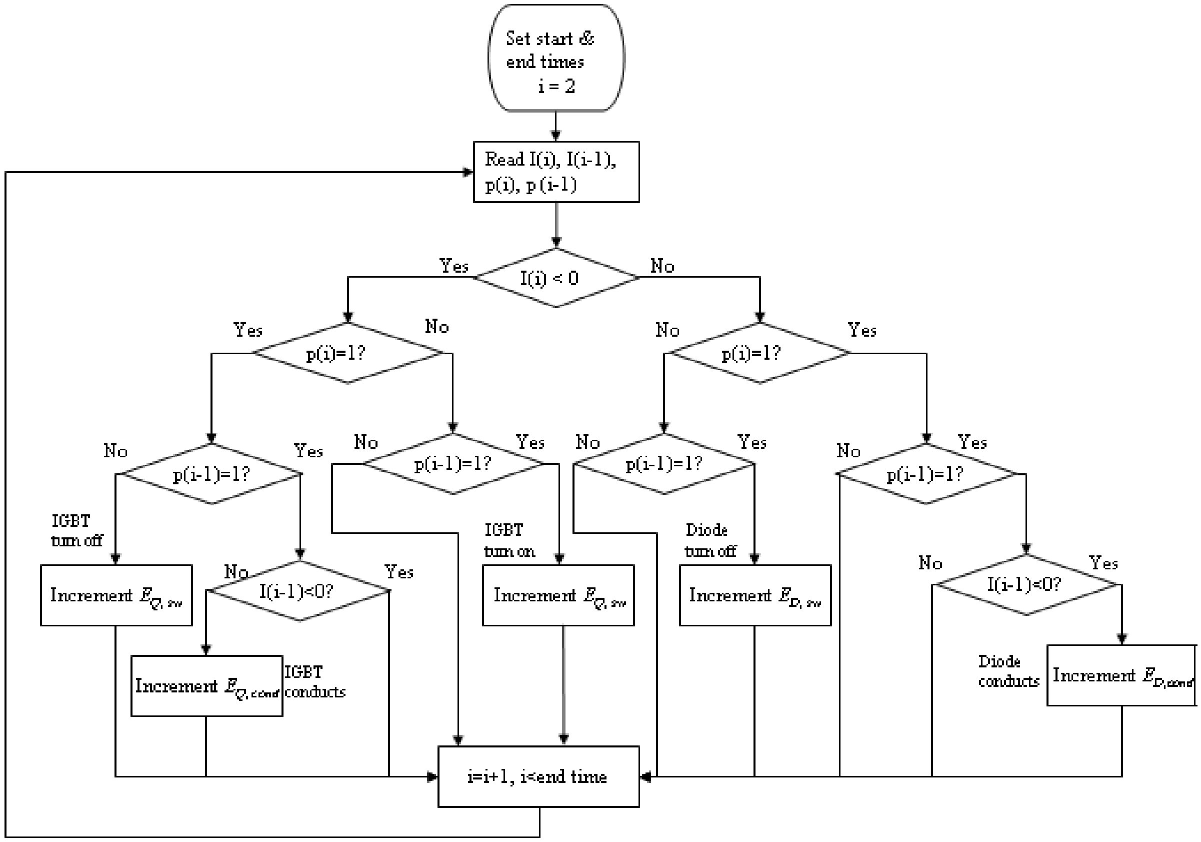

FIGURE 3: FLOW CHART OF TILAS

TABLE 1: FIXED FREQUENCY COMPARISON WITH MELCOSIM

	TILAS (P in (W))					Melcosim (P in (W))					
f (Hz)	$P_{Q,cond}$	$P_{Q,sw}$	$P_{D,cond}$	$P_{D,sw}$	P_{Total}	$P_{Q,cond}$	$P_{Q,sw}$	$P_{D,cond}$	$P_{D,sw}$	P_{Total}	P_{Total} %err
1080	28.07	5.70	12.47	0.79	47.03	28.44	6.17	12.87	0.86	48.34	-2.71
3240	27.26	16.92	11.71	2.43	58.33	27.19	18.06	12.48	2.53	60.26	-3.21
5400	26.30	28.11	10.85	4.07	69.32	26.91	29.9	12.35	4.21	73.37	-5.52
8640	24.94	44.85	9.37	6.52	85.69	26.91	47.84	12.35	6.73	93.83	-8.68

IV. VERIFICATION OF TILAS WITH SIMULATIONS

To verify that TILAS is correctly estimating power losses, a motor simulation was run in Simulink® under different fixed PWM frequencies rather than IFOC at a step of 10 µs. An IGBT-diode module, model CM400DY-12NF from Mitsubishi, was chosen for testing TILAS, with a 400 V system bus. Table 1 shows results from TILAS and results from Melcosim® where P is the power. It is clear that errors in the estimated losses from TILAS and Melcosim are generally less than 9%. Reasons behind the discrepancies could include either the assumption of a pure sine wave in Melcosim, and/or inaccuracy in extracting data points of voltages and switching energies from the datasheets.

V. ANALYSIS OF LOSSES UNDER HYSTERETIC CONTROL

The IFOC is analyzed in Simulink. The system switching frequency is naturally bounded by the motor's inductive characteristics, and its upper bound can be varied by varying the hysteresis band. TILAS allows available software to adapt a fixed frequency for estimating power losses under aperiodic switching. Thus, the following measurements used with fixed frequency schemes were recorded in the simulation: power factor between the fundamental components of the phase voltages and currents, modulation index based on the fundamental voltage, and four frequencies. These frequencies are: the maximum switching frequency, f_{max}, half of f_{max}, the average frequency, f_{avg}, and the frequency of transitions, f_t. f_{avg} is computed by averaging the frequency over time for every time step, while f_t is the number of transitions per second at steady state. The simulation time in Simulink for both PWM and hysteretic control is less than one minute, and the results from TILAS are available in less than one second. Table 2 compares the results from TILAS and Melcosim using the four frequencies mentioned above.

TABLE 2: TILAS COMPARED TO MELCOSIM UNDER HYSTERETIC CONTROL

	TILAS (P in (W))					Melcosim (P in (W))						
f_{max} (Hz)	$P_{Q,cond}$	$P_{Q,sw}$	$P_{D,cond}$	$P_{D,sw}$	P_{Total}	f (Hz)	$P_{Q,cond}$	$P_{Q,sw}$	$P_{D,cond}$	$P_{D,sw}$	P_{Total}	P_{Total} %err
4380	14.82	6.79	3.31	1.20	26.12	f_{avg} 2270	16.38	8.29	3.71	1.41	29.79	14.05
					26.12	$f_{max}/2$ 2190	16.38	8	3.71	1.36	29.45	12.75
					26.12	f_t 2169	16.38	7.92	3.71	1.35	29.36	12.41
					26.12	f_{max} 4380	16.38	16	3.71	2.72	38.81	48.59
7780	14.44	13.25	3.01	2.50	33.21	f_{avg} 4450	15.31	15.56	3.46	2.7	37.03	11.51
					33.21	$f_{max}/2$ 3890	15.31	13.6	3.46	2.36	34.73	4.58
					33.21	f_t 4263	15.31	14.91	3.46	2.58	36.26	9.19
					33.21	f_{max} 7780	15.31	27.2	3.46	4.72	50.69	52.64
14600	13.95	24.51	2.38	4.93	45.77	f_{avg} 8445	15.44	29.69	3.49	5.14	53.76	17.46
					45.77	$f_{max}/2$ 7300	15.44	25.67	3.49	4.44	49.04	7.14
					45.77	f_t 8000	15.44	28.13	3.49	4.86	51.92	13.44
					45.77	f_{max} 14600	15.44	51.33	3.49	8.88	79.14	72.91
17150	13.39	34.88	1.80	7.00	57.08	f_{avg} 12000	15.44	42.19	3.49	7.3	68.42	19.87
					57.08	$f_{max}/2$ 8575	15.44	30.15	3.49	5.21	54.29	-4.88
					57.08	f_t 11450	15.44	40.26	3.49	6.96	66.15	15.90
					57.08	f_{max} 17150	15.44	60.3	3.49	10.43	89.66	57.09

The results from TILAS closely match Melcosim's results at f_t for different frequency bounds. This suggests that designers controlling a three-phase inverter under hysteresis with an upper frequency bound can use f_t as a starting point for their design.

VI. EXPERIMENTAL VERIFICATION OF THE TOOL

To verify the accuracy of TILAS, it was run on hardware results from a resistive-inductive (R-L) load driven by an inverter. Sample measurements are shown in Figure 4. The upper waveform represents the load current on phase "a", and the lower waveform represents the gate switching signal of the upper IGBT on phase "a". Measurements were recorded and the gate switching signal saved as 0 when the gate was low and 1 when the gate was high. The measurements were then fed to TILAS and power losses were estimated. A process-level flow chart for using TILAS is shown in Figure 5.

The window chosen includes six cycles. If a 400V system bus voltage, and a current waveform with a peak of 30A, shown in Fig. 4, were used, the power losses estimated by TILAS and Melcosim are shown in Table 3.

TABLE 3: RESULTS TILAS AND MELCOSIM FROM SAMPLE HARDWARE MEASUREMENTS SHOWN IN FIGURE 4

Tool	f_{max} (Hz)	P_Q (W)	P_D (W)	P_{Total} (W)
TILAS	10000	19.719	1.854	21.573
Melcosim	10000	17.25	4.08	21.33

The results shown in Table 3 show that TILAS was able to estimate the total power losses in the IGBT-diode pair from hardware measurements very. It is also shown that the results from TILAS match those from Melcosim. Inaccuracies in individual IGBT and diode power losses are mainly due to the inaccurate extraction of the necessary data points from the datasheet, and the idealized assumptions used in Melcosim.

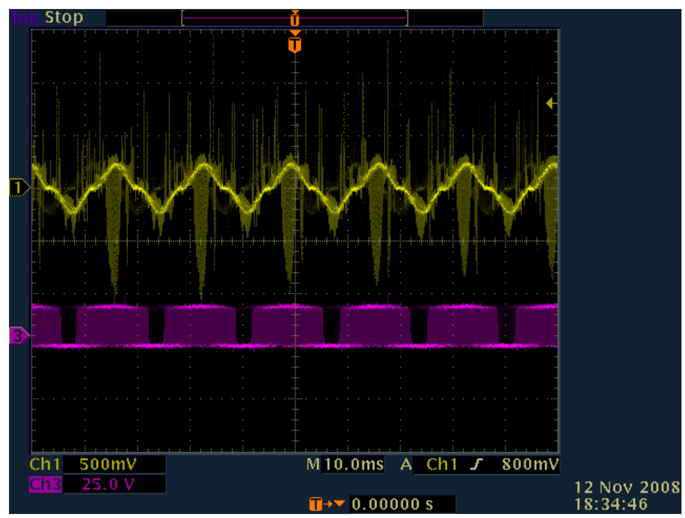

FIGURE 4: SAMPLE MEASUREMENTS OF THE PHASE CURRENT AND UPPER SWITCHING SIGNAL

VII. CONCLUSION

A simple analysis tool for power loss estimation in IGBTs and diodes, TILAS, was presented. The tool has only two inputs, phase current and upper IGBT switching waveforms, and uses simple data extracted from datasheets. The tool was verified by analyzing a constant-frequency PWM scheme and compared to available commercial software.

Results suggest that available tools can be adapted for hysteresis switching by using the number of switch transitions per second as the switching frequency. TILAS was run on experimental waveforms to verify its ability to use experimental data and estimate losses of real systems. The tool is expected to be easily extended to include other converter topologies such as choppers, H-bridges, and multilevel converters.

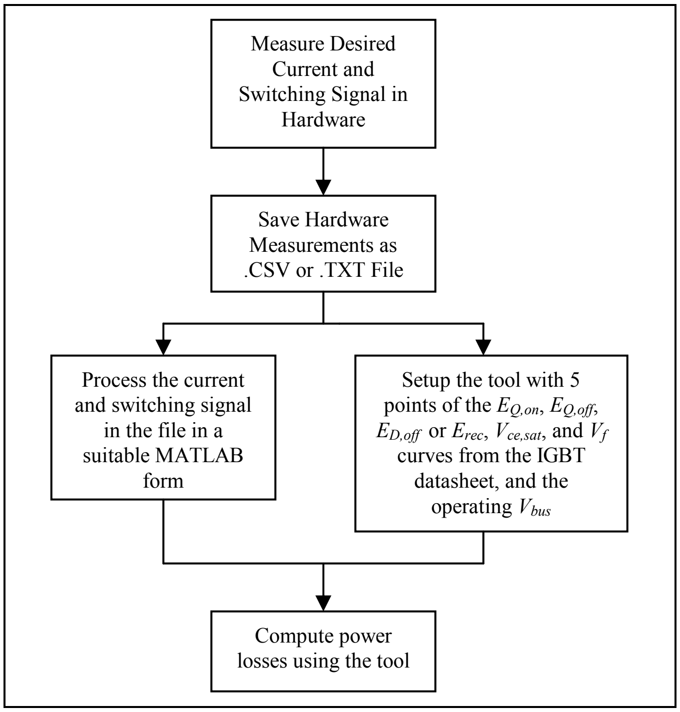

FIGURE 5: PROCESS-LEVEL FLOW CHART FOR USING TILAS

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