Considering Power Losses of Switching Devices in Transient Simulations through a Simplified Circuit Model

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Abstract—**A simple model is proposed to simulate IGBT's losses with standard electromagnetic simulation programs. A method for extracting the model parameters from manufacturers power losses computing programs is proposed. The model is validated by comparing the obtained results with those provided by the manufacturers. The simulations take into account different manufacturers (such as Semikron, ABB and Mitsubishi) and rated powers ranging from 20 kVA to 3 MVA. The power losses provided by simulations are quite accurate and the additional computational cost is negligible.**

Index Terms—**Wind energy conversion, Frequency regulation, Variable speed generators.**

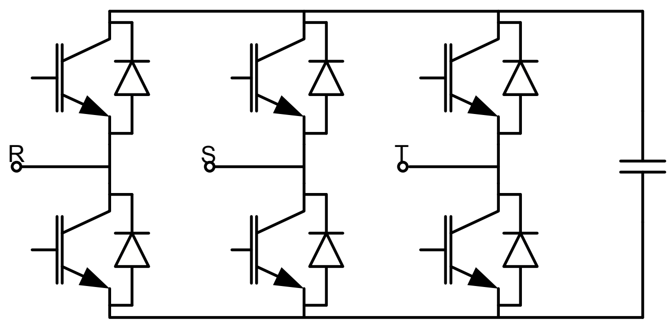

Fig. 1. Two-level, three-phase VSC diagram.

I. Introduction

SEVERAL models with different degree of complexity have been developed in order to simulate IGBT's behavior [1]. In order to compute losses accurately, physical models are required [2]-[3]. In case of simulating these models, the integration time steps have to be smaller than $0.1\mu s$. As a consequence, the computational cost of the simulations increases, being impossible to carry out simulations of a few seconds. Moreover, commercial available programs for computing electromagnetic transients (such as EMTDC/PSCAD or MATLAB/SimPower) do not include precise diode and IGBT models considering the commutation transitions. For instance, in the case of MATLAB/SimPower a turn-off transient is taken into account, but the results are not accurate for the computation of power losses. As a consequence, power losses cannot be computed accurately when conventional electromagnetic simulation programs, with usual time steps of around $5\mu s$ and simulation intervals of a few seconds, are used [4]. This paper proposes a simplified model to take into account power losses in an accurate manner within conventional electromagnetic simulation programs. The paper is focused on the computation of power losses for the two-level three-phase voltage source converter (VSC), and is organized as follows. First, a description of the power losses of different components of a VSC is made. Then, the proposed model is derived taking into account the influence of different operation parameters on power losses. Finally, several simulation results comparing the power losses obtained by the proposed model with those given by manufacturers are presented.

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This work was supported by the Spanish MEC under projects ENE2007-62997 and ENE2007-68032-C04-02 and Junta de Andalucía under project P06-TEP-01882.

Paper submitted to the International Conference on Power System Transients (IPST2009) in Kyoto, Japan June 3-6, 2009.

II. Components of power losses

The considered VSC switching element is an IGBT with a fly-wheel diode. In a two-level three-phase configuration there are at least six non-ideal IGBT's and six diodes, as shown in Fig. 1, to which non instantaneous on-off transients are associated. During those transients both the current and voltage in IGBT's terminals are high, leading to short-duration but high power losses. This situation not only applies to the IGBT's but also to the diodes during switching periods. Collectively, these losses are called commutation losses and must be considered in realistic simulations. On the other hand, in the saturation state, when the conducting current is maximum, both the IGBT's and the diodes present voltage drops opposed to the circulating current. Such voltages originate in the junction voltage and conduction resistance. The product of these voltages and the currents determines the conduction power losses. In this work both the switching and conduction losses of the IGBT's and associated diodes are considered for the VSC case.

A. IGBT power losses

As stated above, IGBT losses can be divided in two types. On the one hand, the conduction losses, due to the forward voltage (between 1 and $3\,V$) and the resistance of the IGBT and diodes, which is in the order of few $m\Omega$. Therefore, the conduction losses can be modeled as

$$P_{Cond}^{IGBT} = v_{on} I_c + R_{on} I_c^2, \quad (1)$$

where v_{on} is the IGBT forward voltage and I_c is the RMS current through the device.

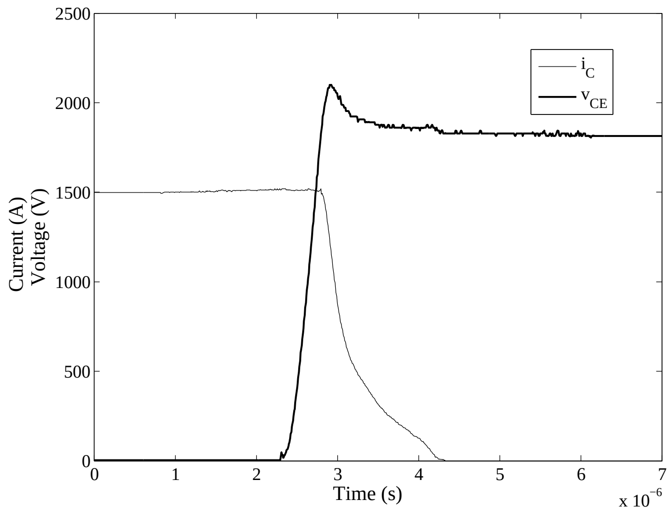

Fig. 2. Current and voltage of the IGBT during on-off commutation.

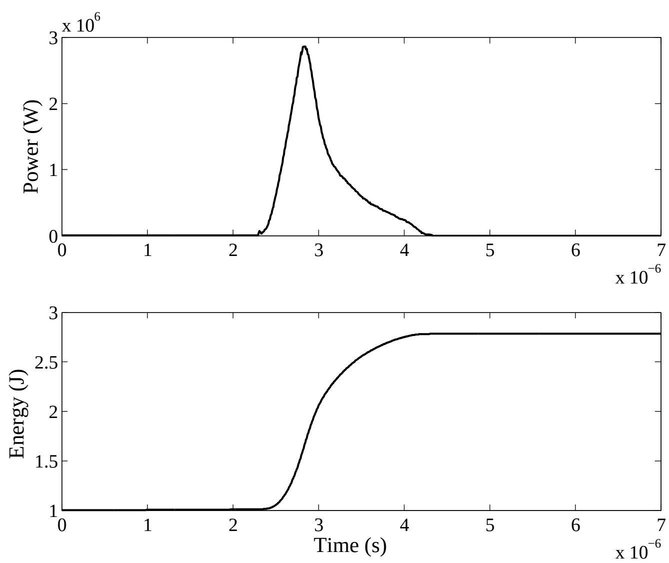

Fig. 3. Power losses and energy of the IGBT during on-off commutation.

On the other hand there are the switching losses. In Fig. 2 the voltage and current across an IGBT terminals, when its state changes from conduction to blocking, are shown. During this transient, the power shown in Fig. 3 arises. In the same figure the associated energy, E_{off}, is given.

The turn-on switching transient voltage and current waveforms of the IGBT can be seen in Fig. 4, while the power loss and dissipated energy, E_{off}, are shown in Fig. 5.

The number of these turn-on and turn-off transients in a period of time is given by the switching frequency. Therefore, the dissipated energy is accumulated during a period of time. The IGBT switching power dissipation is given by the total sum of E_{on} and E_{off} energies within one time interval divided by its duration. The energies E_{on} and E_{off} depend on several factors, but one of the most important is the inverter RMS current value. The IGBT manufacturers provide curves of this power as a function of the RMS current, I_c, through the IGBT. Those curves are obtained experimentally for a determined load, temperature and DC voltage. The total power dissipation of the switch can be calculated as the sum of the conduction losses, given by (1), an the switching power losses.

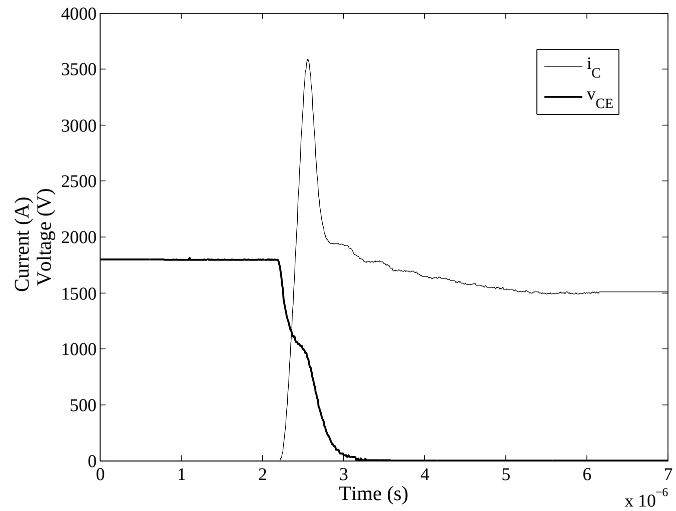

Fig. 4. Current and voltage of the IGBT during off-on commutation.

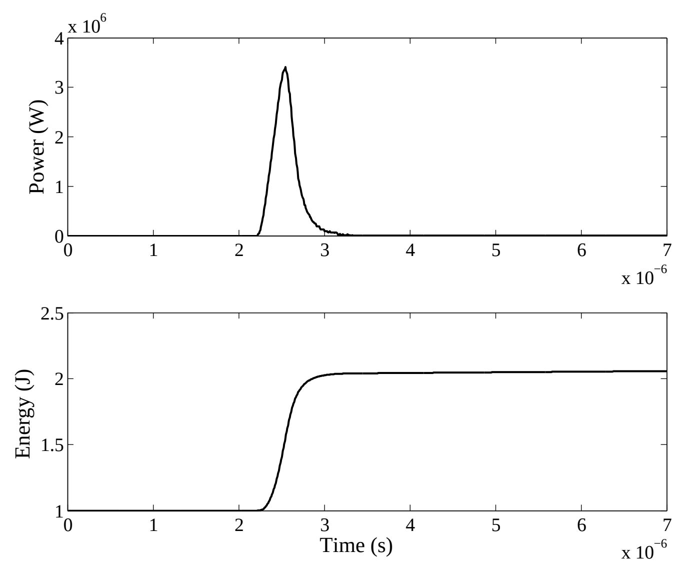

Fig. 5. Power losses and Energy of the IGBT during off-on commutation

B. Diode power losses

The antiparallel diode associated with the IGBT gives rise to conduction and switching losses too. The junction voltage causes a power loss as in the case of the IGBT, that can be modeled as:

$$P_{Cond}^{DIODE} = v_f I_f$$

where v_f is the diode's forward voltage and I_f is the RMS current value through it.

In the case of the switching losses, it is common to consider only the turn-off transition. In Fig. 6 the currents and voltages at diode terminals are shown. The power dissipation and the energy for this commutation can be observed in Fig. 7

As in the case of the IGBT, the total power loss of the diode is obtained as the sum of the conduction losses and the

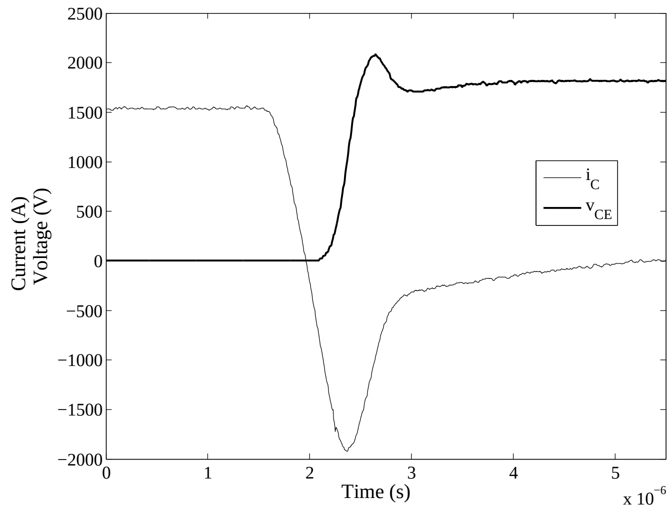

Fig. 6. Current and voltage of the diode during on-off commutation.

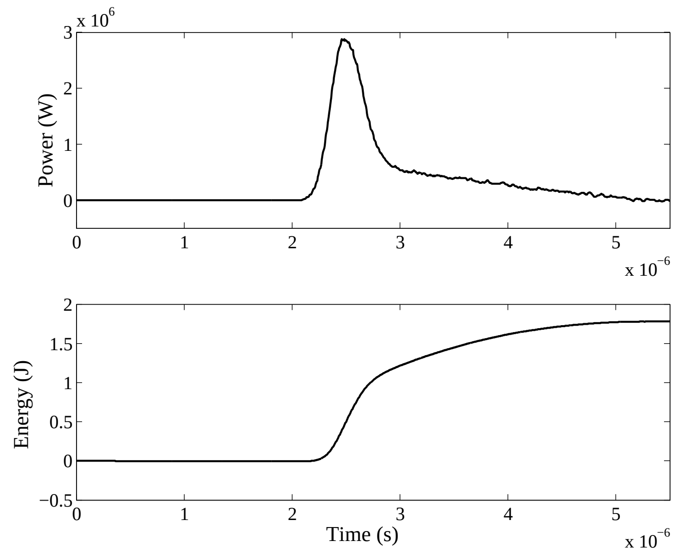

Fig. 7. Power losses and energy of the diode during on-off commutation.

product of the number of switchings in one second and the associated energy.

C. Snubbers power losses

With an inductive load at the VSC terminals, a sudden interruption of current flow would lead to a sharp rise in voltage across the IGBT. A snubber circuit prevents this undesired voltage by conducting the residual transient current.

Currently, the main manufacturers are offering IGBTs with a smooth switching characteristic without the need for any dv/dt or peak-voltage limiters such as snubbers. Therefore, the power losses associated with these auxiliary circuits are not taken into account in this work.

D. Total power losses

The figures above show the currents, voltages, powers and energies for the on-off and off-on transitions of the IGBTs and diodes. They were obtained for a given current through the IGBT, I_c, and the diode, I_f, with a determined DC voltage and temperature. Under these conditions, the total power dissipation for each IGBT-diode pair is given by:

$$P_{Loss} = P_{Cond}^{IGBT} + P_{Conm}^{IGBT} + P_{Cond}^{Diode} + P_{Conm}^{Diode}$$

III. Proposed model for the representation of power losses

The switching transitions of diodes and IGBTs shown in the previous section last for about a microsecond. This fact motivates the use of time steps in the order of hundreds of nanoseconds, so that these switching processes and their associated power losses are simulated precisely. However, these tiny time steps are not suitable in case of conventional electromagnetic transients, with total simulation times of a few seconds, due to the huge computational time needed to solve the problem [5]. Moreover, commercial packages available to solve electromagnetic transients such as EMTDC/PSCAD and Matlab/SimPower do not incorporate precise diode and IGBT models taking into account these switching transitions. In the Matlab/SimPower case, only the IGBT turn-off time is considered but the computation of power losses is not accurate enough, in addition to the problem of using reduced time steps. As a consequence, it is necessary to develop a model taking into account the power losses in an alternative way, trying to circumvent the difficulties associated to the incorporation of switching transients of power electronic devices, such as diodes and IGBTs, in conventional electromagnetic simulation programs.

The alternative chosen in this work to model power losses is to use the data given by the manufacturer of power electronic components. Nowadays, manufacturers such as Semikron, ABB or Mitsubishi offer free software for computing the power losses of their products. Semikron has a web-based power loss computation program called *SemiSel* for the low and medium power IGBTs [6]. ABB has developed a program for the computation of power losses called *SimulationTool* for the high power range of IGBTs [7]. Finally, Mitsubishi offers the software *Power Module Loss Simulator* for the high power range of IGBTs [8]. In spite of being different programs for computing device power losses, all of them are based in the same assumptions, being it possible to calculate the power losses for a particular application such as a single-phase or three-phase VSC considering several factors like rated power, rated current, rated power factor, ambient temperature, etc. It is important to know which of these factors are the key parameters affecting the power losses in order to derive a simplified model from the data given by the manufacturers throughout these simulations tools. In this sense, a huge number of simulations have been carried out in order to asses the power loss dependance on the operational parameters used to compute the power losses. Table I summarizes the results of these simulations including the analyzed operational parameters, the dependance of power losses on these parameters and the variation of the parameters for a given application. On the one hand, there are parameters that, in spite of influencing considerably the power losses, are kept constant for a given application. So, the contribution of these parameters to the

TABLE I
VSC POWER LOSSES DEPENDANCE ON SOME OPERATIONAL PARAMETERS

Parameter	Dependance	Variation
DC bus voltage (V_{dc})	High	$\approx$ Const.
Commutation frequency (f_{sw})	High	Const.
RMS phase current (I_p)	High	Variable
Modulation index (m)	Low	Variable
	IGBT: high	Variable
Power Factor ($cos\varphi$)	Diode: high	Variable
	Switch: moderate	Variable
Device temperature (T_{dev})	Moderate	Variable
Ambient temperature (T_{amb})	Moderate	$\approx$ Const.

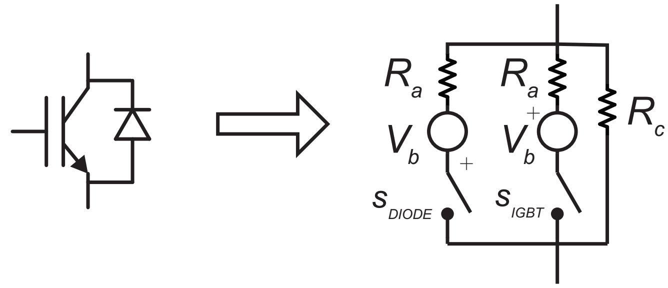

Fig. 8. Proposed model for the power switch composed of an IGBT and its antiparallel diode.

power losses can be considered almost constant. This is the case of the DC bus voltage and the commutation frequency. On the other hand, there are parameters both affecting notably the power losses and varying during the operation of the converter. These parameters are the RMS phase current and the device temperature. However, note that the device temperature depends on the RMS phase current. As a consequence, it is possible to assume that the power losses depend on the phase current exclusively.

The following quadratic equation is proposed to relate the power losses given by the manufacturer, P_{loss}^{man}, to the RMS phase current of the VSC, I_{ph}:

$$P_{loss}^{man} = aI_{ph}^2 + bI_{ph} + c \tag{2}$$

where the parameters a, b and c are unknowns that have to be adjusted using the power loss computation programs provided by the manufacturers. Once the operational conditions of the converter (such as DC bus voltage, switching frequency, power factor, ambient temperature, etc.) have been established, a number of simulations varying the VSC phase current, I_{ph}, from no load to its rated value are carried out, yielding the simulated power loss curve as a function of the phase current. Then, the parameters a, b and c are adjusted using a least mean square technique.

Note that the previous computations relate the VSC power losses with the VSC phase current, but this is not the final purpose of this work. The objective is to develop a power loss model for a power electronic switch composed of an IGBT and its antiparallel diode, without any precise description of the switching transitions. The proposed model is shown in Fig. 8. It considers the IGBT and diode as ideal switches along with the following additional components to take into account the simplified power loss formulation given by (2):

- Series resistor (R_a). This component models the part of power losses depending on the square of the RMS value of the current through the IGBT and diode. As a consequence, this series resistor is related to the parameter a of (2).
- Shunt resistor (R_c). This component models the power losses that depends on the square of the DC voltage. In case of using a PWM technique to obtain the output voltage of the VSC, the control algorithm should maintain the DC voltage as close as possible to its reference value. Hence, this shunt resistor is related to parameter c that takes into account the constant term of power losses.
- Series voltage source (V_b). This component of the circuit models the losses linearly depending on the RMS value of the IGBT or diode current, being related to the parameter b.

It has been assumed the same series resistor and voltage source for both the IGBT and diode due to parameter computation requirements (same number of circuit components as parameters in the power loss expression). In order to compute the parameters R_a, R_c and V_b a relationship between the RMS values of the power switch current and the VSC phase current has to be derived. The instantaneous value of the phase current of a two level VSC, i_{ph}, is related to the instantaneous current of the upper and lower power switches, i_{ps1} and i_{ps2} respectively, as follows:

$$i_{ph} = i_{ps1} - i_{ps2}$$

The current through the power switches has two terms corresponding to the IGBT and diode currents:

$$i_{ph} = i_{ps1} - i_{ps2} = i_{IGBT1} - i_{D1} - i_{IGBT2} + i_{D2}$$

Note that at a given time instant t only one of these currents is non-zero. As a consequence, the IGBT and diode currents are orthogonal functions, that is:

$$\int_0^T i_{IGBT1} i_{IGBT2} dt = \int_0^T i_{IGBTi} i_{Dj} dt = 0$$

Due to the orthogonality between these functions, the RMS value of the squared phase current can be formulated as:

$$I_{ph}^2 = I_{IGBT1}^2 + I_{D1}^2 + I_{IGBT2}^2 + I_{D2}^2$$

Moreover, due to the half-wave symmetry, the RMS values of the IGBT and diode for the upper and lower switches are the same:

$$I_{ph}^2 = 2I_{IGBT1}^2 + 2I_{D1}^2 = 2I_{ps1}^2$$

The power losses for the proposed model of Fig. 8 can be formulated as a function of the RMS power switch current as:

$$P_{ps} = R_a I_{ps}^2 + V_b I_{ps} + \frac{V_{dc}^2}{R_c} = \tag{3}$$

$$= \frac{R_a}{2} I_{ph}^2 + V_b \frac{I_{ph}}{\sqrt{2}} + \frac{V_{dc}^2}{R_c} \tag{4}$$

Finally, the parameters of the circuit shown in Fig. 8 are obtained by comparing (2) and (4):

TABLE II
PROPOSED VSC'S CHARACTERISTICS

Characteristics	VSC 1	VSC 2	VSC 3	VSC 4
Rated Power (kVA)	20	165	1000	3000
DC Voltage (V)	700	1100	1100	2200
Switching freq. (Hz)	5000	2000	1500	1000
Cooling	Air	Water	Water	Water
Manufacturer	Semikron	Semikron	Mitsubishi	ABB

$$R_a = 2a \quad (5)$$

$$V_b = \sqrt{2}b \quad (6)$$

$$R_c = \frac{V_{dc}^2}{2c} \quad (7)$$

IV. MODEL VALIDATION

The power loss model has been applied to different VSC's for validation purposes. The parameters of the VSC's used in the simulations are shown in Table II. Note that the simulated converters present different rated power, switching frequency and DC voltage. The model validation procedure can be summarized as follows:

- Power loss computation using the software packages given by the manufacturers. The power losses are computed for the VSC's using the parameters shown in Table II as a function of the phase current.
- Computation of parameters a b and c of (2) using a least mean square algorithm.
- Computation of parameters R_a, R_c and V_b as a function of a b and c using (5)-(7).
- Simulation of the VSC using the simplified power loss model shown in Fig. 8. The simulations are performed taking into account the load conditions used in the power loss software supplied by the manufacturers.

The simulation results are presented in Figs. 9 to 12. These figures include the power losses computed by simulation using:

- The manufacturer software packages.
- The series resistor and forward voltage included in the IGBT and diode data sheet.
- The proposed power loss model.
- A corrected power loss model.

The first conclusion that can be derived analyzing the power loss curves shown in figures 9 to 12 is that the power losses cannot be computed accurately using the data sheet parameters (curves named *No fit*) in simulations that do not consider a physical model of the power electronic devices. This fact has motivated the development of the proposed simplified model. However, it can be advised that the proposed model (curves named as *First simulation*) differs from the actual power losses given by the manufacturer. In order to analyze the cause of the error, a comparison between the parameters a, b and c of (2) and those resulting from the simulation of the proposed power loss model is carried out. The results are shown in Table III. Note that the quadratic and constant terms are almost the same, the error lying in the linear term. In order to overcome this shortcoming, a correction of the voltage V_b is proposed. In fact, the corrected voltage V_b is computed using a proportional rule between the actual value proposed by the manufacturer and the value obtained from the simulations. After this correction (curves named as *Corrected*) several simulations with different load conditions and power factors ranging from 0.1 to 0.9 have been carried out, leading virtually to no differences between the simulated and the manufacturer power losses. This agreement can be also noticed in the parameters a, b and c computed form the simulations of the corrected model presented in Table III.

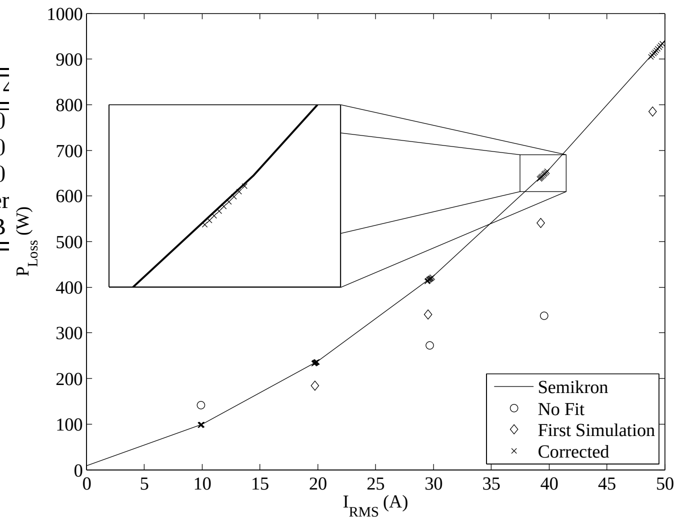

Fig. 9. Power losses computed by different methods for VSC 1 ($20\,kVA$).

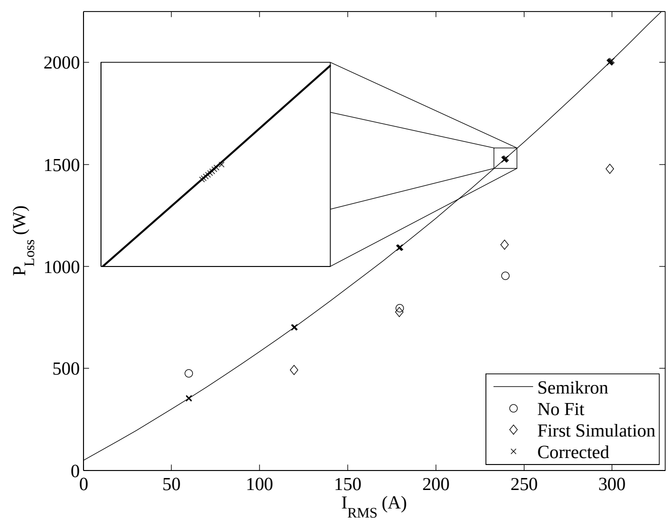

Fig. 10. Power losses computed by different methods for VSC 2 ($165\,kVA$).

V. CONCLUSIONS

This paper has analyzed the viability and accuracy of a simplified power loss computation model for power switches composed of an IGBT and an antiparallel diode. Accurate computations of power losses using conventional electromagnetic transients software require reduced time steps in order to

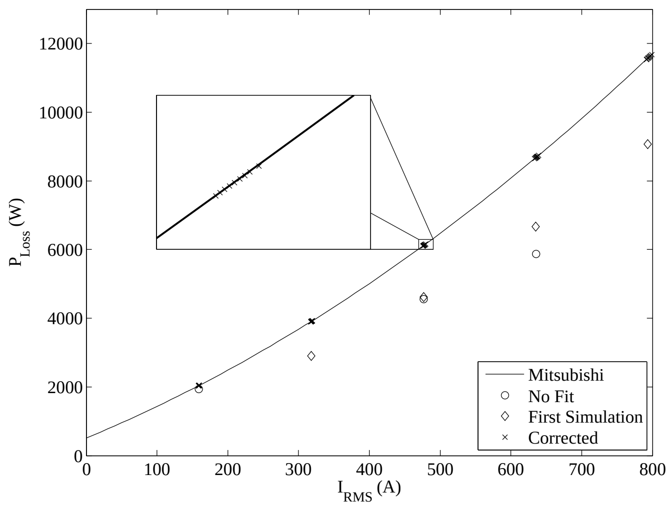

Fig. 11. Power losses computed by different methods for VSC 3 (1 MVA).

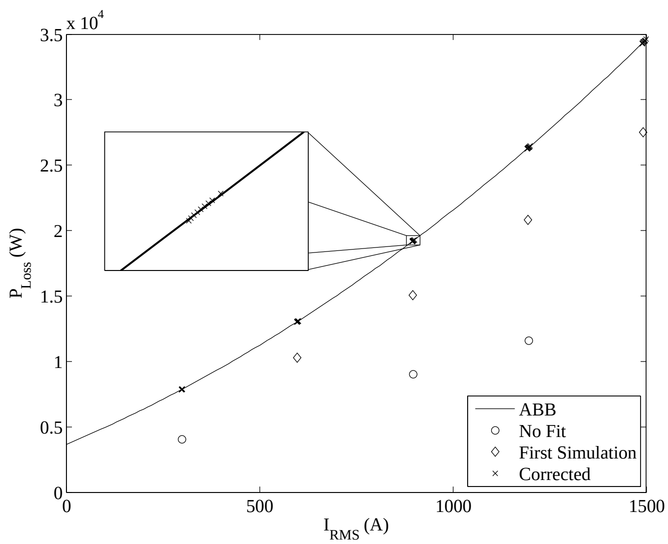

Fig. 12. Power losses computed by different methods for VSC 4 (3 MVA).

TABLE III
COMPARISON OF THE PARAMETERS a, b AND c FOR DIFFERENT POWER LOSS COMPUTATION METHODS

Case		a	b	c
VSC 1	Values from manufacturer	0.04	1.11	1.48
	Values from first simulation	0.04	1.35	1.48
	Values after correction	0.04	1.11	1.48
VSC 2	Values from manufacturer	0.00761	2.17	8.048
	Values from first simulation	0.00687	1.32	8.546
	Values after correction	0.00762	2.16	8.040
VSC 3	Values from manufacturer	0.0060352	4.73	48.29
	Values from first simulation	0.0060354	2.98	48.19
	Values after correction	0.006035	4.73	48.06
VSC 4	Values from manufacturer	0.0009092	2.075	608.9
	Values from first simulation	0.0007805	1.323	608.9
	Values after correction	0.0009092	2.076	608.5

take into account the switching processes in both IGBT and diode. Moreover, commercially available programs for computing electromagnetic transients (such as EMTDC/PSCAD or MATLAB/SimPower) do not include accurate diode and IGBT models that consider switching transitions. The proposed model, based on linear circuit components, uses the power loss information given by the manufacturers. The advantage of the proposed simplified model is that it can be used in conventional electromagnetic transients software with usual integration time steps. After deriving the proposed circuit model, some simulations have been performed for different VSC's. The results show that a model correction is needed in order to obtain accurate enough results. Once the correction is applied, the simplified power loss circuit model has been simulated with different load and power factor conditions, leading to good agreement between the simulated and actual VSC power losses.

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