# Real-time Prognosis of Failure of the IGBT in a Conversion Chain

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Abstract: In this paper, the problem of prognosis of failure of Insulated Gate Bipolar Transistors (IBGT) in a DC-DC converter is studied. Indeed, the degradation of IGBT can be caused by several factors (electrical, thermal and mechanical stresses,aging, ...). This degradation can be assessed in relation to the variation of the internal resistance of the IGBT. Likewise, we determined the remaining useful life (RUL) of the IGBT compared to the variation of its internal resistance and the duty cycle of the IGBT control signal, which are both estimated in this paper.

## 1 INTRODUCTION

Insulated Gate Bipolar Transistors (IBGT) are very often used in the design of powerful energy conversion chains. And these conversion chains like DC-DC converters, choppers and inverters have very varied fields of application. Among others, we can cite the fields of aeronotics, electric vehicles, renewable energy (Wang et al., 2012).

Static data in the literature has shown that components with higher failure rates are semiconductors (IGBT or Mosfet) and electrolitic capacitors. It is also indicated in the literature (Yang et al., 2010; Langueh et al., 2019) that most of the faults causing the unavailability of the electrical energy conversion chains come from around 34% of the failure of the IGBTs.

Many researchers have worked on the estimating of the remaining useful lifetime (RUL) of power switches. The RUL methods are mostly either model-based or data-driven approaches (Dusmez et al., 2017). In the first case approaches (model-based), typically junction temperature information is required (Gillis, 1966; Bayerer et al., 2008) and allows to estimate the number of cycles to failure under given junction temperature swing amplitude. The data-driven methods involve processing experimental data to derive an empirical degradation model. The degradation data is generally the variation of the internal resistance at the ON-state of power MOSFETs or IGBTs (Zheng et al., 2014; Celaya et al., 2011). Most of the time, the degradations observed on the IGBTs (Mosfets) are often caused by electrical, thermal and mechanical stresses, (Sathik et al., 2015; Celaya et al., 2012) or by aging. The monitoring of the degradation of the parameters of these electronic components is therfore necessary in order to perform the faillure detection and to predict the maintenance.

Several parameters can then be monitored using different methods in order to achieve these objectives. Among others, we can cite the estimate of the internal resistance $R_{on}$ of the IGBT (Langueh et al., 2019; Alyakhni et al., 2019), as well as its aging monitoring, the current variation in IGBTs (Mohamed-Sathik et al., 2019) the variation of the characteristics of the capacitors in a DC-DC converter, i.e. the estimation of the variation of ESR (Equivalent Series Resistance) of the capacitors (Kulkarni et al., 2011; Kulkarni et al., 2012).

The estimation of the parameters to be monitored can be done using several approaches. Still in the literature, the most commonly used approach is the Extended Kalman Filter (EKF)(Singleton et al., 2015).

Other authors have proposed in (Reif et al., 1999), an observer for nonlinear systems in continuous time where the gain of the observer is calculated by a differential equation of Riccati similar to the EKF. Despite great use, only the local convergence of the EKF can be guaranteed. In this paper, we will use a sliding-mode observer (Levant, 2007; Levant, 2003) to estimate the internal resistance $R_{on}$ of the considered DC-DC converter and the duty cycle of the IGBT control signal. Then we will use these estimates to predict the remaining useful life (RUL) of the IGBT.

This paper will be organized as follows: In the section 2, the problem statement will be presented. After that, the observability of the ON-state resistance

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$R_{on}$ and the duty cycle of the control signal will be studied in Section 3 and then a sliding-mode observer is proposed. A RUL computation will be proposed followed by an example with simulation results in section 4 and, finally in a conclusion in the last section.

## 2 PROBLEM STATEMENT

Let us consider a DC-DC converter (Al-Sheikh et al., 2014) operating in closed loop as presented in (Langueh et al., 2019). Denote $s(t)$ the control signal of the IGBT and $d$ the duty cycle of the control signal. The IGBT is in the ON-state for a duration $T_{ON} = d\ T_s$ when $s(t) = 0$ and in the OFF-state for the duration $T_{OFF} = (1-d)T_s$ when $s(t) = 1$. Figures 1 and 2 respectively show the electrical diagrams of a DC-DC Boost converter in cases where the IGBT is in On-State (activated) and then OFF-State (deactivated).

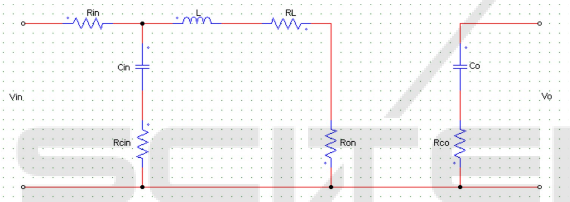

Figure 1: DC-DC Boost converter circuit configuration (ON-state).

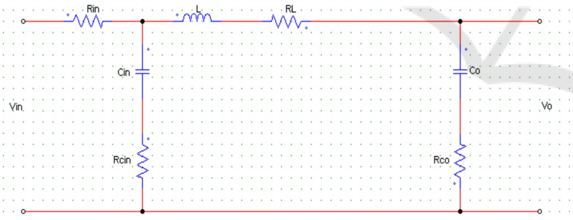

Figure 2: DC-DC Boost converter circuit configuration (OFF-state).

In the case where the IGBT is in its ON-state, based on Ohm's law and Thevenin's principle, the dynamics of the system can be written in the following form:

$$\begin{cases} V_{in} & = R_{in}I_{in} + V_{C_{in}} + R_{C_{in}}I_{C_{in}} \\ I_{in} & = I_L + I_{C_{in}} \\ V_{C_{in}} & = L\frac{dI_L}{dt} + (R_L + R_{on})I_L - R_{C_{in}}I_{C_{in}} \\ I_{C_{in}} & = C_{in}\frac{dV_{C_{in}}}{dt} \\ V_o & = V_{C_o} - R_{C_o}I_o \\ I_o & = -C_o\frac{dV_{C_o}}{dt} \\ I_{C_o} & = -I_o \end{cases} \tag{1}$$

Similarly, in the case where the IGBT is in its OFF-state, the dynamics of the system can be written in the following form:

$$\begin{cases} V_{in} & = R_{in}I_{in} + V_{C_{in}} + R_{C_{in}}I_{C_{in}} \\ I_{in} & = I_L + I_{C_{in}} \\ V_{C_{in}} & = L\frac{dI_L}{dt} + (R_L + R_{C_o})I_L + V_{C_o} - R_{C_o}I_{C_o} - R_{C_{in}}I_{C_{in}} \\ I_{C_{in}} & = C_{in}\frac{dV_{C_{in}}}{dt} \\ V_o & = V_{C_o} + R_{C_o}(I_L - I_o) \\ I_o & = I_L - I_{C_o} \\ I_{C_o} & = C_o\frac{dV_{C_o}}{dt} \end{cases} \tag{2}$$

By denoting the state vector $x$, the output (measures) vector $y$ and the input vector $u$ as follow:

$$x = \begin{pmatrix} I_L \\ V_{C_{in}} \\ V_{C_o} \\ R_{on} \end{pmatrix},\ y = \begin{pmatrix} V_o \\ I_{in} \end{pmatrix}\ u = \begin{pmatrix} V_{in} \\ I_o \end{pmatrix},$$

the dynamic of the whole system can be written as a following nonlinear system:

$$\begin{cases} L\dot{x}_1 & = & V_{in} - V_o - R_{in}I_{in} + R_L x_1 \\ & & +(V_o - x_1x_4)s \\ (R_{C_{in}} - R_{in})C_{in}\dot{x}_2 & = & V_{in} - x_2 - R_{in}x_1 \\ R_{C_o}C_o\dot{x}_3 & = & V_o - x_3 \\ \dot{x}_4 & = & \beta(x_4 - R_{on_{init}}) \\ d & = & 1 - \frac{I_o}{x_1}\ \forall\ x_1 \neq 0 \end{cases} \tag{3}$$

The aim of this article is to estimate from measured values and known constants, the state $x_1$ (the current $I_L$ in the inductance which is difficult to measure) and the duty cycle $d$ (also difficult to measure) of the control signal $s(t)$ of the IGBT. A prognosis for converter failure will then be proposed based on the previously estimated states. Since the duty cycle $d$ of the control signal $s(t)$ is a function of the state $x_1(t)$, the estimation of the latter also makes it possible to obtain the estimate of $d$.

## 3 OBSERVABILITY STUDY AND PROPOSAL OF AN OBSERVER

In this section, the observability of the system is studied and we proposed a sliding mode observer in order to obtain finite-time estimates of the system states.

### 3.1 Observability Study for DC-DC Converter

To simplify our study, it was carried out in steady state. Then, the average values of the variations of voltages and currents are given by:

$$\langle\frac{dV_{C_{in}}}{dt}\rangle_{avg} = \langle\frac{dV_{C_o}}{dt}\rangle_{avg} = \langle\frac{dI_L}{dt}\rangle_{avg} = 0.$$

Then, we have:

$$\begin{cases} 0 & = V_{in} - V_o - R_{in} I_{in} + R_L x_1 + (V_o - x_1 x_4)s \\ 0 & = V_{in} - x_2 - R_{in} x_1 \\ 0 & = V_o - x_3 \end{cases} \tag{4}$$

It has been shown in (Langueh et al., 2019) that the system (4) is observable and we obtain:

$$\begin{cases} x_1 & = & y_2 + (R_{in} + R_{C_{in}})\dot{y}_2 \\ x_2 & = & -R_{in} y_2 + (R_{in} + R_{C_{in}}) R_{C_{in}} C_{in} \dot{y}_2 \\ x_3 & = & y_1 \\ x_4 & = & \frac{1}{x_1}\left(\frac{RL}{R_{C_{in}}}\dot{y}_2 + \frac{L}{R_{C_{in}} C_{in}}(y_2 - x_1)\right. \\ & & \left. + x_2 + R_{C_{in}} y_2\right) - R_L \\ d & = & 1 - \frac{I_o}{x_1} \end{cases} \tag{5}$$

with $R = R_{in} + R_{C_{in}}$.

The singularity problem that state $x_1$ could have caused is nonexistent since, in steady state, state $x_1$ is always non-zero.

A sliding mode observer can then be used to estimate the states of the system considered.

## 3.2 Sliding Mode Observer for State Estimation

In the literature, there exists several types of observers to estimate the states of this class of dynamic systems. Our choice fell on this type of observer because not only does it make it possible to obtain convergence in finite time but also because the chattering (Levant, 2010) generated by this type of observers coincides with the oscillations observed in the currents and voltages in the DC-DC converters.

Indeed the Levant differentiator allows to estimate in finite-time the outputs of the consisidered system and their successive derivatives. Then, the estimates of the states $x(t)$ can be obtained from the estimates of the outputs and their successive derivatives. It therefore seems necessary to make a little recall on this type of observer.

### 3.2.1 Recall on High Order Sliding Mode (HOSM)

This method is based on the so-called "real-time exact robust HOSM differentiator" (Levant, 2003; Levant and Livne, 2012). The design of such a observer is recalled in the following.

Let us consider a signal $y(t) \in C^k$ (at least $k$ times derivable) and suppose that $(y, \cdots, y^{(k)}) = (z_1, \cdots, z_{k+1})$. The High Order Sliding Mode observer proposed in (Levant, 2005) is given as follow:

$$\begin{aligned} \dot{\hat{z}}_1 &= -\lambda_0 M^{\frac{1}{k}} |\hat{z}_1 - y|^{\frac{k}{k+1}} sign(\hat{z}_1 - y) + \hat{z}_2 = v_1; \\ \dot{\hat{z}}_2 &= -\lambda_1 M^{\frac{1}{k-1}} |\hat{z}_2 - v_1|^{\frac{k-1}{k}} sign(\hat{z}_2 - v_1) + \hat{z}_3 = v_2; \\ &\vdots \\ \dot{\hat{z}}_k &= -\lambda_{k-1} M^{\frac{1}{2}} |\hat{z}_k - v_{k-1}|^{\frac{1}{2}} sign(\hat{z}_k - v_{k-1}) + \hat{z}_{k+1} \\ &= v_k; \\ \dot{\hat{z}}_{k+1} &= -\lambda_k M sign(\hat{z}_{k+1} - v_k). \end{aligned}$$

where $M$ is chosen to be greater than the $k^{th}$ derivative of $y(t)$, $\lambda_i$ are positive design parameters. It should be noted that the setting of these parameters is described in detail in (Levant, 1998) and (Levant, 2003). Let the estimation errors defined as: $e_i = z_i - \hat{z}_i$, the estimation errors's dynamics are given by:

$$\begin{aligned} e_1 &= \hat{z}_1 - y; \\ e_2 &= \dot{e}_1 = \lambda_0 M^{\frac{1}{k}} |e_1|^{\frac{k}{k+1}} sign(e_1); \\ &\vdots \\ e_k &= \dot{e}_{k-1} = \lambda_{k-1} M^{\frac{1}{2}} |e_{k-1}|^{\frac{1}{2}} sign(e_{k-1}); \\ e_{k+1} &= \dot{e}_k = \lambda_k M sign(e_k). \end{aligned}$$

It has been proved in (Levant, 2003) that there exists a $t_0$ such that $\forall t > t_0$, we have

$$e_i = z_i - \hat{z}_i = 0 \text{ pour } 1 \leq i \leq k+1.$$

### 3.2.2 Application to DC-DC Boost Converter

Consider a change of variable define the following dynamics:

$$\begin{cases} z_1 & = y_2 \\ z_2 & = \dot{y}_2 \\ z_3 & = \ddot{y}_2 \\ z_4 & = y_1 \end{cases} \tag{6}$$

By applying the High Order Sliding Mode observer to system (6), one obtain:

$$\begin{cases} \dot{\hat{z}}_1 & = -\lambda_0 M^{1/3} |\hat{z}_1 - y_1|^{2/3} sign(\hat{z}_1 - y_1) + \hat{z}_2 = v_1 \\ \dot{\hat{z}}_2 & = -\lambda_1 M^{1/2} |\hat{z}_2 - v_1|^{1/2} sign(\hat{z}_2 - v_1) + \hat{z}_3 = v_2 \\ \dot{\hat{z}}_3 & = -\lambda_2 M \; sign(\hat{z}_3 - v_2) \\ \hat{z}_4 & = z_4 \end{cases} \tag{7}$$

with $\lambda_0 = 3$, $\lambda_1 = 1.5$, $\lambda_2 = 1.1$ and $M$ is chosen large enough to obtain a finite-time convergence of the observer.

The estimates of the states of the DC-DC Boost converter are then given by:

$$\begin{cases} \hat{x}_1 & = & \hat{z}_1 + R\hat{z}_2 \\ \hat{x}_2 & = & -R_{in}\hat{z}_1 + RR_{C_{in}}C_{in}\hat{z}_2 \\ \hat{x}_3 & = & \hat{z}_4 \\ \hat{x}_4 & = & \frac{1}{\hat{x}_1}\left(\frac{RL}{R_{C_{in}}}\hat{z}_2 + \frac{L}{R_{C_{in}}C_{in}}(\hat{z}_1 - \hat{x}_1)\right. \\ & & \left. + \hat{x}_2 + R_{C_{in}}\hat{z}_1\right) - R_L \\ \hat{d} & = & 1 - \frac{I_o}{\hat{x}_1} \end{cases} \tag{8}$$

Now, based on the estimate of the states of the DC-DC Boost converter and the duty cycle of the control signal of the IGBT, we will propose in the following section, the prognosis of the Remaining Useful Life (RUL) of the IGBT.

## 4 PROGNOSIS OF THE RUL AND SIMULATED RESULTS

In this section, we have proposed a new approach to predicting the RUL of an IGBT in a DC-DC converter, based on the measurements of the input voltage and the output voltage as well as the output current.

From the results obtained by Lai et al in (Lai et al., 2018), we can determine the fatigue degree by calculating the damage $D$ as follow:

$$D = \frac{R_{on}(t) - R_{on_{init}}}{R_{on_{max}}} \tag{9}$$

where $R_{on_{max}}$ represents the maximum value of the ON-state resistance of Mosfet before faillure and $R_{on}(t) = \hat{x}_4(t)$. On the other hand, given that the converter studied is supposed to be in closed loop, we will use the variation of the estmate duty cycle of the IGBT to determine its RUL. Let $d(t)$ denote the ideal duty cycle as follows:

$$d(t) = \frac{V_o - V_{in}}{V_o}$$

and $\hat{d}(t)$ the estimate of $d(t)$. We can therefore determine the variation of the duty cycle as follows:

$$\%d = \frac{\hat{d}(t) - d(t)}{100} \tag{10}$$

We performed simulations using Matlab/Simulink. Consider a DC-DC Boost converter whose configuration is summarized in the following table:

Table 1: Parameters of the DC-DC converter.

| **Parameters** | **Symbols** | **Values** | **Units** |
|---|---|---|---|
| Input capacitor | $C_{in}$ | 80 | $\mu F$ |
| Input capacitor ESR | $R_{C_{in}}$ | 100 | $m\Omega$ |
| Inductance | $L$ | 146 | $\mu H$ |
| Inductor resistance | $R_L$ | 5 | $m\Omega$ |
| Output capacitance | $C_o$ | 5 | $\mu F$ |
| Output capacitor ESR | $R_{C_o}$ | 80 | $m\Omega$ |
| IGBT ON-STATE resistance | $R_{on}$ | 1 | $m\Omega$ |
| Switching frequency | $f_s$ | 15 | $kH_z$ |

The parameters of the degradation model of the internal resistance $R_{ON}$ of the IGBT are $\alpha = 0,001676$ and $\beta = 0,0001611$.

The results of the simulations are shown in the following figures.

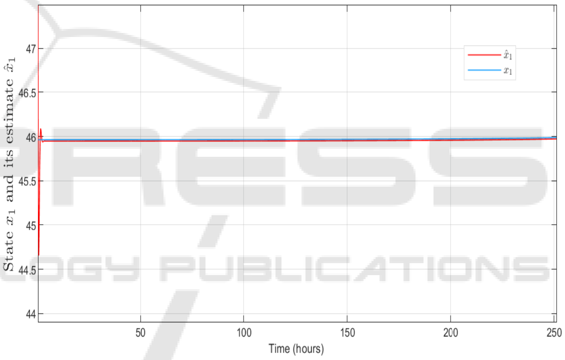

Figure 3: State $x_1$ and its estimate $\hat{x}_1$.

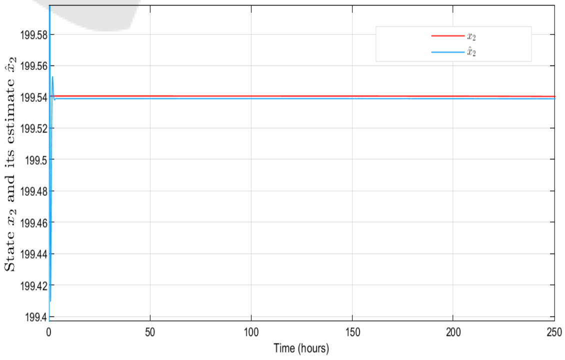

Figure 4: State $x_2$ and its estimate $\hat{x}_2$.

Figures 3, 4, 5, 6 and 7 show that the estimated states $\hat{x}_1, \hat{x}_2, \hat{x}_3, \hat{x}_4$ and the duty cycle $\hat{d}$ converge well in finite time. Figure 8 and 9 also shows the estimates of the IGBT's RUL respectively according to the estimations of $R_{ON}$ and the duty cycle. The RUL thresh-

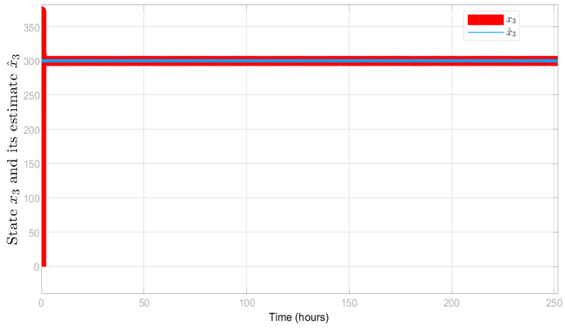

Figure 5: State $x_3$ and its estimate $\hat{x}_3$.

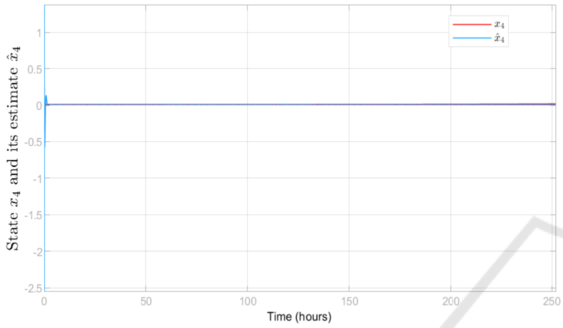

Figure 6: State $x_4$ and its estimate $\hat{x}_4$.

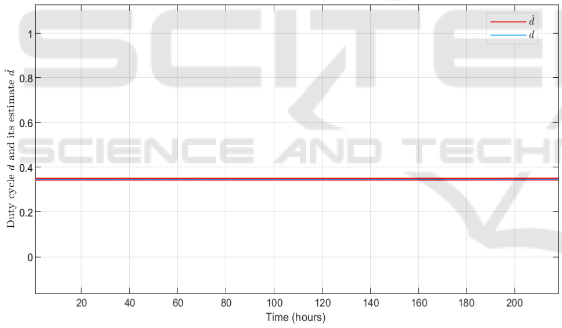

Figure 7: Duty cycle $d$ and its estimate $\hat{d}$.

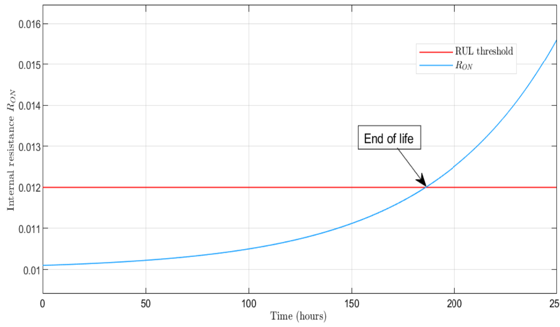

Figure 8: RUL according to $R_{ON}$.

old is set at 20% increase in the internal resistance Ron of the IGBT, which corresponds to a variation of 0.4% increase in the duty cycle.

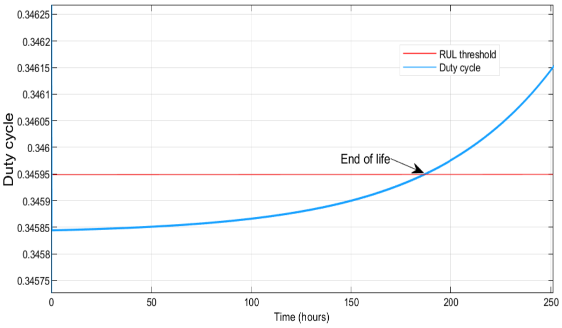

Figure 9: RUL according to duty cycle.

In this simulation case (ideal system), the end of life of the IGBT is $T = 185h$. But in the real case the end of life of the IGBT can be defined as follows:

$$T_{End} = min\left\{T_{End_d}, T_{End_{Ron}}\right\} \tag{11}$$

where $T_{End_d}$ $T_{End_{Ron}}$ are respectively the end of life calculated from the estimates of the duty cycle $d$ and the internal resistance $R_{ON}$. The thresholds of variations are defined based on experiments. They can vary depending on the authorized failure degree and the operating time in failure mode (and therefore depending on the application field).

## 5 CONCLUSION

In this paper, the online prognosis of RUL of IGBT built into a DC-DC Boost converter has been presented. From the measurements of the input current ($I_{IN}$) and the output voltage ($V_O$), we first obtained an estimate of the current ($x_1$) in the inductance and the voltage ($x_2$) in the output capacitor (voltage filter). Then these previous estimates allowed us to obtain an estimate of the internal resistance of the IGBT in its ON-state and the duty cycle of the control signal of the IGBT. This ultimately served to predict the remaining useful life (RUL) of the IGBT operating on a DC-DC converter. A simulation example has been proposed to illustrate the results obtained. An application on a real system (test bench) will be carried out and the results obtained will be presented in our next paper.

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