Model Based Parametric Fault Detection in Power Electronic Circuits

Kang Yue1, Yu Liu1,2,*, Rong He1, Minfan Fu1 and Haoyu Wang1
1. School of Information Science and Technology, ShanghaiTech University, Shanghai, China
2. Key Laboratory of Control of Power Transmission and Conversion, Ministry of Education, Shanghai, China
*Email: liuyu@shanghaitech.edu.cn

Abstract—This paper proposes a model based method to detect parametric faults in power electronic circuits. The method first presents a systematic way to build an accurate mathematical model of any power electronic circuits that describes all the physical laws of the circuit of interest. The consistency between the measurements and the mathematical model is used as an indicator to detect parametric faults. The method only needs terminal voltage and current measurements of the circuit and does not require additional measurements. Hardware experiments on an example buck converter demonstrate the feasibility and validity of the proposed parametric fault detection method.

Keywords—parametric fault detection, power electronic circuit, systematic model, fault indicator

I. INTRODUCTION

With an increasing penetration of the power electronics, the reliability and safety demands of power electronic circuits are growing especially in smart grid [1], electronic vehicle [2] and aerospace applications [3]. Fault detection is used to monitor the operating condition and determine whether there is any fault inside the system. Once faults are detected, the signal can be sent to system controller for further action. Analytical fault detection schemes attract more and more attention from researchers compared to hardware fault detection schemes since they are less expensive, occupy less space and require less hardware complexity. Analytical fault detection methods for power electronic circuits can be mainly classified into signal based methods, knowledge based methods and model based methods [4].

Signal based methods utilize the characteristics of signals instead of mathematical models of the circuit of interest for fault detection [4]. These methods usually assume that specific signal characteristics which only emerge during faults can be clearly extracted. The fault detection decision is made based on the extracted characteristics and prior knowledge on the characteristics during faults. Examples of extracted characteristics include those in time domain (covariance of the sensing signals, magnitude of phase current, etc.) [5] and frequency domain (spectrum) [6]. Nevertheless, the main disadvantage of signal based methods is that it is generally hard to select a certain set of characteristics that can clearly differentiate the fault conditions from the normal operating conditions, especially for circuits with variable operation modes [7].

To further take advantage of available signal data, knowledge based methods have been applied in power electronic circuits to effectively detect faults. Instead of manually selecting specific signal characteristics as in signal based methods, these methods learn from available signal data and reveal the characteristics that indicate the occurrence of faults. The knowledge based methods can be categorized into qualitative methods (fault tree, expert system, etc.) [8] and quantitative methods (SVM, neural networks, fuzzy logic, etc.) [9] [10]. The knowledge based method can deal with very complex circuits, however, it requires a huge number of data that can cover all kinds of circuit operating conditions (normal operations, different locations and types of faults), which may be difficult to obtain in practice. In addition, the computational cost is also much increased.

To make full use of the information not only from measurements but also from the circuit (physical laws that the circuit should obey, including characteristics of each circuit element, topology of the circuit, etc.), the model based methods have been introduced. Specifically in dealing with parametric faults, most of the literatures employ the parameter identification approaches, the main idea of which is to first write the physical relation among available measurements and the parameters of interest and then mathematically solve the parameters of interest [11-13]. Additional measurements have been added to the power electronic circuit to ensure redundancy of the parameter identification problem [14]. Moreover, additional signals with user-defined features are injected to the circuit, to further improve parameter identification accuracy [15].

Existing model based parametric fault detection methods in the literature have the following characteristics that may limit the effectiveness and the applicability of these methods. First, to achieve parametric fault detection, existing methods have to calculate parameters of all components of interest, which could be a large computation burden especially in complex power electronic systems. If there is ‘one indicator’ of the system healthy condition, the parametric fault can be detected when the system is unhealthy, and at that time the parameter identification procedure can be initialized to accurately capture the changed parameter of the circuit. Second, most of existing methods introduce additional measurements near the component of interest to achieve parametric fault detection, which could be more expensive and complex in practice.

Therefore, this paper proposed a model based parametric fault detection method for power electronic circuits. The method first systematically builds a mathematical model that describes all the physical laws that the circuit of interest...
should obey. This proposed systematic modeling procedure works for any power electronic circuit and only requires terminal measurements of the circuit which are typically available with original hardware. Next, the parametric fault is detected by an indicator that checks the consistency between the measurements and the model. The rest of the paper is arranged as follows. Section II introduces the proposed systematic modeling procedure of any power electronic circuit. Section III describes the generation of the parametric fault indicator. Section IV verifies the feasibility and validity of the proposed parametric fault detection method through hardware experiment on a buck converter. Section V draws a conclusion and introduces the future work.

II. SYSTEMATIC MODELING PROCEDURE FOR POWER ELECTRONIC CIRCUITS

This section introduces a systematic modeling procedure for any power electronic circuits. With this procedure, an accurate model that describes all the physical laws of the interested power electronic circuit can be generated for the parametric fault detection purpose. Power electronic circuits usually consist of switches, linear elements (inductors, capacitors, resistors) and sometimes even nonlinear elements (for example, transformers with saturation characteristics, nonlinear resistors, etc.). By assuming that the switches are ideal, the system can be discretized into several operating conditions where each operating condition corresponds to one possible combination of all switching states (for each switch, the state can be either on or off). For each operating condition, the model of the circuit has the following standard syntax,

\[ y_{\text{actual}}(t) = Y_{eq} x(t) + D_{eq1} \frac{dx(t)}{dt} + C_{eq1} \]

\[ \theta = Y_{eq2} x(t) + D_{eq2} \frac{dx(t)}{dt} + C_{eq2} \]  

where \( y_{\text{actual}}(t) \) is the actual measurements of the system (here we usually assume that the circuit is only equipped with terminal voltage and current measurements, to minimize the number of required measurements); \( x(t) \) is the state of the system; the first equation set connects the states and terminal current \( i(t) \). The circuit elements such as inductors and capacitors are linearly modeled with parasitic parameters, where the inductor is modeled as RLC in parallel and the capacitor is modeled as RLC in series. The nonlinearity of the circuit could be also modeled through the proposed syntax but is not considered in this example. The buck circuit model can be expressed in equation (1) with the following definition of variables (note that the following example model of the buck circuit remains the same for different combinations of switching states),

\[ y_{\text{actual}}(t) = \begin{bmatrix} u(t) \\ i(t) \end{bmatrix}, \quad x(t) = [v_{C1}(t) \quad i_1(t) \quad v_{C2}(t) \quad i_2(t)]^T, \]

\[ Y_{eq1} = \begin{bmatrix} 1 & 0 & 1 & R_L \\ 0 & 1 & 1/R_C & 0 \end{bmatrix}, \quad D_{eq1} = \begin{bmatrix} 0 & 0 & 0 & L_C \\ 0 & 0 & 0 & C_i \end{bmatrix}, \]

\[ Y_{eq2} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & -R & -R_i & R_i \end{bmatrix}, \quad D_{eq2} = \begin{bmatrix} 0 & -L & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \]

and all other matrices are zero matrices, where the parameters \( R, L, C, R_i, C_i, R_C, L_C \), and variables \( v_{C1}(t), i_1(t), i_2(t), u(t) \) are defined in Fig. 1.

\[ \begin{aligned}
\text{Fig. 1 Buck circuit equivalent model}
\end{aligned} \]

III. GENERATION OF PARAMETRIC FAULT INDICATOR

The model in equation (1) is described in algebraic differential equation. To solve the state \( x(t) \) of the system, equation (1) was first equivalently converted into pure algebraic equation using integration methods. Here the trapezoidal integration method is applied to the first and second equation set of equation (1) over the time window \([t-h, t]\), where \( h \) is the sample interval. The results after integration are shown in equation (2),

\[ y(t) = z(x(t)) = Y_{eq} x(t) + C_{eq} + N_{eq} x(t-h) + M_{eq} y(t-h) \]

\[ + \begin{bmatrix} x(t)^T \\ \ldots \\ \ldots \end{bmatrix} F_{eq}^{(i)} x(t) \]

where \( y(t) = [y_{\text{actual}}(t) \quad \theta \quad 0 \quad 0]^T \) is the measurement vector; \( z(x(t)) \) is the function of state \( x(t) \); \( x(t-h) \) and \( y(t-h) \) are past history state and measurement vectors and are treated as known constants; \( Y_{eq}, F_{eq}^{(i)}, C_{eq}, N_{eq} \) and \( M_{eq} \) are parameter matrices that can be calculated by equation (1) and the integration process.

2934
To solve state $x(t)$ in equation (2), the state estimation algorithm using weighted least square method is utilized. It is equivalently to solve the following optimization problem,

$$\min_{x(t)} J(x(t)) = (z(x(t)) - y(t))^T W (z(x(t)) - y(t))$$

where $W = \text{diag}\{1/\sigma_1^2, 1/\sigma_2^2, \ldots, 1/\sigma_n^2\}$ is the weight matrix, and $\sigma$ is the measurement error standard deviation of each measurement (with the assumption that all the measurement errors obey Gaussian distribution). Note that the error standard deviations of zeros in $y(t)$ are selected to be much smaller than those of actual measurements, since these rows represent internal constraints among states of the circuit.

The best estimated state vector $\hat{x}(t)$ should satisfy the necessary condition that $\partial J(x(t))/\partial x(t) = 0$. Therefore, $\hat{x}(t)$ can be calculated through the following iterative algorithm until convergence,

$$x^{(t)} = x^{(t-1)} - (H^T W H)^T \frac{H^T W (z(x^{(t-1)}) - y(t))}{J_t}$$

where $H$ is defined as $\partial z(x)/\partial x$ at $x = x^{(t-1)}$.

Substitute $\hat{x}(t)$ to equation (4) to calculate the value $J(t)$, which is called chi-square value. If the model is consistent with the measurements of the circuit, the value $J(t)$ obeys the chi-square distribution with a degree of freedom $(m-n)$, where $m$ is the number of measurements and $n$ is the number of states [16]. On the other hand, if the value $J(t)$ does not obey the chi-square distribution, it is concluded that there is a parametric fault inside the power electronic circuit. Here, we simply select the average value of $J(t)$ as the indicator of parametric fault: if the average value exceeds a certain threshold, the parametric fault is detected.

IV. EXPERIMENTS OF PARAMETRIC FAULT DETECTION FOR BUCK CONVERTER

To verify the effectiveness of the proposed fault detection method, an experiment of a typical buck converter is conducted as shown in Fig. 2. The equivalent circuit of the buck converter is the same as shown in Fig. 1.

Voltage instantaneous measurement $u(t)$ and current instantaneous measurement $i(t)$, as defined in Fig. 1, are captured by an oscilloscope. The measurement errors of the oscilloscope are assumed to obey Gaussian distribution, with 1% standard deviation. The parameters of this system during normal operating condition are showing in Table I and all the parameters of inductors, capacitors and resistors defined in Fig. 1 are measured off-line by an LCR meter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source voltage $V_{dc}$</td>
<td>5 V</td>
<td>$L$</td>
<td>627 μH</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>20 kHz</td>
<td>$C_1$</td>
<td>12.314 μF</td>
</tr>
<tr>
<td>Sample rate</td>
<td>100 MHz</td>
<td>$R_1$</td>
<td>0.7 kΩ</td>
</tr>
<tr>
<td>Load $R$</td>
<td>10 Ω</td>
<td>$L_2$</td>
<td>15.391 nH</td>
</tr>
<tr>
<td>$C$</td>
<td>169.47 μF</td>
<td>$R_2$</td>
<td>202.20 mΩ</td>
</tr>
</tbody>
</table>

Next, the parametric fault detection results of three cases are demonstrated, to test the buck converter with different degrees of parametric faults caused by different values of the circuit inductor. Each case compares the practical results with the theoretical results. The practical results directly utilize the measurements from the oscilloscope, while the theoretical results utilize the measurements from a numerical buck circuit simulation platform built in PSIM with identical parameters. Note that for the theoretical results, 1% Gaussian distributed measurement errors are intentionally added to the measurements to make it comparable to the practical results.

A. Case I: Normal operating condition

![Fig. 2 Practical experiment conditions](image2)

![Fig. 3 Practical results, normal operating condition](image3)
The proposed method is first tested during normal operating condition, where the circuit is without parametric faults (the values of all the parameters in the circuit are consistent with the expected values). The practical results and the theoretical results are shown in Fig. 3 and Fig. 4, respectively. Inside each figure, the actual values, the estimated values and the residuals (difference between the estimated and actual values) of the voltage measurement and the current measurement are depicted in subfigures (a) and (b), respectively. The chi-square value is provided in subfigure (c). It can be seen that the theoretical results highly agree with the practical results. The residuals of voltage and current measurements are very small, which also validate that the measurements are consistent with the mathematical model. Also, the chi-square value is near 0 most of the time.

Note that the residuals and the chi-square value of the practical results are with very small oscillations while the theoretical results are with no oscillations. As a result, the average chi-square value is around 0.3671 for practical results and 0.0709 for theoretical results. This is probably due to the fact that there still exists a little difference between the derived mathematical model and the actual physical model of the circuit. Nevertheless, the practical chi-square value is still extremely small, which indicates healthy condition of the circuit of interests. Therefore, no parametric fault is detected in this case.

B. Case 2: Parametric fault of the inductance, \( L = 495 \mu H \)
This case tests the proposed method during a parametric fault of the inductance, where the original 627 μH circuit inductor is replaced with a new 495 μH circuit inductor. The rest of the circuit is not changed. The practical results and the theoretical results are shown in Fig. 5 and Fig. 6, respectively. Inside each figure, the actual values, the estimated values and the residuals (difference between the estimated and actual values) of the voltage measurement and the current measurement are depicted in subfigures (a) and (b), respectively. The chi-square value is provided in subfigure (c). The theoretical results highly agree with the practical results. We can see that for both practical and theoretical results, there exists obvious difference between the estimated measurements and the actual measurements. The residuals of measurement voltage and current in both figures increase dramatically compared to case 1 (the maximum absolute voltage residual is around 0.025 V and the maximum absolute current residual is around 0.02 A). Also, the chi-square value clearly differs from that in normal operating conditions: the waveform becomes triangular, oscillating from 0 to around 10. Here the average chi-square value is selected as the simple criterion for the parametric fault. The average chi-square value is around 3.0545 for practical results and 2.7841 for theoretical results, which are much larger than the average chi-square value in case 1. Therefore, a parametric fault is detected in this case.

C. Case 3: Parametric fault of the inductance, \( L = 375 \, \mu \text{H} \)

This case tests the proposed method during a parametric fault of the inductance, where the original 627 μH circuit inductor is replaced with a new 375 μH circuit inductor. The rest of the circuit is not changed. The practical results and the theoretical results are shown in Fig. 7 and Fig. 8, respectively. Inside each figure, the actual values, the estimated values and the residuals (difference between the estimated and actual values) of the voltage measurement and the current measurement are depicted in subfigures (a) and (b), respectively. The chi-square value is provided in subfigure (c). The theoretical results still highly agree with the practical results. We can see that for both practical and theoretical results, the residuals become quite large: the maximum absolute voltage residual is around 0.05 V and the maximum absolute current residual is around 0.05 A. Also, the chi-square value oscillates from 0 to around 50. Similarly, the average chi-square value is selected as the criterion: the average chi-square value is around 16.5506 for practical results and 16.2312 for theoretical results, which are obviously larger than the average chi-square value in case 1 and 2. Therefore, a parametric fault is detected in this case and the parametric fault is more severe than the fault in case 2.

V. CONCLUSIONS AND FUTURE WORK

In this paper, a model based parametric fault detection method has been proposed for power electronic circuits. The method only needs terminal measurements and does not require additional measurements from the circuit. The systematic way of establishing a mathematical model that describes all the physical laws that any power electronic circuit should obey is described. Afterwards, instead of identifying all parameters of the circuit elements, the “one indicator” that checks the consistency between the measurements and the accurate model of the circuit is introduced to detect parametric faults. Experimental results on an example buck converter prove that the proposed
method can effectively detect parametric faults. Although the paper only utilizes an example buck converter for validation, the proposed parametric fault detection method can be applied to more complex power electronic circuits. Future work may include minimizing the calculation burden to achieve online monitoring and identifying the specific faulted device after the fault indicator detects parametric faults in the power electronic circuit.

REFERENCES


