Time-variant in-circuit impedance monitoring based on the inductive coupling method

Zhao, Zhenyu; See, Kye-Yak; Chua, Eng-Kee; Narayanan, Arun Shankar; Chen, Wayne;
Weerasinghe, Arjuna

2018

Zhao, Z., See, K.-Y., Chua, E.-K., Narayanan, A. S., Chen, W., & Weerasinghe, A. (2019).
Time-variant in-circuit impedance monitoring based on the inductive coupling method.
IEEE Transactions on Instrumentation and Measurement, 68(1), 169-176.
doi:10.1109/TIM.2018.2838198

<https://hdl.handle.net/10356/90257>

<https://doi.org/10.1109/TIM.2018.2838198>

© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be
obtained for all other uses, in any current or future media, including
reprinting/republishing this material for advertising or promotional purposes, creating new
collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted
component of this work in other works. The published version is available at:
<https://doi.org/10.1109/TIM.2018.2838198>

Downloaded on 26 Apr 2023 18:24:41 SGT

Time-Variant In-Circuit Impedance Monitoring Based on the Inductive Coupling Method

Zhenyu Zhao¹, Kye-Yak See¹, Eng-Kee Chua¹, Arun Shankar Narayanan¹, Wayne Chen², and Arjuna Weerasinghe¹

¹School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore

²SMRT Corporation Ltd, Singapore

Abstract—In-circuit impedance extraction of a time-variant electrical system is essential for real-time condition monitoring purpose. This paper looks into the design consideration of real-time in-circuit monitoring for a time-variant system based on inductive coupling approach and Discrete Fourier Transform in a moving window. By using two clamped-on type inductive probes, the proposed setup eliminates the need of voltage sensors to measure the terminal voltages of system-under-monitoring (SUM) and hence, eliminates direct electrical contact with the SUM. Therefore, it facilitates ease of mounting and disassembly. Experiment results show that with careful design consideration, the proposed method has the ability to measure the in-circuit impedance of a time-variant system in real-time, which facilitates useful inputs for early detection of abnormality of the monitored electrical system that is time-variant in nature.

Index Terms—Discrete Fourier Transform in a moving window, inductive coupling, time-variant in-circuit impedance monitoring.

I. INTRODUCTION

With the widespread use of switching devices in most electrical systems, time-variant electrical parameters of the systems provide valuable inputs for condition monitoring purposes. Time-variant in-circuit impedance information of an operating electrical system is useful to detect early signs of abnormality for preventive measures. There are various time-variant impedance measurement methods reported. In general, they are categorized into two approaches. The first approach measures the voltage and current signals associated with the operation of the SUM and detects any variations from their norms but it requires more extensive analysis to avoid false alarm [1]. The other approach injects a known test signal into the SUM through a device and analyses its response [2-5]. In most cases, an electrically connected voltage sensor with the SUM is necessary, which requires special provision for such a connection. In reality, the high-voltage parts of the SUM are insulated for safety reasons and therefore accessibility for making direct electrical contact to the SUM can be challenging for these conventional voltage sensors. The proposed method in this paper adopts an inductive coupled approach to overcome this limitation [6]. Two clamped-on type inductive probes, one as an injecting probe and the other as a receiving probe, are

employed for the in-circuit impedance extraction. The inductive probes have no direct electrical contact with the SUM and therefore eliminates the safety hazards. Also they can be easily mounted onto and removed from the insulated high-voltage cables of the SUM, which makes the on-site implementation simple.

Typically, a vector network analyzer (VNA) and two clamped-on type inductive probes are the basic measurement instruments of the proposed method. The VNA generates and tracks a series of known test signals to the SUM through the injecting and receiving inductive probes, respectively. Firstly, the two probes are properly characterized as two-port networks. Then, by treating the two inductive probes and the SUM as three cascaded two-port networks, the impedance of the SUM can be extracted. This technique has been well established for time-invariant system to extract in-circuit impedance response in frequency-domain [7, 8]. However, its use to extract time-variant impedance of the SUM, especially those with high frequency switching rates, such as power electronic systems has not been explored. This paper describes the extension of the proposed technique for time-variant in-circuit impedance extraction. By injecting a small perturbation sinusoidal signal at a chosen frequency into the time-variant electrical system, the time-domain voltages and currents at ports of data acquisition (DAQ) device are extracted. Then, through the Discrete Fourier Transform (DFT) in a moving window algorithm, the voltages and currents at the specified frequency are obtained. The moving window size is fixed and the DFT is performed to obtain dynamic voltages and currents at different time instances. Finally, the time-variant in-circuit impedance of system is determined using the cascaded two-port networks. In this moving window DFT algorithm, the window is shifted one sample at a time. Hence, it has a better capability to detect the dynamic changes of in-circuit impedance of a time-variant system as compared with the other DFT algorithms whose window is shifted multi-sample at a time [9].

The organization of this paper is as follows. The basic setup and principle of the time-variant in-circuit impedance monitoring will be introduced in the next section. In section III, the real-time in-circuit impedance extraction with DFT algorithm is presented with experimental validation on a time-invariant electrical network and a time-variant switching electrical network. Then, the measurement accuracy of the

proposed method is discussed. The same switching electrical network will be used as an example to demonstrate the ability of the proposed method for real-time condition monitoring purpose. The final section concludes the paper.

II. BASIC SETUP OF TIME-VARIANT IN-CIRCUIT IMPEDANCE MONITORING

Fig. 1 shows a time-variant electrical network powered by a power source through electrical conductors. The time-variant electrical network together with the power source and connecting wires can be treated as a SUM, where Z_S and Z_W are the impedances of the source and wiring. Z_{TVN} together with a switch S symbolizes the time-variant electrical network where impedance changes with the state of the switch. The monitoring setup is a DAQ system, which consists of two clamp-on type inductive probes, DAQ measurement device, and a computer with programmable software. Port 1 of the DAQ device injects a small signal into the SUM through one of the inductive probes. The same signal is tracked and measured by port 2 of the device through the other inductive probe. The injecting and receiving probes with the respective wires being clamped can be modelled as two-port networks M_{inj} and M_{rec} , respectively [7]. The two-port network is expressed in terms of transmission ($ABCD$) parameters, and will be referred to as two-port $ABCD$ network that follows [10]. Similarly, the SUM can be modelled as another two-port $ABCD$ network denoted as M_{SUM} . Since the three two-port $ABCD$ networks are cascaded, the resulting two-port network, M can be expressed as:

$$M = M_{inj} M_{SUM} M_{rec} \quad (1)$$

Fig. 2 shows the equivalent cascaded two-port $ABCD$ networks of the measurement setup shown in Fig. 1. In Fig. 2, V_{sig} is the signal source with output impedance $Z_{o,sig}$. $Z_{i,osc}$ is the input impedance at port 2 of the DAQ; V_1 and I_1 are the voltage and current at port 1, respectively; V_2 and I_2 are the voltage and current at port 2; and Z_{SUM} is the equivalent in-circuit impedance of the SUM. Z_{SUM} can be extracted once M_{SUM} is evaluated as follows [10]:

$$M_{SUM} = \begin{bmatrix} A_{SUM} & B_{SUM} \\ C_{SUM} & D_{SUM} \end{bmatrix} = \begin{bmatrix} 1 & Z_{SUM} \\ 0 & 1 \end{bmatrix} \quad (2)$$

Fig. 1. Measurement setup of the time-variant in-circuit impedance monitoring using inductive coupling method

Fig. 2. Cascaded two-port networks of the measurement setup shown in Fig. 1

From Fig. 2, the overall two-port network measured by the DAQ is:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_{inj} & B_{inj} \\ C_{inj} & D_{inj} \end{bmatrix} \begin{bmatrix} A_{SUM} & B_{SUM} \\ C_{SUM} & D_{SUM} \end{bmatrix} \begin{bmatrix} A_{rec} & B_{rec} \\ C_{rec} & D_{rec} \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (3)$$

Substituting (2) into (3):

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_{inj} & B_{inj} \\ C_{inj} & D_{inj} \end{bmatrix} \begin{bmatrix} 1 & Z_{SUM} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_{rec} & B_{rec} \\ C_{rec} & D_{rec} \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (4)$$

Based on (4), Z_{SUM} can be extracted as:

$$Z_{SUM} = \frac{V_1 - A_{inj}(A_{rec}V_2 + B_{rec}I_2) - B_{inj}(C_{rec}V_2 + D_{rec}I_2)}{A_{inj}(C_{rec}V_2 + D_{rec}I_2)} \quad (5)$$

As mentioned earlier, M_{inj} and M_{rec} can be pre-characterised individually. $v_1(t)$ and $v_2(t)$ are the voltages at ports 1 and 2 of the two-port network M at time t , which can be measured directly using a DAQ system. In order to obtain the magnitudes and phases of V_1 and V_2 , DFT is performed in a moving window. The window size, N is fixed and DFT is performed to obtain dynamic voltage equivalents at different time instances, thereby obtaining V_1 and V_2 . The DFT in a moving window is given by:

$$V_k(m) = \sum_{n=m-N+1}^m v(n) e^{-2\pi i k [n-(m-N+1)]/N} \quad (6)$$

where N is the number of sampling points of the fixed moving window size and m is the $(m+1)^{th}$ discrete sample during the monitoring process. $V_k(m)$ is the dynamic voltage equivalents at time t and specific frequency point k [11] and $v(n)$ is the $(n+1)^{th}$ discrete sampling voltage value in time-domain. In contrast to DFT with a fixed window, whose range of n is between 0 and $N-1$ [11], the range of n of DFT in a moving window is a variable with the value of m . Using Euler's formula, (6) can be expressed in a trigonometric functions form as follows:

$$V_k(m) = \sum_{n=m-N+1}^m v(n) \left[\cos\left(2\pi k \frac{n-m+N-1}{N}\right) - j \sin\left(2\pi k \frac{n-m+N-1}{N}\right) \right] \quad (7)$$

Further simplifying (7):

$$V_k(m) = \sum_{n=m-N+1}^m v(n) \left[\cos\left(2\pi k \frac{n-m-1}{N}\right) - j \sin\left(2\pi k \frac{n-m-1}{N}\right) \right] \quad (8)$$

Using (8), the V_1 and V_2 at different time point t can be obtained. Once V_2 is known, I_2 can be calculated with $V_2/Z_{i,osc}$. After obtaining Z_{SUM} , Z_{TVN} can be extracted by de-embedding Z_S and Z_W from Z_{SUM} .

Fig. 3. The algorithm of Discrete Transform Fourier in a moving window

The algorithm of DFT in a moving window is given in Fig. 3. The program starts with samples $v_1(t)$ and $v_2(t)$ when $t = 0$. m corresponds to the $(m+1)^{th}$ sample during the whole monitoring process, which is equal to the sampling time point t multiply by the sampling rate $1/\Delta t$. When $m \geq N - 1$, the DFT is performed and V_1 and V_2 are obtained. Obtaining of V_1 and V_2 at time t is based on the latest N samples in time-domain, which is from $(m-N+1)\Delta t$ to $m\Delta t$. Therefore, the N samples are dynamically selected and are relative to the sampling time instance t . Once V_2 at time instance t is obtained, the corresponding I_2 also can be extracted using $I_2 = V_2/Z_{i,osc}$. Thus, Z_{SUM} at that specific time point t can be calculated based on (5) and subsequently Z_{TVN} is determined through de-embedding as explained. The next step is to judge whether the sampling time point t has reached the last sampling time point (t_{end}). The algorithm ends when $t \geq t_{end}$. Otherwise, resetting $t = t + \Delta t$, a new sampling cycle will commence and the same process is repeated until $t \geq t_{end}$.

During the moving window DFT process, the selection of test signal frequency (f_{sig}), sampling rate (f_s) and moving window size (N) is important since their values can influence the accuracy of the measurement results. First of all, f_s should be at least 10 times larger than f_{sig} to ensure that the magnitude of sampled signal will not deviate significantly [12]. Hence, in the experiment that follows, f_s is set as $10f_{sig}$, which gives 10 sampling points in each cycle of the injected sinusoidal signal. In addition, every DFT performed shall contain data of 10 complete cycles of the sinusoidal signal as per the rule of thumb to achieve good accuracy [13]. Therefore, N is set at 100. Note that the selection of f_s and N depends on the frequency of impedance change (f_{ch}) of a time-variant system. To achieve valid and accurate DFT result, the time interval of N samples (N/f_s) must be much smaller than $1/f_{ch}$.

III. EXPERIMENTAL VALIDATION

For experimental validation, the DAQ system used consists of NI PXI module with NI PXI-1031 back-panel, NI PXI-5412 signal generator card, NI PXI-5922 signal acquisition card and NI PXI-8360 computer interface card. A laptop with programmable software is for the implementation of DFT algorithm given in Fig. 3. The NI PXI-5412 arbitrary waveform generator with output impedance ($Z_{o,sig}$) of 50Ω is used to generate a small sinusoidal signal with frequency f_{sig} . The NI PXI-5922 high-resolution oscilloscope with an input impedance ($Z_{i,osc}$) of 50Ω is used to measure the injected signal. It has two channels: channel 0 and channel 1 to sample the voltages $v_1(t)$ and $v_2(t)$, respectively. The NI PXI-8360 card allows the user to control the NI PXI and Compact Peripheral Component Interconnect (PCI) systems from a personal computer (PC) using a fully transparent MXI-Express link. As the maximum sampling rate of the oscilloscope (NI PXI-5922) for the measurement is slightly over 5 MHz, f_s is set at 5 MHz to evaluate the maximum f_{ch} , where the measurement setup can detect. Based on the earlier mentioned guideline, the signal frequency f_{sig} is chosen as 500 kHz. As this paper focuses on the concept behind the proposed method, an oscilloscope with higher sampling rate should be used for SUM with requirements of higher f_{ch} . Considering the size of the SUM in the experiment, the two inductive probes chosen are Tektronix CT1 current probes (25 kHz to 1 GHz). One of the Tektronix CT1 current probes is used as the injecting probe and the other is used as the receiving probe. A test fixture and a VNA is used to characterized M_{inj} and M_{rec} [7] and their respective $ABCD$ parameters are given as follows when $f_{sig} = 500$ kHz:

$$M_{inj} = \begin{bmatrix} 5.0025 + j0.0055 & 0.6073 + j0.8127 \\ 0.0981 - j0.0076 & 0.2129 + j0.0145 \end{bmatrix} \quad (9)$$

$$M_{rec} = \begin{bmatrix} 0.2087 + j0.0081 & 0.5445 + j0.5481 \\ 0.0868 - j0.0079 & 5.0329 + j0.0082 \end{bmatrix} \quad (10)$$

A. In-circuit Impedance Monitoring of Time-Invariant Electrical Network

Before the experimental validation of the proposed method for time-variant electrical system, it is necessary to test it on a time-invariant system first. A circuit with a combination of R, L and C is emulated as the electrical network to be monitored, as shown in Fig. 4. The values of the components in Fig. 4 are: $R_1 = 4.7 \Omega$, $C_1 = 330 \text{ pF}$, $L = 15 \mu\text{H}$, $C_2 = 100 \text{ nF}$ and $R_2 = 51 \Omega$. The supply voltage is set at $V_s = 5 \text{ V}$. Injecting the test signal with frequency f_{sig} into this electrical network, the real-time in-circuit complex impedance was measured using the proposed method. For validation purpose, the in-circuit measurement result from the proposed method will be compared with the off-line measurement result of the same electrical network using PM6306 RCL meter.

Fig. 4. Measurement setup of the RLC electrical network

Figs. 5. (a) and (b) show the magnitude and phase of the measured impedance, respectively. The means and standard deviations of both methods are also shown in Table I. Using the measurement results from PM6306 as references, the magnitude and phase measurement errors using the proposed method are calculated to be 0.2% and 1.3%, respectively. It demonstrates that the measurement results using the proposed method agree well with those obtained from PM6306.

Fig. 5. (a) Magnitude and (b) phase of the measured impedance monitored using the proposed method (solid line) and Agilent 4294A (dash line)

Table I. Comparison of magnitude and phase of the measured impedance between in-circuit and off-line methods

	The Proposed Method		PM6306 RCL Meter	
	Mean	Standard Deviation	Mean	Standard Deviation
Magnitude (Ω)	45.24	0.0025	45.13	0.0040
Phase ($^\circ$)	88.7	0.0032	87.6	0.0020

B. In-circuit Impedance Monitoring of Time-Variant Electrical System

To emulate a time-variant electrical system, a DC/DC switching circuit with a power MOSFET shown in Fig. 6 is used as an example.

Fig. 6. Measurement setup of the switching DC/DC circuit

The values of the components are: $R_1 = 1 \Omega$, $C_1 = 4.7 \mu\text{F}$, $L = 1 \text{ mH}$, $C_2 = 47 \mu\text{F}$ and $R_2 = 51 \Omega$. The N-type power MOSFET has a reverse diode (D_r) and an equivalent parasitic capacitance (C_p). A gate drive signal with period T and duty cycle $D = 0.5$ is connected to the gate of the MOSFET to control its switching frequency, $f_{sw} = 1/T$. The equivalent impedance of the MOSFET at the specified frequency is denoted as Z_M and its value depends on whether the MOSFET is in the 'on' or 'off' state. D' is a diode with opposite switching states to the MOSFET. The input supply voltage (V_s) is set at 1 V. Z_s is the Thevenin equivalent impedance of the input

power supply, which includes a shunt capacitor as an output filter. Thus, the time-variant electrical network can be equated as two separate time-invariant networks when MOSFET is 'on' and 'off', respectively. Considering that the time-variant impedance of the switching circuit cannot be measured using conventional off-line impedance analyzer, and the impedance in steady state of each switching cycle is same with the impedance of the two separate time-invariant electrical networks when the MOSFET is always 'on' or 'off', the measurement result when MOSFET is always 'on' or 'off' can be taken as reference impedance to validate the performance of the proposed method when the electrical network is constantly switching 'on' and 'off'. Since the proposed method has been proved to measure the real-time in-circuit impedance of a time-invariant electrical network in the previous part, the method of selecting the measurement result when MOSFET is always 'on' or 'off' as the reference impedance is feasible. Other than that, for a DC/DC switching network, its f_{ch} is same as f_{sw} . As mentioned earlier, accurate impedance measurement of the DC/DC switching network requires $(N/f_s) \ll 1/f_{sw}$. Considering N and f_s are selected as 100 and 5 MHz in the experiment, respectively; it is found that $f_{sw} \ll 50$ kHz. Hence, an experiment is conducted to evaluate it.

Figs. 7 to 9 show the measured real-time impedance using the proposed method when f_{sw} is 1 kHz, 10 kHz and 50 kHz, respectively. The impedances when MOSFET is always 'on' and 'off' are also indicated as references for comparison purpose. As explained, N/f_s (20 μ s) should be much smaller than $1/f_{sw}$. Therefore, when $f_{sw} = 1$ kHz, its performance to capture the 'on' and 'off' real-time impedances is better, as f_s/f_{sw} at 1 kHz is much higher than f_s/f_{sw} at 10 kHz. By increasing f_{sw} to 50 kHz, the impedance changes can no longer be captured as $1/50$ kHz = 20 μ s is same as N/f_s , causing the DFT algorithm unable to obtain the dynamic impedance changes of the switching network. Hence, proper choices of f_s and N are essential for a given f_{sw} to satisfy $(N/f_s) \ll 1/f_{sw}$. For a smaller N/f_s , a more accurate measurement result will be obtained. For time-variant system where $f_{sw} \geq 50$ kHz, an oscilloscope with higher sampling rate is necessary.

Fig. 7. (a) Magnitude and (b) phase of the measured impedance shown in Fig. 6 at $f_{sw} = 1$ kHz

Fig. 8. (a) Magnitude and (b) phase of the measured impedance shown in Fig. 6 at $f_{sw} = 10$ kHz

Fig. 9. (a) Magnitude and (b) phase of the measured impedance shown in Fig. 6 at $f_{sw} = 50$ kHz

Tables II and III show the mean magnitude and phase of the measured impedance from the measurement data of Figs. 7 and 8, as well as those from with MOSFET always in ‘on-state’ and ‘off-state’. The magnitude and phase deviations are rather small when $f_{sw} = 1$ kHz and 10 kHz. Using the measured results when switch is always in ‘on-state’ and ‘off-state’ as references, the steady state measured impedance magnitude and phase errors of the proposed method are 7.7% and 0.5%, respectively.

The measured impedance in each switching transition has an oscillatory behaviour due to the existence of junction capacitance of power MOSFET and the inductance of the circuit loop [14-16]. Using the time-domain peak transient voltage and current values as reference, the corresponding in-circuit impedance from the proposed method is extracted for comparison purpose. From Figs. 7 and 8, the maximum transient impedance values obtained using the proposed method when $f_{sw} = 1$ kHz, 10 kHz are 326.81 Ω and 333.61 Ω , respectively. Using the measured time-domain peak transient voltage and current, the impedances computed are 357.16 Ω ($f_{sw} = 1$ kHz) and 378.13 Ω ($f_{sw} = 10$ kHz), respectively. The transient in-circuit impedance measurement errors when $f_{sw} = 1$ kHz and 10 kHz are 8.5% and 11.8%, respectively.

Table II. The steady state magnitude of impedance from Figs. 7 and 8

	$f_{sw} = 1$ kHz, 10 kHz		Reference Values	
	‘on’	‘off’	Always ‘on’	Always ‘off’
	Mean Values (Ω)			
1 kHz	7.56	252.32	7.55	273.50
10 kHz	7.58	265.95		

Table III. The steady state phase of impedance from Figs. 7 and 8

	$f_{sw} = 1$ kHz, 10 kHz		Reference Values	
	‘on’	‘off’	Always ‘on’	Always ‘off’
	Mean Values ($^\circ$)			
1 kHz	50.12	-84.64	50.22	-85.00
10 kHz	50.09	-84.58		

C. Discussion on measurement accuracy

The measurement errors of the proposed method can be analysed in terms of measurement errors in steady state and transient state. For an intuitive analysis in steady state error, (5) is simplified based on $I_2 = V_2/Z_{i,osc}$:

$$Z_{SUM} = \frac{V_1}{V_2} \cdot \frac{1}{A_{inj} \cdot (C_{rec} + D_{rec}/Z_{i,osc})} - \frac{A_{rec} + B_{rec}/Z_{i,osc}}{C_{rec} + D_{rec}/Z_{i,osc}} - \frac{B_{inj}}{A_{inj}} \quad (11)$$

From (11), the steady state error is contributed by V_1/V_2 extraction error, inductive probes characterization error and $Z_{i,osc}$ error. V_1/V_2 extraction error is a combination of signal acquisition error, Analog to Digital sampling error and DFT error. In the experiment, CT1 inductive probe is used to extract signal with an acquisition error of $\pm 3\%$. Besides these, 10 points are sampled in each cycle, so the maximum sampling error is around -4% [12]. Since integer number of cycles (10 cycles) of the single frequency sinusoidal signal is used to do DFT, the DFT process is theoretically of zero error [13]. Furthermore, the characterization error of injecting and receiving inductive probes is about $\pm 0.3\%$ when $f_{sig} \leq 10$ MHz [7] and the error of input impedance of NI PXI-5922 oscilloscope card used in the experiment is $\pm 2.0\%$. All these errors are common for other measurement methods too and are acceptable.

The transient state error is not only determined by the above-mentioned factors, but also the moving window size. In the experiment, the window size is set as 100, which means the measured real-time impedance is based on its last 100 sampled points. Therefore, when the dynamic change duration of a SUM is shorter than the time interval of 100 sample points, the measurement accuracy of the dynamic results deteriorates. What is more, for a window with a fix size, the shorter the dynamic change duration, the higher the error, which explains why the proposed method has a relatively higher transient state error.

IV. REAL-TIME CONDITION MONITORING APPLICATION

This section illustrates how the proposed method can be applied in real-time condition monitoring of the in-circuit impedance of a time-variant electrical network. The same switching circuit in Fig. 6 is used as a test case. These are the signal parameters used in the experiment: $f_s = 5$ MHz, $f_{sig} = 500$ kHz, $f_{sw} = 1$ kHz and $D = 0.5$. Firstly, the circuit starts

operating at normal temperature. Then, a heating element is applied on the MOSFET to emulate the MOSFET operation at a high temperature, and the resulting real-time in-circuit impedance is re-measured. The measurement results are presented in Fig. 10. It is clearly observed that the magnitude and phase of the measured impedance deviate from their original values at normal temperature when the MOSFET is in 'off' state. It has demonstrated the ability to extract real-time in-circuit impedance of the proposed method provides valuable information on the abnormal behaviour of the MOSFET due to overheating. This early detection allows necessary remedial action for corrective measures, saving the electrical system from premature damage without warning.

Fig. 10. (a) Magnitude and (b) phase of the measured impedance when MOSFET operates at normal temperature and high temperature

V. CONCLUSION

By treating the inductive probes and system under monitoring (SUM) as cascaded two-port *ABCD* networks and using a fixed size moving window DFT, a time-variant in-circuit impedance monitoring technique is described and developed in this paper, which has the merits of easy-mount-

easy-disassemble and eliminates direct electrical contact with the SUM. For validation purpose, a switching DC/DC circuit is selected as a test case to verify the ability of the proposed technique to monitor in-circuit impedance of a time-variant electrical system with reasonably good accuracy. Such ability is useful to monitor a time-variant electrical system for abnormal behaviours that serve as early signs of device's defect. To ensure the proposed technique functions well, the changing frequency of the active device must be known so that proper choice of the sampling frequency can be done to ensure good accuracy.

ACKNOWLEDGMENTS

This research work was conducted in the SMRT-NTU Smart Urban Rail Corporate Laboratory with funding support from the National Research Foundation (NRF), SMRT and Nanyang Technological University; under the Corp Lab@University Scheme.

REFERENCES

1. Pedersen, K.O.H., A.H. Nielsen, and N.K. Poulsen, "Short-circuit impedance measurement," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 150, no. 2, pp. 169-174, Mar. 2003.
2. Asiminoaci, L., et al., "A new method of on-line grid impedance estimation for PV inverter," in *19th Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Feb. 2004, pp. 1527-1533.
3. Ishigure, N., K. Matsui, and F. Ueda, "Development of an on-line impedance meter to measure the impedance of a distribution line," in *IEEE International Symposium on Industrial Electronics Proceedings (ISIE)*, Jun. 2001, pp. 549-554.
4. Matsui, K., N. Ishigure, and F. Ueda, "On-line impedance meter to measure the impedance of a distribution line using inverter," in *27th Annual IEEE Industrial Electronics Society (IECON)*, Nov. 2001, pp. 1230-1236.
5. Timbus, A.V., et al., "Online grid measurement and ENS detection for PV inverter running on highly inductive grid," *IEEE power electronics letters*, vol. 2, no. 3, pp. 77-82, Nov. 2004.
6. Forgacs, R.L., "In-circuit impedance measurement using current sensing," *IEEE transactions on instrumentation and measurement*, vol. 34, no. 1, pp. 6-14, Mar. 1985.
7. Li, K.R., K.Y. See, and X.M. Li, "Inductive coupled in-circuit impedance monitoring of electrical system using two-port ABCD network approach," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 9, pp. 2489-2495, Feb. 2015.
8. Rathnayaka, S.B. and K.Y. See, "Early detection of induction motor's defects using an inductively coupled impedance extraction method," in *IEEE International Electric Machines and Drives Conference (IEMDC)*, May 2017, pp. 1-6.
9. Park, C.-S. and S.-J. Ko, "The hopping discrete Fourier transform," *IEEE Signal Processing Magazine*, vol. 31, no. 2, pp. 135-139, Feb. 2014.
10. D. Pozar, "Microwave engineering", New York: John Wiley & Sons, 2012.
11. Briggs, W.L. and V.E. Henson, "The DFT: an owner's manual for the discrete Fourier transform," Philadelphia: SIAM, 1995.
12. Pelgrom, M.J., "Analog-to-digital conversion," New York: Springer, 2013.
13. Zhan, L.C., et al., "Phase estimation of sinusoid signal based on DFT and error analysis," *Journal of Beijing University of Aeronautics and Astronautics*, vol. 33, no. 5, pp. 580-584, May 2007.
14. Chen, Z., D. Boroyevich, and R. Burgos, "Experimental parametric study of the parasitic inductance influence on MOSFET switching characteristics," in *25th Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Jun. 2010, pp. 164-169.
15. Wang, Z., et al., "Analysis of stray inductance's influence on SiC MOSFET switching performance," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, Sept. 2014, pp. 2838-2843.
16. Wang, J., et al., "Characterization and experimental assessment of the effects of parasitic elements on the MOSFET switching performance,"

IEEE Transactions on Power Electronics, vol. 28, no. 1, pp. 573-590, Apr. 2012.

Zhenyu Zhao received the B.Eng. degree in electrical engineering from Huazhong University of Science and Technology, Wu Han, China, in 2015, and the M.Sc. degree from the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, in 2016. He is currently working toward the Ph.D. degree in Nanyang Technological University. His research interests include fault diagnosis and online impedance monitoring techniques.

Kye-Yak See (SM'02) received the B.Eng. degree from the National University of Singapore, Singapore, in 1986, and the Ph.D. degree from Imperial College London, U.K., in 1997. He was with Singapore Technologies Electronics, Singapore, as a Senior Engineer, from 1986 and 1991. From 1991 to 1994, he was a lead Design Engineer with ASTEC Custom Power, Singapore. Since 1997, he has been with Nanyang Technological University (NTU), Singapore, as a Faculty Member. He is currently an Associate Professor with the School of Electrical and Electronic Engineering, NTU. He holds concurrent appointment as Director of the Electromagnetic Effects Research Laboratory and Director of SMRT-NTU Smart Urban Rail Corporate Laboratory. His current research interests are electromagnetic compatibility (EMC), signal integrity and real-time condition monitoring.

Dr. See was the Founding Chairs of the IEEE Electromagnetic Compatibility (EMC) Chapter, and the IEEE Aerospace and Electronic Systems and the IEEE Geoscience and Remote Sensing Joint Chapter in Singapore. He was the Organizing Committee Chairs of 2006 EMC Zurich Symposium and 2008 Asia Pacific EMC Conference; General Chair of 2015 Asia Pacific Conference on Synthetic Aperture Radar. He has been the Technical Editor of the IEEE Electromagnetic Compatibility Magazine since January 2012.

Eng-Kee Chua received his B.Eng. (Honours) in Electrical Engineering from the University of New South Wales in 1998, M.Eng and Ph.D from Nanyang Technological University in 2002 and 2008. He worked as a research scientist in Institute of High Performance Computing, A*STAR for 5 years. Currently he is with Nanyang Technological University working as research fellow. He is the senior member of IEEE and EMC/MTT/AP societies and serves as a reviewer of referred international journals and conferences. He was the member of

steering committee and the publication chair of APEMC 2012. His research interests include computational electromagnetic, modelling of interconnect structures, the modelling and analysis of the EMI/EMC/SI/PI for printed circuit structures, and railway fault detection algorithm.

Arun Shankar Narayanan completed his B Tech. and PhD degrees from National University of Singapore in 2011 and 2016 respectively. Prior to that, he was holding various engineering positions in Hewlett Packard and National Instruments Singapore. Currently a Research Fellow at Nanyang Technological University Singapore, he works in condition monitoring of railway electrification systems under the SMRT-NTU Smart Urban Rail Corporate Laboratory. His research interests also include adaptive streaming technologies and data

analysis techniques.

reliability.

Wayne Chen completed his B.Eng. (Honours) in Mechanical Engineering from Nanyang Technological University in 2008. He worked as a defence engineer in the Defence Science and Technology Agency as a combat systems engineer for 7 years. Currently, he is with SMRT as a principal engineer in the Permanent Way department. He was involved the operations and maintenance of condition monitoring systems of the MRT network and also the conduct of engineering analysis to identify the root causes of defects in an effort to enhance track

Arjuna Weerasinghe received the B.Sc. degree in electrical engineering from University of Moratuwa, Colombo, Sri Lanka, in 2015. He is currently perusing the Ph.D. degree in Nanyang Technological University Singapore.

From 2015 to 2017 he was a Motion Control and Robotics Engineer in Singapore. His research interests include electromagnetic compatibility and analog integrated circuit design.