Influence of Very Fast Voltage-Oscillation with Polarity Reversalon Partial Discharge Inception Probability for Twisted Enameled-Wires

Kazunori Kadowaki, Yujiro Takemura and Ryotaro Ozaki

Abstract: This paper presents an experimental study on repetitive partial discharge inception probability of twisted enameled wires subjected to modified inverter-surges. In order to obtain the probability curves as a function of the voltage amplitude, we develop an automatic measurement system of partial discharge inception probability for the twisted enameled wires subjected to the repetitive pulses with step-by-step increasing in the voltage height. Very fast oscillated pulses with or without polarity-reversal and an impulse-like pulse without oscillation are used as the modified inverter-surges. In the test for the impulse-like voltage, repetitive partial discharge inception voltage (RPDIV) decreases with increasing the pulse width. On the other hand, RPDIV for the polarity-reversed pulse with a higher oscillation cycle is lower than that for the pulse with lower oscillation cycle. The difference of PD inception probability between the voltage waveforms will be discussed on the basis of charge dynamics on the wire surfaces.
Index Terms: modified-inverter-surge, repetitive partial discharge, automatic measurement, polarity-reversed pulse, twisted-pair

1. Introduction

It is very important to improve the reliability and safety of power drive systems of hybrid and electric vehicles from the practical point of view. One of problems is the degradation of motor coil insulations subjected to high voltage pulses with high repetition rate. Enameled wires in inverter-fed motors are subjected to oscillated pulses which are superimposed on a square voltage from a PWM-inverter-circuit, so called inverter-surges [1]. In the last decade, many researchers studied partial discharge (PD) phenomena caused by modified inverter surges. Impulse-like voltages or square-like voltages are used as a modified inverter surge in many cases [2]-[4]. However, actual voltage waveform of the inverter surge is not a simple impulse but a very fast damped oscillation with changing its polarity [5]. From this viewpoint, it is very important to clarify the influences of voltage waveforms on repetitive partial discharge inception voltages (RPDIV) for enameled wires. RPDIV is defined as a critical voltage that the inception probability of the partial discharges is up to 50 % [6].

Since 2008 to 2010, a round-robin test for RPDIV measurement was carried out by six labolatories in Japan in order to standardize measurement method for RPDIV [7]. Influences of experimental conditions, such as humidity and repetition number of measurement, were discussed on the basis of the results on RPDIV measurement for a common sample subjected to monopolar impulse voltages.

There are many studies on influence of voltage waveforms on RPDIV [8]-[11]. However, the characteristics of PD inception probability as a function of the applied voltage have not been studied in detail. In the present study, PD inception probability for a twisted pare sample consisting of two enamelled wires is evaluated in detail by an automatic measurement system for various modified inverter surges[4]. The automatic measurement system allows us to obtain not only RPDIV but also PD probability curves as a function of the applied voltage. Influences of several parameters, pulse width, oscillation cycle and time interval from pulse to pulse, are studied by using the automatic measurement system.

2. Experimental procedure

(1) Automatic measurement system

Figure 1 shows a schematic layout of an automatic measurement system for partial discharge

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inception probability. To obtain PD probability curves, the voltage pulses are repeatedly applied to a twisted pare sample with step-by-step increasing in amplitude [5][7]. Ten voltage pulses with a same amplitude are applied to the sample at a time interval T_c. The initial applied voltage is sufficiently lower than RPDIV. After the ten times application, successive ten pulses slightly higher than the previous pulses are applied to the sample. The rise step ΔV is set 10 V in all tests. When the amplitude is up to a sufficient high voltage to induce PD, the applied voltage is reset to the initial value. This sequence is repeated for ten times with one twisted-pare sample.
The above procedure is the same as that in the round-robin test to measure RPDIV [7]. One difference between the round-robin test and this study is how to strage large amount of partial discharge signals. In the round-robin test, a large number of detected signals were stored in a digital oscilloscope and then they were observed by naked eye to estimate RPDIV. In this study, a discharge light is not only detected but also transformed into a logic pulse signal by a special optical sensor of our own making. The sensor consists of a photomultiplier (Hamamatsu Photonics Co., H5783-06) and a successive TTL pulse generator. The logic signal of partial discharge is automatically stored in a computer. The sequence of the pulse voltage repetition is also controlled by the computer, so that statistical data of the probability curve is automatically obtained. The schematic diagram of the optical sensor and the control program can be found on the Web [12].

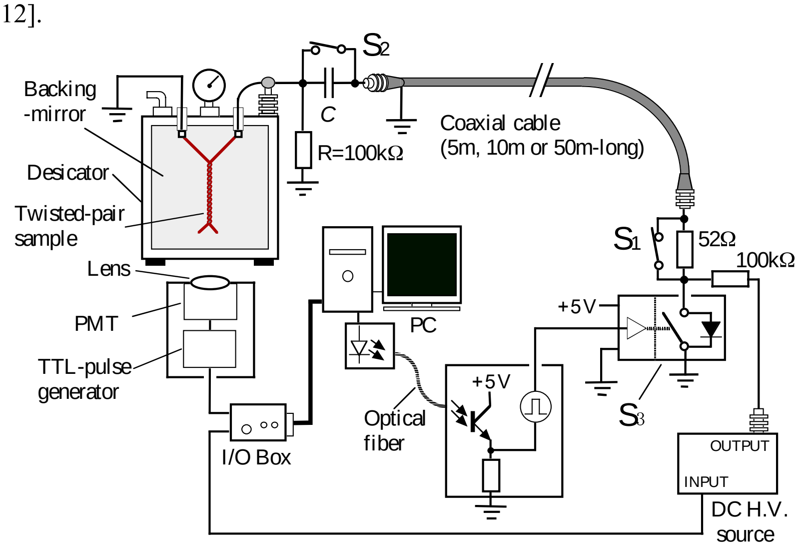

Figure 1. Experimental arrangements.

(2)Voltage waveforms

Typical waveforms of the applied voltage are shown in Figure 2(a) for impulse-like voltages having various exponential tails and in Figure2(b) for the very fast-oscillated pulses with polarity-reversal. The impulse-like voltage with the height V_0 can be produced by closing a semiconductor switch S_3 (Behlke Co. HTS-71-62B) in Figure1 after a capacitor at the front of a coaxial cable is charged by a dc voltage source of $-V_0$. To produce the impulse voltage, other switches S_1 and S_2 are kept open. The half width of the voltage pulse can be controlled by a *CR* circuit at the front of the coaxial cable. The influence of the pulse width on RPDIV is studied using the impulses with various time constants of the order from 1 μs to 100 μs. If S_1 is kept close, the very fast voltage oscillation is caused by direct grounding because reciprocation of the traveling wave occurs with changing its polarity due to impedance-mismatching between the cable (52 Ω) and the grounding end (0 Ω)[13]. When S_2 is kept open, the voltage oscillation is superimposed on the impulse voltage, so that the voltage is oscillated between 0 to $2V_0$. On the other hand, the voltage is oscillated between $-V_0$ to $+V_0$ as shown in figure 2(b) when S_2 is kept close. The frequency of the voltage oscillation is proportional to the cable length. In the present study, three kinds of cable lengths, 5 m, 10 m and 50 m are chosen, so that the oscillation cycles (T_{osc}) are set to 100 ns, 200 ns and 1μs respectively.

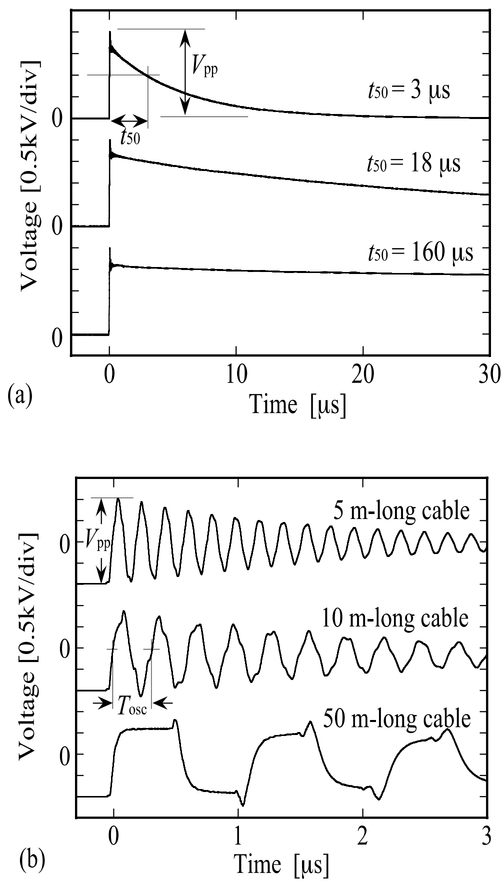

Figure 2. Voltage waveforms for (a) impulse-like pulse and for (b) very fast polarity-reversal pulse.

(3)Test sample

Figure3 shows a photograph of a test sample. A twisted-pair sample made with polyamide-imide enameled wire (AIW, Sumitomo Wintec Co., 0.8 mm in diameter of conductor, 33μm in thickness of enamel layer) is used as a test sample. One wire is always grounded whereas the other wire is connected to the pulse generator as shown in Figure1. Therefore, field intensity at contact points of the twisted wires becomes higher than that at the end point of the wire. We confirm that no discharge light is observed at the wire end, whereas intense light is observed along the twisted area.

It is known that RPDIV strongly depends not only on humidity but also on temperature [14]-[18]. Kikuchi et al reported that RPDIV decreased with increasing relative humidity at a low temperature, whereas it slightly increased with increasing relative humidity at a high temperature[15]. In order to avoid the change in RPDIV due to these environmental factors, the sample is suspended in a desiccators filled with dry air at 23 ± 3 °C in atmospheric pressure. Characteristics of partial discharge inception probability as a function of the peak to peak value of the applied voltage (V_{pp}) are compared between the various modified inverter surges.

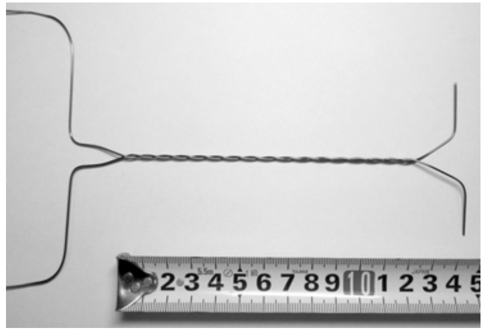

Figure 3. Photograph of twisted pair sample

3. Results and discussion

(1) Effect of polarity reversal

Relationships between V_{pp} and PD inception probability are shown in Figure4 for the very fast oscillated pulses (T_{osc}=100 ns) with and without polarity reversals. Each plot in Figure4 corresponds to mean value for 1000 measurements (10 pulses $\times$ 10cycles $\times$ 10 samples). V_{pp} corresponding to RPDIV is 1940 V for the pulse without polarity reversal, whereas it is 2010V for the pulse with polarity reversal. It should be noted that the voltage across the two wires subjected to the pulse with polarity reversal is V_0, which corresponds to only the half of V_{pp}. On the other hand, the voltage across the wires subjected to the pulse without polairty reversal is $2V_0$. This fact suggests that pre-charging by dc -V_0before the polarity reversal has an effect to enhance the field strength between the two wires, so called space charge effect[5][18]. It is known that surface residual charges produced by the dc bias enhance the field strength across the air gap just after the polarity reversal. The mechanism of the field enhancement by the residual charges on the wire surface can be explained as follows. A sectional view of contact area of the twisted pair subjected to the polarity reversed pulse from $-V_0$ to $+V_0$ and its equivalent circuit are shown in figures 5(a) and 5(b) respectively. During the dc charging by $-V_0$, considerable charges must be produced near the contact point of the two wires and then they spread along the wire surface. Due to the surface charge accumulation, most part of the applied voltage is divided into the two enamel layers before the polarity reversal. When the polarity reversal from $-V_0$ to $+V_0$ occurs at $t = 0$, the voltage $V_g(t)$ across the air gap after $t = 0$ can be expressed as follows.

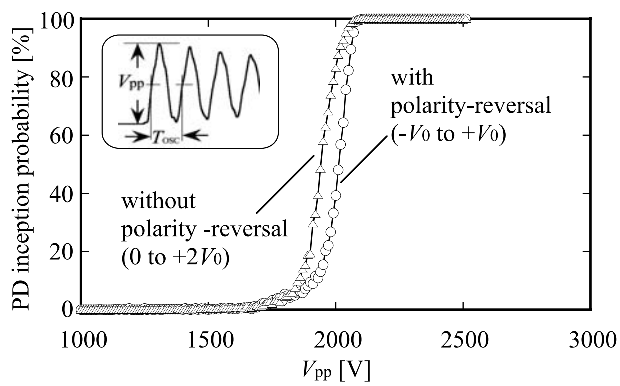

Figure 4. Relationships between peak-to-peak voltage and PD inception probability for the oscillated pulses with and without polarity-reversal.

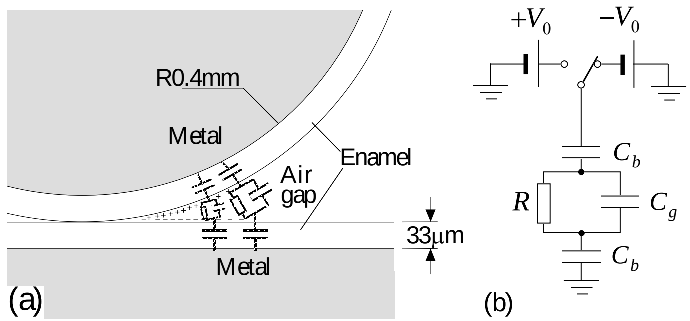

Figure 5. Sectional view of the contact point of the twisted pair sample and corresponding equivalent circuit.

$$V_g(t) = \frac{C_b}{C_g + \frac{C_b}{2}} V_0 \exp\left\{ -\frac{t}{R\left(C_g + \frac{C_b}{2}\right)} \right\} \tag{1}$$

where C_g, C_b and R represent the capacity of the air gap, the capacity of the enamel layer and the resistance along the enamel surface respectively. The derivation of Eq. (1) is described in our previous paper in detail[19].

Eq. (1) indicates that V_g (+0) can be higher than V_0. If C_g is much smaller than C_b, Eq. (1) is approximated as follows.

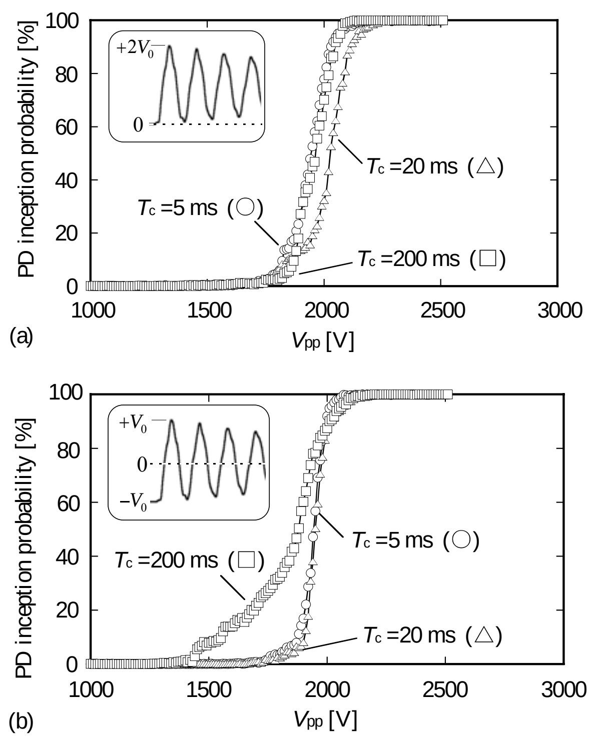

Figure 6. Relationships between peak-to-peak voltage and PD inception probability for dc charging times (T_c, =5, 20 and 200 ms), (a) the oscillated pulse without polarity reversal, (b) the oscillated pulse with polarity-reversal.

$$V_g(t) \approx 2V_0 \exp\left\{-\frac{2t}{RC_b}\right\} \qquad (2)$$

Relationships between V_{pp} and PD inception probability with various pulse repetition rates (pps : pulse per second) are shown in Figure6(a) for the oscillated pulse without polarity reversal and in Figure6(b) for the oscillated pulse with polarity reversal. The dc charging time (T_c), corresponding to the time interval from pulse to pulse, is set to 200 ms by 5 pps repetition and is set to 20 ms by 50 pps repetition. The probability curve for the polarity reversed pulse with T_c=200 ms shows that the partial discharge occurs at lower voltage. This is because the longer charging time is sufficient to produce many surface charges. This fact demonstrates that the surface charges on the enameled wire has an important role for the partial discharge propagation just after the polarity reversal.

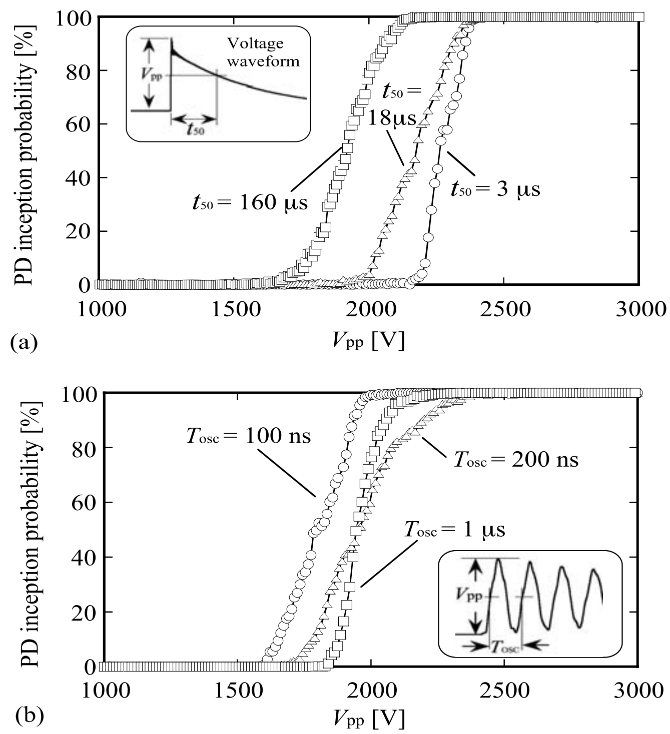

Figure 7. Relationships between peak-to-peak voltage and PD inception probability for (a)impulse-like pulse and for (b) oscillated pulse with polarity reversal.

(2)Effect of pulse width

Relationships between V_{pp} and PD inception probability are shown in figure 7(a) for the impulse-like pulse with various half widths (t_{50}) and shown in figure 7(b) for the polarity-reversed pulse with various oscillation cycles (T_{osc}). RPDIV for the impulse-like pulse is 2270 V for t_{50}=3 μs, 2090 V for t_{50}=18 μs and 1920 V for t_{50}=160 μs respectively. The probability curves in figure 7(a) indicate that RPDIV decreases with increasing the pulse width [11][20]. The reason why RPDIV for the longer pulse is low can be explained as follows. Probability of the initial electron emission per unit time is constant because this phenomenon is based on stochastic mechanism. Therefore, propagation probability of an avalanche produced by the initial electron must be increased with increasing the pulse width so that RPDIV for the longer pulse becomes small. However, RPDIV for the very fast oscillated pulse does not decrease with decreasing the oscillation cycle. It should be noted the very fast oscillated pulse with T_{osc} =100 ns induces the partial discharge at lower voltage though the pulse width is very short as shown in figure 7(b). RPDIV is 1800 V for T_{osc} =100 ns, 1950 V for T_{osc} =200 ns and 1950 V for T_{osc} =1 μs respectively. One of the reason why RPDIV for the very fast oscillation becomes low is probably that the time lag of the discharge initiation increases with increasing the oscillation cycle. The time lag is defined as the time from the front of the polarity reversed voltage pulse to the discharge initiation. We observed the discharge light signal from the photomultiplier on the oscilloscope to measure the time lag. Laue plots of time lag distribution of partial discharge caused by the oscillated pulse with polarity reversal for various V_{pp} are shown in Figure8(a) for T_{osc} =100 ns, in Figure8(b) for T_{osc} =200 ns and in figure 8(c) for T_{osc} =1 μs. These plots indicate that the mean time lag of the partial discharge propagation for T_{osc} =100 ns is shorter than that for T_{osc} =200 ns. It is important point that the voltage across the air gap V_g (t) is up to a maximum value just after the polarity reversal ($t=+0$) and then it decrease exponentially as shown in Eq.(1) and Eq.(2). Therefore, RPDIV for the very fast oscillated pulse depends on the oscillation cycle.

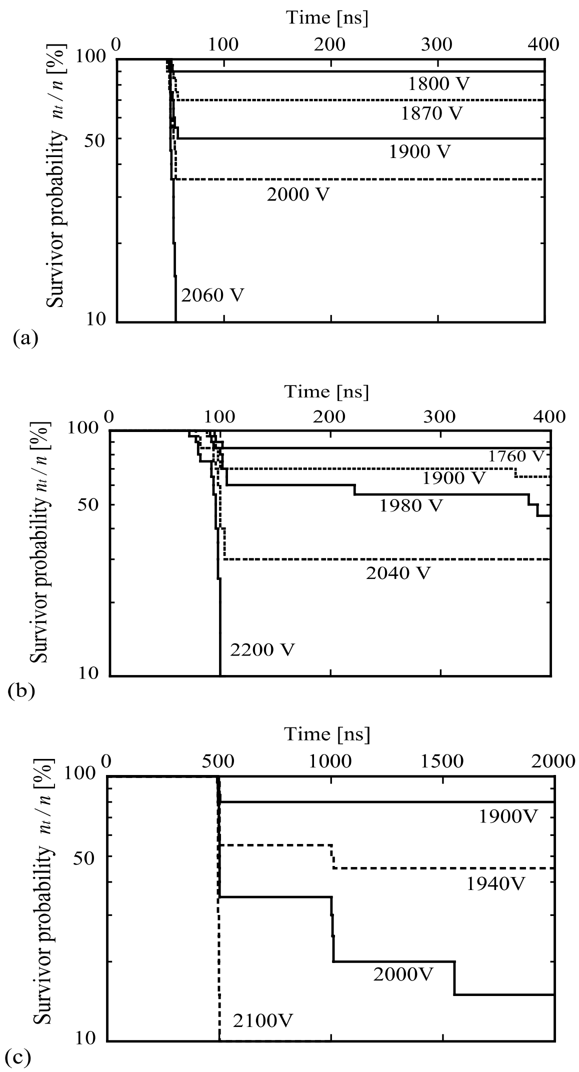

Figure 8. Laue plots of time-lag of the discharge initiation caused by the polarity-reversed pulses for (a) T_{osc} =100 ns, for (b) T_{osc} =200 ns and for (c) T_{osc} =1 μs respectively.

4. Conclusions

Influences of the voltage shape of the modified inverter surges on RPDIV were studied for the twisted enameled wires. In order to obtain PD probability curves as a function of the applied voltage, we made an automatic measurement system. Results were obtained as follows.

The PD inception probability for the oscillated pulse with polarity reversal from $-V_0$ to $+V_0$ was compared with that the pulse without polarity reversal from 0 to $+2V_0$. Voltage across the two enameled wires to cause PD for the pulse with polarity reversal was almost the half of that for the pulse without polarity reversal. This was because the field strength at the air gap between the enameled wires are enhanced by the residual surface charges produced by the dc charging before the polarity reversal.

To examine the influence of pulse width on RPDIV, the impulse-like voltages with various widths were repeatedly applied to the sample. Results showed that RPDIV for the impulse-like voltage strongly depended on the pulse width. RPDIV decreased with increasing the pulse width. To examine the effect of the very fast oscillation of the polarty-reversed pulse on RPDIV, the polarity reversed pulses with various oscillation cycles were repeatedly applied to the sample. RPDIV for the pulse with 100 ns of the oscillation cycle became lower than the other pulses with longer cycles.

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Kazunori Kadowaki was born in Japan on November 22, 1965. He received the B.S., M.S., and Ph.D. degrees in electrical and electronic engineering from Ehime University, Matsuyama, Japan, in 1988, 1990, and 2002, respectively. In 1990, he joined Nitto Denko Corporation. Since 1996, he has been with the Faculty of Engineering, Ehime University, where he is currently Professor with the Graduate School of Science and Engineering. He has been engaged in research on space-charge distribution in solid dielectrics, dc prebreakdown phenomena of liquid/solid composites, treeing degradation diagnosis and pulsed-power application for gas pollution control, and inactivation of microorganisms in water. Dr. Kadowaki is a member of the Institute of Electrical Engineers of Japan and a member of IEEE.

Yujiro Takemura was born in Japan on May 21, 1988. He obtained hid B.Eng and M.Eng in electrical and electronic engineering from Ehime University in 2010 and 2012 respectively. He joined Kansai Electric Power Co. since 2012. During his years in Ehime University, he had been engaged in research about electrical insulation for enameled wires subjected to repetitive inverter surges.

Ryotaro Ozaki was born in Japan in 1976. He received the M.Eng. degree in material engineering from Ehime University in 2002 and the Ph.D. degree in electronic engineering from Osaka University in 2005. He became a research associate at National Defense Academy of Japan in 2005 and has been an associate professor of Ehime University since 2012. From 2008 to 2009, he was a visiting researcher at the University of Texas at Dallas. His research interests are in liquid crystals, functional molecules and polymers, photonic crystals, and electromagnetic analysis.