ESD detection by transient earth voltage

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Abstract. We measured transient earth voltages (TEVs) accompanied with electrostatic discharges (ESDs) to investigate the possibility of ESD detection using the TEV. Clear TEV signals could be observed in spark, brush, and propagating brush discharges even when an ESD event detector failed. Therefore, ESD detection using the TEV may be significantly more effective as an auxiliary monitor, while the TEV signals accompanied with cone discharges could not obviously be detected. In addition, the features of the TEV depend on the type of ESDs; therefore, the TEV could also be used to identify the potential of the occurrence of problems and hazards by ESDs.

1. Introduction
Electrostatic discharges (ESDs) sometimes cause problems and hazards in industry, e.g., malfunction of electronic equipment, damage to electronic devices, and occasional fire or explosion. When a gas discharge occurs between an object and the earth, the earth voltage instantly and transiently varies. Monitoring of the transient earth voltage (TEV), therefore, could be effective to detect discharges and thus assess and prevent such problems and hazards. In electric power plants, partial discharge detection using a set of probes including the TEV, UHF, acoustic emission, and current is used to maintain the equipment \cite{1, 2}. In electronics industry, ESD detection using an electromagnetic wave radiated from ESDs is generally used as a monitor in ESD management; thus, ESD event detectors are commercially provided. However, ESD event detectors sometimes fail because the detection depends on the distance from ESDs. In addition, some investigations regarding explosions during the water-jet washing operations of the oil cargo tanks in very large crude carriers showed that ESD detection using electromagnetic radio signals was reasonably and practically inapplicable \cite{3, 4}. In this paper, we report the results of the measurements of TEVs accompanied with spark, brush, propagating brush, and cone discharges and consider the possibilities for detecting ESD using the TEV.

2. Experimental
We used the same apparatus described in \cite{5}, in which TEV signals accompanied with corona discharges were previously investigated. ESDs except for cone discharges were produced on an earthed copper plate (1 m disc) placed on an insulator of foamed polystyrene, and their TEV signals on the earthed copper plate were observed with an oscilloscope. In addition, electromagnetic wave accompanied with the discharges were also examined with an ESD event...
Spark discharges, as shown in figure 1(a), were produced at a gap (with separation of 0.3, 0.6, or 0.9 mm) between the copper plate and a metal sphere (30 mm in diameter) connected to a capacitor (7, 20, or 40 pF) charged by a DC high voltage of a few kV via a resistance of 60 GΩ. Thus, the spark discharges occur repeatedly when the electric field in the gap is over the breakdown field for air. TEV signals accompanied with spark discharges with different capacitors and gap separations were examined.

Brush and propagating brush discharges were produced on a charged insulating sheet (PTFE


Figure 3. Typical TEV signals accompanied with (a) a spark discharge with a capacitor of 7 pF and a gap separation of 0.3 mm, (b) a brush discharge with a tribo-charged PTFE sheet, (c) a propagating brush discharge with a corona-charged PTFE sheet, and (d) a brush discharge that occurs during peeling of a tribo-charged polyester sheet from the earthed plate.

of 0.2 mm in thickness or polyester of 0.1 mm) placed on the earthed copper plate when an earthed sphere of 30 mm in diameter approaches the sheet, as shown in figure 1(b). Here, the sheets were charged by tribo-charging with an industrial-use tissue paper for brush discharges and by corona charging of -20 kV for propagating brush discharges.

In addition to the ordinary brush discharge above, TEV signals accompanied with brush discharges that took place when a tribo-charged sheet peeled from the earthed copper plate were examined.

TEV signals accompanied with cone discharges that occurred inside an earthed tank during a circulated pneumatic transport of PP pellets (approximately 3 mm in diameter) were examined with the use of the same equipment as in [6, 7], as shown in figure 2. The TEV signals, including those through a capacitive probe using a PVC sheet of 0.3 mm in thickness, were measured at the outside wall of the earthed tank. The light emitted from cone discharges that occurred on the heap of the pellets inside the tank was also observed with a photomultiplier connected to an optical fibre, where the one-side tip of the optical fibre was placed near the heap inside of the tank to introduce the light emitted from the cone discharge. Here, the optical fibre has directivity so that the light emitted from only cone discharges to which the fibre is directed is detectable. The electromagnetic radio signals accompanied with cone discharges were also measured at the outside of a window mounted on the tank by using an output signal of a high-frequency amplifier of the ESD event detector.

3. Results and discussion
Typical TEV signals accompanied with different types of discharges are shown in figure 3. All the signals have an underdamped transient response that is significantly dependent on the type of discharges. Since the TEV is a resultant phenomenon in which the discharge current flows to
the earth, representing the discharge as an \( RLC \) series circuit, the TEV signal, \( V_{TEV} \), may be expressed by

\[
V_{TEV}(t) = Ae^{-\alpha t} \sin \omega_d t,
\]

using attenuation \( \alpha \) to describe the envelope of the decayed oscillation, and damped resonance frequency \( \omega_d \),

\[
\alpha = \frac{R}{2L} \text{ and } \omega_d = \omega_0 \sqrt{1 - \zeta^2}
\]

where \( \omega_0 = \frac{1}{\sqrt{LC}} \) and \( \zeta = \frac{\alpha}{\omega_0} = \frac{R}{2} \sqrt{\frac{C}{L}} \). Here, it is likely that \( R \) corresponds to the resistance of discharge; \( L \) represents the inductance of cables for earthing; and \( C \) describes the capacitance of the discharge gap for spark discharges and that of an insulating sheet used for brush and propagating brush discharges. Coefficient \( A \) is related to the potential resulting from charge accumulated on an object and the charge itself before ESDs. Furthermore, the time integration of \( V_{TEV} \) may be related to charge transferred by a discharge. Thus, we expect that the TEV can provide information of discharges occurred. Such equivalent circuit analyses on the underdamped currents observed in spark, brush and propagating brush discharges were conducted also in [8, 9].

A typical TEV signal of spark discharges is shown in figure 3(a). The signals were underdamped responses having relatively higher peaks and a long envelope. The feature of the TEV signals of spark discharges depends on the gap separation. Their amplitude, which has a maximum peak of several hundreds of volts, increases as the separation increases because the onset voltage of spark discharge increases with increasing the gap separation; an increase from \(~400\) to \(~900\) V was observed in the gap separation from 0.3 to 0.9 mm. In addition, the amplitude depends slightly on the capacitor because the charge accumulated in the capacitor is higher with a higher capacitor at the same onset voltage. These results indicate that a TEV signal seems to provide information regarding discharge energy as well as the onset voltage. Here, the onset voltages at different separations are lower than the voltage for charging of 2.0 kV, which was the minimum voltage examined in all separations. Furthermore, the amplitude of the TEV signals of spark discharges was the highest in these measurements in all types of discharges; thus, ESD detection using the TEV appears to be useful because the result implies the fact that spark discharge is most hazardous and incendive in terms of energy density in time and space. However, it should be noted that, if the surface charge on insulating sheets is much higher, higher amplitude of the peaks may be expected for propagating brush discharges. A clear influence of the capacitor and gap separation on the duration of the TEV, however, could not be observed. This denotes that the resistances of spark discharges describing attenuation \( \alpha \) are comparable under the conditions investigated.

The TEV accompanied with brush discharges could be detected, as shown in figure 3(b). The duration of the signals was much shorter, resulting in fewer peaks; in addition, the amplitude of the peaks was much lower than that of other types of discharges. The results of these TEV signals are likely to represent lower discharge energies and incendivity characterising brush discharges.

The TEV signals of propagating brush discharges are very different from others, in which a clearly resonant (underdamped) response having relatively higher peaks and a longer envelope was observed, as shown in figure 3(c). The underdamped resonant frequency, \( \omega_d \), depends slightly on the sheet materials used. In addition, the amplitude of the maximum peak of the polyester sheet (\(~100\) V) was higher than that of PTFE (\(~40\) V) because the surface potential of a corona-charged polyester sheet (\(-6\) kV) was larger than that of the PTFE sheet (\(-3.5\) kV). These results also suggest that the TEV includes information of propagating brush discharges that are more hazardous and incendive.

TEV signals accompanied with discharges occurred when charged sheets peeling from an earthed plate were similar to those of the brush discharge described above, as shown in figure 3(d). In addition, polarity dependency could be observed, in which the polarity of the first peak
depended on the polarity of charged sheets: for example, polyester is positively tribo-charged; then, a negative first peak was observed, and negatively tribo-charged PTFE yielded a positive first peak. This indicates that the TEV could also estimate the polarity of the charged object that is discharged.

Consequently, we found that the TEV signals accompanied with spark, brush, and propagating brush discharges could be clearly observed because the discharge currents flow to the earth in these measurements. Nevertheless, an ESD event detector frequently failed to detect discharges. Therefore, ESD detection using the TEV may be significantly more effective as an auxiliary monitor when discharges occur to earthed objects; in addition, the measurement technique is very easy. Furthermore, since the features of TEV signals, in particular, their amplitude and duration, depend on the properties of discharges, the use of TEV enables not only ESD detection but also identification of the type of discharge as well as the potential for problems and hazards by the ESDs. Such identification is significantly important for reliable assessment because most ESDs whose energies are low, such as corona discharges, are not hazardous and can maintain charges at a safe level in many situations; on the other hand, ESDs are unavoidable phenomena which can lead to problems and hazards.

However, the detection of cone discharges using TEV failed. A set of measured signals of

![Figure 4](image-url)
light emission, TEV, TEV with a capacitive probe, and electromagnetic wave accompanied with a cone discharge is shown in figure 4. Only the light emission from cone discharges could be clearly measured; however, the TEVs and electromagnetic radio signals synchronised with the light emission could not be detected. Furthermore, the TEV signals have high-level periodic noises coming from the controllers’ clocks used in the pneumatic transport facility, where such noises were observed even without pellet transport. No observation of TEV signals accompanied with cone discharges may occur because most of the current of the cone discharge does not flow to the earth and the discharge is enclosed within the earthed tank as follows: when a cone discharge occurred, the same number of electrons and positive ions are produced; then, most positive ions move toward the heap of negatively charged pellets, and the electrons, including negative ions produced by attachment by these electrons, may move toward the earthed tank wall. During these processes, the total charge in the tank as well as the induced charge on the earthed tank wall does not change, resulting in no response in the TEV signal unless most electrons, including the negative ions, reach the wall because of collisions with a number of pellets existing in space until reaching the wall. This interpretation is similar to the principle of a Faraday cup in that the charges separated or discharged inside the cup cannot be measured. Further investigation, involving noise reduction with a band-path filter and a high-frequency amplifier adapted to TEV signals, will be required to verify the interpretation.

4. Conclusions
In conclusion, we found that the TEV can be used to detect ESDs when ESDs occur to earthed objects; in addition, the TEV could help identify potential problems and hazards on the basis of the detected ESDs. In this regards, ESD detection using TEV is viable and effective as an auxiliary measure when other methods fail. For cone discharge detection using TEV, however, further investigation, including noise reduction, will be required.

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