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Performance of Backfill Material for Grounding System under High Voltage Condition

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Abstract. Grounding (or earthing) play the main role to in order to protect electrical equipment, building and life from lightning, switching and earth fault occurrences. A good grounding system must be able to dissipated this unwanted charge in very fast time and this can be achieved by reducing the grounding resistance. Introduction to backfill material to be filled into grounding pit is widely implemented in order to lowering the resistance of grounding system. This paper investigates the performance of marconite, cement and sand as part of backfill materials for ufer type grounding system under alternating high voltage and impulse voltage condition. The purpose of high impulse voltage experiments is to determine the performance of above said materials under transient condition while the alternating high voltage experiment to observed the behaviour backfill material under leakage or fault current occurrence. The findings reveal that performance of grounding system may significantly change from the expected result at design stages.

1. Introduction

Electrical grounding systems are developed to dissipate unwanted electrical charges due to lightning, switching and earth fault as fast as possible. These charges usually dissipated through the earth. Therefore, the analogy of ideal soil can be said to be equal of a “natural capacitor” that has unlimited charging capacity and zero discharging capability. In designed grounding systems to fulfil the requirement for lightning protection, considerably large amount of lightning-brought charge has to be dispersed by the grounding system within micro-second time scale [1]. When lightning occurs, it will generate overvoltage and overcurrent which is dangerous to people, buildings and other structures. Lightning strikes can damage any structure and its contents, and can incur failure of equipment especially electrical and electronic systems [2]. Soil have different resistivity depends on its geographical location, chemical content and physical properties [3]. Soil resistivity is the main factor that influencing the resistance of grounding system. In other words, soil with high grounding impedance is less efficient to dissipates transient charge into the soil mass comparing to soil with low grounding resistance. Introduction to backfill material was spread the research in grounding system performance enhancement. The key rule to determine the suitability of any backfill material is it must have conductance properties, where the larger amount of it then then will decreasing the total resistance. Researchers have started to explore the various backfill materials to be used in order to reducing grounding resistance since the past several decades. Traditional grounding system using salt and coal as the backfill material but the deterioration of the performance due to water flow caused by rain and made researchers to find new material as alternative. Some backfill material such as bentonite and marconite were introduced as the backfill material with the lower resistance characteristic and can last more longer than others material. Most study focusses the effectiveness of backfill materials in decreasing grounding resistance for many years with assumption that the lower resistance will results the good performance of grounding system itself. The development of more accessible impulse generator then easier the study on behaviour of backfill materials to control the performance of grounding system under transient signal condition. Unfortunately, there is still no extensive research on the behaviour of backfill material under high voltage (HV) condition although the significance of understanding of them is realised.

2. Methodology

Grounding is the process of connecting any metallic object electrically to the ground by the way of a grounding electrode system. The grounding electrodes should be tested according National Electric Code (NEC) to ensure that the resistance to ground are below 25 Ω [4]. In Malaysia, grounding resistance of residential house and commercial building should below than 10 Ω according to Energy Commission of Malaysia standard [5]. There have several types of grounding system existing such as driven rod, grounding plate, mesh grid, concrete encased electrode, ufer/building foundation and electrolytic electrode. Ufer grounding or building foundations provides direct contact the of concrete with the earth which the diameter of rebar is at least 1.27 cm and that there is a direct metallic connection from the service ground to the rebar embedded inside the concrete [6]. This concept is based on the conductivity of the concrete and the large surface area. This will usually provide a grounding system that can handle very high current loads. The primary drawback occurs during fault conditions where if the fault current is too great compared with the area of the rebar system, the moisture in the concrete heats up and rapidly expands thus cracking the surrounding concrete and threatening the integrity of the building foundation [7].

Ufer grounding system is consisting of rebar as the conductor and concrete as the main component. Concrete mixture consist of cement, sand, gravel, water and categorized into several grade depending on the required mechanical compressive strength. This research only focusing to investigates the performance of selected raw material in concrete consist of marconite as the backfill material, cement and sand as the concrete components respectively. Electrical properties of concrete are mostly determined by the characteristic of cement. A typical concrete consists of three main phases namely the mortar phase, aggregate phase and the interfacial transition zone phase [8]. Mortar is the hydrated cement (transformation of cement from powder to paste after mixed with water), aggregate is composition of sand and gravel while the boundary of mortar and aggregate namely interfacial transition zone.

Marconite is a granular material made by electrically conductive carbon that can be mixed with ordinary cement and water to form a conductive concrete. In grounding system development, it often mixed with cement in suitable portion before poured into grounding pit. The resistivity of marconite is of the order of 0.001 ohm-m and even when mixed with cement, its resistivity is still only 0.1 ohm-m, significantly lower than either normal concrete (sand and cement) or Bentonite. The process to characterize and quantify the chemical elements containing inside marconite sample was performed using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) [9]. There are traces of Carbon, Molybdenum and Sulphur ions in the sample. The higher percentage of carbon explains the higher conductivity of marconite. Hence, this result validates the significant of marconite usage for the further step of this research to be used as a grounding enhancement material (GEM).

Cement is mainly used to binding all components in concrete preparation. Ordinary Portland Cement (OPC) was chosen to be tested regarding it's characteristic with a premium high quality cement and developed as a superior performance product without any additive material. This type of cement usually used in in Malaysia due its ability to provides an effective solution for construction environment and enhance construction site productivity. Chemical compositions of OPC mainly consists of CaO, SiO2 and Al2O3 elements [10]. Lastly, sand is the last raw material to be tested in this experiment. Fine river sand with the maximum granular size of 1 mm was selected. Any small gravel mixed greater than the maximum size was removed using filter mesh. The sand was dried under sunlight for ten days before carry out the experiment to ensure there has no moisture content inside it that will affected the experiment results. Aggregate is not including in this testing due to its high resistivity characteristic and only acts to strengthen the concrete cast. Thus, study on the behaviour of all of this raw material under HV impulse condition is really justified [11].

2.1. High impulse voltage testing
The first experiment is to applied the high impulse voltage output to the specimen. A single stage marx generator, Haefely Test kit was used was used in this experiment. This high voltage impulse test kit capable to producing high impulse voltage up to 140 kV with time characteristic of 1.2/50 μs. A 50 cm copper coated grounding rod act as the high voltage rod to inject the generated impulse voltage to the material under test. The material to be tested which are marconite, cement and sand are placed inside a cylindrical stainless steel container with dimension of 0.06 m depth and 0.2 m internal diameter. The container is located on a stand with suitable height and is connected to a grounded copper plate in the lab. The output waveform was captured and displayed by a Teledyne Lecroy HDO6054A High Definition Oscilloscope. This oscilloscope capable to captured a signal up to 500 Mhz. Temperature and relative humidity level and in the lab was recorded which are measured by two different model of RH-meters and then the reading both of them were averaged. Figure 1 shows experimental setup that was arranged for high impulse voltage testing and the configuration setup in this testing is shown in Figure 2.

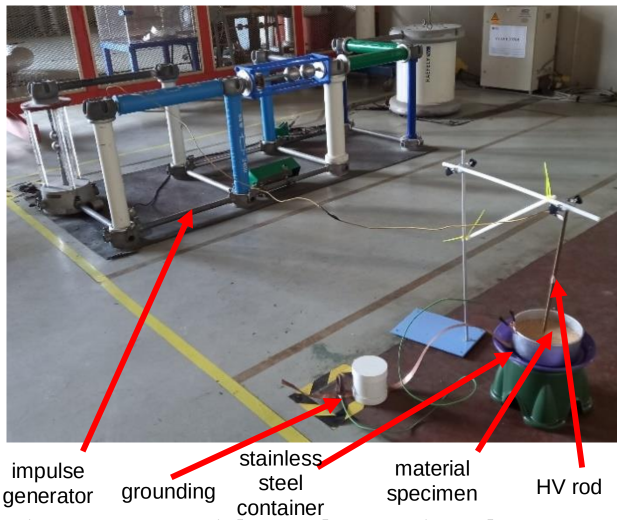

Figure 1. High voltage impulse test experimental setup.

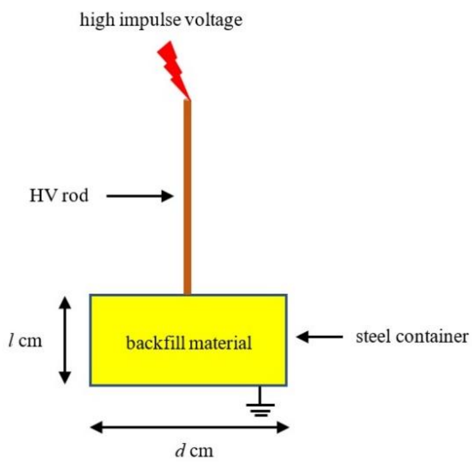

Figure 2. High voltage impulse test configuration setup.

Standard lightning impulse voltage with time characteristic of 1.2/50 μs and positive polarity were planned to be applied by the impulse generator to a 50 mm depth of backfill material. The reason for the chosen method regarding to the most previous work has been done on positive polarity. The 50 mm gap was then filled starting with marconite before high impulse voltage applied on it and the experiment was repeated for others backfill material. The position of the high voltage rod is adjusted so that the tip of it have a gap of 5 cm and just located at the centre of the backfill material surface. This gap was maintained for the testing of next materials.

2.2. Alternating high voltage testing

The second experiment is to applied the Alternating High Voltage (AHV) output with the frequency of 50 Hz into the backfill materials. This experiment was using the same type generator but with no impulse component such as sphere gap module. The term Alternating High Voltage is different comparing to High Voltage Alternating Current (HVAC). In this experiment, high voltage with alternating polarity is generated and applied to the specimen and not alternating polarity current supplied by high voltage source. In fact, the output to be analysed from this experiment are only voltage waveforms while current waveforms are not analysed in this study. This experiment was done by filling a round shape container with the diameter of 40 cm and 10 cm height with the backfill materials to be tested up to 8 cm as shown in Figure 3 and Figure 4. A HV rod with 1.2 cm diameter and 100 cm length was used transfer the generated alternating high voltage to the specimen under test. The HV rod was carefully adjusted so that it just touches the surface of backfill material at the centre. Then, alternating high voltage generated by impulse generator was applied to the specimens starting from minimum value and slowly increased until breakdown occurs. Relative humidity, atmospheric pressure and temperature in the lab was also recorded on 86%, 1010 hPa and 28.7°C respectively.

After that, the experiment was carry out with cement and sand to determine the temperature corresponding to the applied voltage until the breakdown reached. Marconite shows very low breakdown voltage where the main switch of the generator was trip every time the the AHV applied. This happened due to its very high conductivity characteristic. The corresponding temperature at variety applied voltage on the surface of the materials was measured using Testo 875 thermal imager camera. AHV was applied constantly for 10 seconds at the material. The laser pointer of the imager was pointed to the spot at the HV rod that made contact with the material surface. The generator was automatically tripped once breakdown occurred and the corresponding voltage at the breakdown was noted down. Any physical changes to the tested materials such as burning effect, smokes produced and fulgurite formed were also observed.

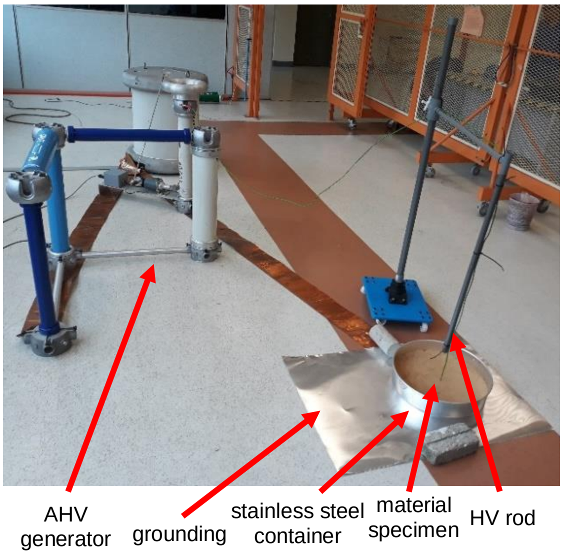

Figure 3. Alternating high voltage test.

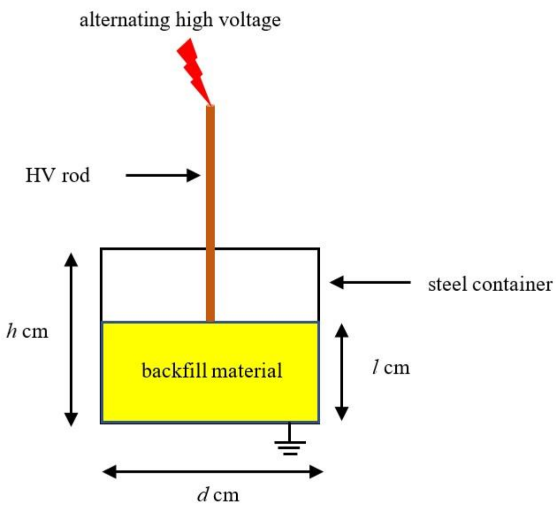

Figure 4. Configuration setup of alternating high voltage test.

3. Result and Discussion

3.1. Performance under high impulse voltage test

The high impulse voltage experimental setup that was arranged in lab generates waveform which is approximately equal to natural lightning flashes although literature have shown that actual lightning is not regular as generated in lab. The tolerance allowed for front time, T1 is ±30%, tail time, T2 is ±20% and peak voltage is ±3%. Standard lightning voltage waveform generated by impulse voltage generator is shown in Figure 5 with T1 is 1.252 μs, T2 is 45.47 μs and peak value up to 30 kV. These value was fulfilling for a standard lightning impulse with 1.2 μs and 50 μs time characteristics. The value of peak voltage can be set by adjusting the spark gap to suitable distance and this proses was repeated for several time until the desired value obtained. Initially, the gap can be adjusted automatically by switch mechanism in control room but due to the faulty switch then the gap was adjusted manually. The breakdown characteristic of air illustrated in Figure 6. This characteristic is subjected to 60 kV impulse voltage. The front time is greater than standard impulse waveform but the tail time is much lower and there have oscillation due to greater impedance of air comparing to impedance of ground. Figure 7 shows the breakdown characteristic of marconite when injected with 30 kV impulse voltage. Regarding to the waveform captured, the voltage cuts off at 16 kV instead of close to 30 kV. There is under-damped oscillation that explain the impedance of marconite is very lower than air.

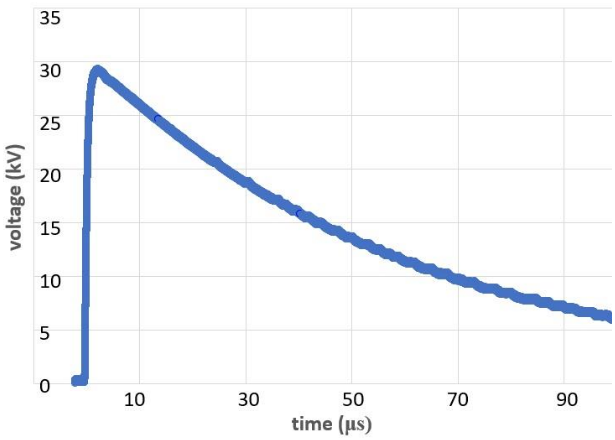

Figure 5. Standard impulse voltage waveform.

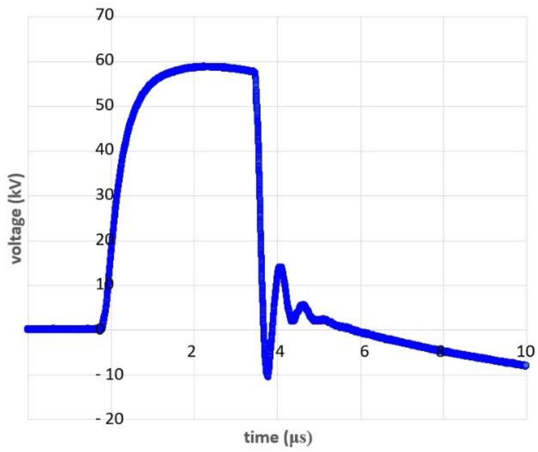

Figure 6. Breakdown characteristic of air.

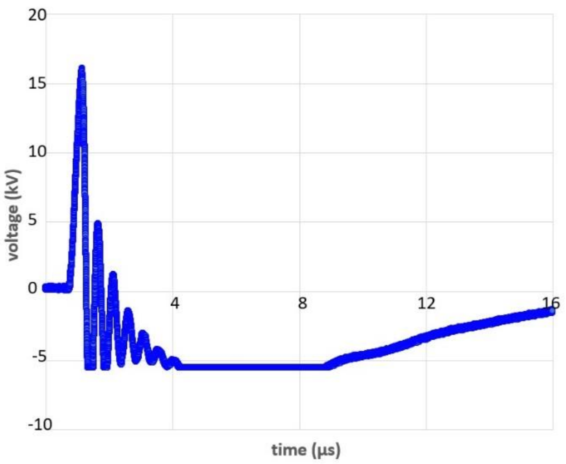

Figure 7. Breakdown characteristic of marconite.

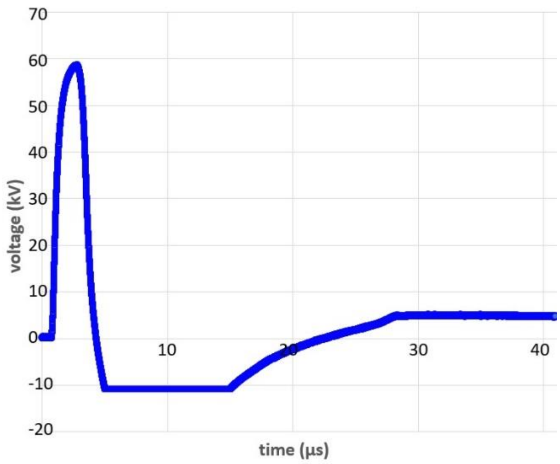

Figure 8. Breakdown characteristic of cement.

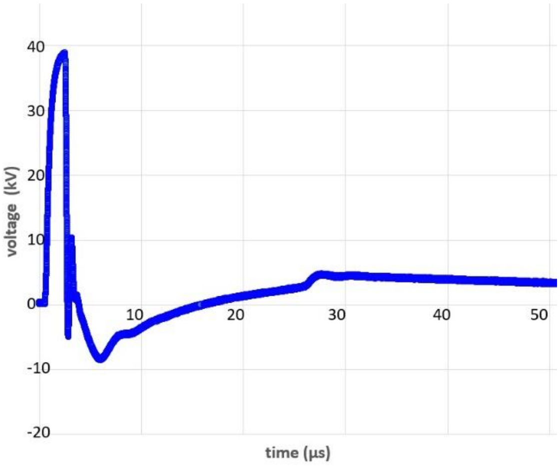

Figure 9. Breakdown characteristic of sand.

The breakdown characteristic of cement is shown in Figure 8 when subjected to impulse voltage of 60 kV. There is no oscillation observed with the breakdown voltage was cut off to 57.57 kV and time to breakdown of 1.11 μs. Figure 9 shows the breakdown characteristic of sand when subjected to 40 kV impulse voltage. There is clear difference of breakdown characteristic between marconite, sand and cement under impulse voltage condition mainly in oscillation pattern. The reason of this situation happen as the fact that sand and marconite is less compact and coarser compared to cement. Hence, the density of air voids should be greater in sand and marconite respectively. Although marconite is also less compact as sand but it is much coarser which caused more oscillation and lower breakdown voltage due to high conductivity properties.

Breakdown characteristics for each material is tabulated in Table 1 with 20 shots of impulse were fired to determine the breakdown voltage and time to breakdown. The experiment was conducted in air conditioned lab that provides the suitable temperature and humidity for the testing due to fluctuating nature humidity and temperature of the atmospheric condition in Malaysia which is a tropical country. The ambient temperature in the laboratory ranged from 28.2°C to 31°C and relative humidity recorded from 73 – 75%. Surrounding pressure was recorded as 1006 hPa throughout the experiment. The testing found that cement has the highest breakdown strength followed by others material although testing has been repeated for several time but the result is the same. Low breakdown voltage is a good property of backfill materials from the perspective of grounding system performance. Backfill material with low breakdown voltage indicates that they are relatively easier to undergo breakdown or ionisation thus lowering their resistivity during lightning strike.

Table 1. Time to breakdown and breakdown voltage.

Material	Time to breakdown (μs)	Average breakdown voltage (kV)
Marconite	0.341	15.92
Sand	1.12	38.4
Cement	1.11	59.55

3.2. Performance under alternating high voltage test

This experiment was conducted to investigates the behaviour of backfill material used in grounding system that took inspiration from the occurrence of leakage current or ground fault. The generator be able to produce alternating high voltage up to 100 kV. Figure 10 illustrated the temperature variation of cement when being subjected to alternating high voltage. The starting applied voltage of 4.7 kV was recorded on 28.3 °C and the temperature was rapidly increased to 58.6 °C at 5.2 kV before slowly decreased until the generator switch tripped on 17.51 kV at 33.7 °C. Temperature variation characteristic of sand as appears in Figure 11. Unlike cement characteristic, sand shows the shape almost similar to hyperbolic function. The initial applied voltage was recorded on 1.5 kV at 26.7 °C and slowly increased until reached to 7 kV before the temperature increased rapidly to 129 °C when it breakdown at 10.54 kV.

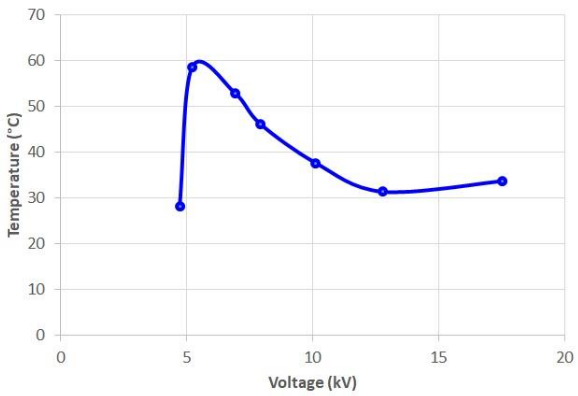

Figure 10. Temperature corresponding to applied alternating high voltage on cement.

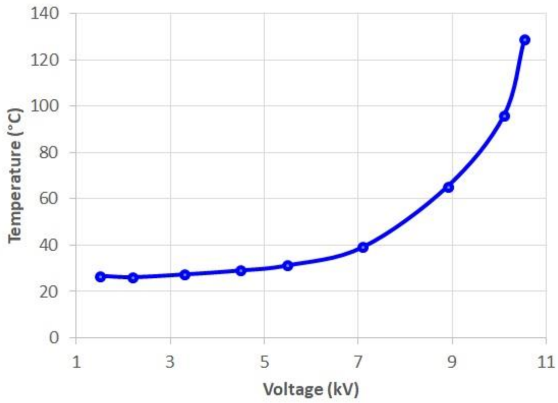

Figure 11. Temperature corresponding to applied alternating high voltage to sand.

Fulgurites formation is developed from the material is exposed to high temperature condition. In natural phenomena, fulgurites formation will be founded after the event of lightning strikes in the area covered with sand like beach. Fulgurites formation was observed only on sand after this experiment as shown in Figure 12. and no fulgurites formation found on cement and marconite. Under impulse conditions, no fulgurites formation observed on backfill materials and this believed due to the very short duration of low amplitude current impulse applied to the material. The variation temperature corresponding to applied voltage was measured using thermal imager as shown in Figure 13.

Figure 12. Fulgurite formation observed on sand after alternating high voltage testing.

Figure 13. Temperature variation measurements.

4. Conclusion

The experiment to determine the behaviour of various backfill materials under high voltage conditions were successfully carried out. These material has been tested under high impulse voltage and alternating high voltage and the results obtained is very useful in development of grounding system. The findings of this research can be summarized that the breakdown voltage for marconite is the lowest of the materials which suggests that it will give the lowest ground potential rise when implemented in real application as backfill material to enhance the performance of grounding system. Next, alternating high voltage breakdown strength of marconite is less than cement and sand. The work of this research thus suggests that marconite is a good backfill material among the selected specimens. High impulse voltage testing is recommended for future work of moistened cement and sand. Then, negative polarity impulse testing on backfill material should be conducted to compare and the evaluate the behaviour of them with the result obtained from this research. Lastly, it is suggested to testing the backfill material using high impulse current to investigates their performance in further research.

5. Acknowledgement

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