Lightning Induced Damage in Floor Heating Cables

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***Abstract*— Modern day electric floor heating cables can now be found under tiles and carpet, in a cement screed or within the concrete base of a floor. Unfortunately, increasing extreme weather events and their associated thunderstorms are having a noticeable impact on electric floor heating installations in Australia. There are patterns of failures emerging that implicate lightning induced mechanisms because these patterns often differ from those found on AC mains distribution systems. This paper describes the key features of the main types of floor heating systems installed in Australia and then presents examples of damage, most likely due to lightning because of corroborating evidence, that have been collated over many years. Suggestions for the mechanisms that may be at play are made along with possible solutions being investigated for mitigating this increasing and costly problem.**

***Index Terms*—earth potential rise, floor heating, lightning, surges, surge protection.**

I. INTRODUCTION

Prior to Covid, electric floor heating sales in Australia had increased 15-20% per annum. There are now over 7 importers, along with internet sales, from manufacturers all around the world. Utilisation of the thermal mass of a concrete floor, for storing excess power from a rooftop solar photovoltaic system, has also contributed to increased sales. An infrared photo of a typical installation is shown in Figure 1.

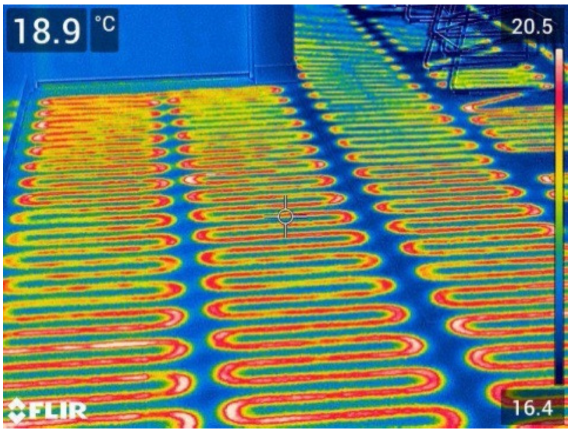

Figure 1. Infrared camera photo of a floor heating mat installation.

II. FLOOR HEATING TYPES

There are two main forms of floor heating: Electric and Hydronic. Both systems are installed for space heating in Australia. There is also a "self-regulating heat trace cable" which is mostly used for temperature control, frost protection, and de-icing. These cables are in lower numbers and no lightning induced failures have been reported in these systems.

A. Hydronic Heating

This system consists of a series of plastic pipes embedded within the floor with hot/cold water circulated from a remote source. It is not directly affected by lightning.

B. Electric Floor Heating Cables

These cables have a coaxial style of construction with one or two insulated active (live) conductors surrounded by a protective earth screen. The earth screen is covered with an impact-resistant thermoplastic insulation. The active (A) conductors are insulated with a high temperature thermoplastic insulation and, more commonly nowadays, with a Teflon type of insulation. The conductors may be made of copper or a combination of nickel, chromium, and copper. Due to the competiveness of the industry, manufacturers have been reluctant to divulge information on their specific conductor or insulation materials. All floor heating cables have non-heating "Cold Tails" which connect the power supply to the actual floor heating cable embedded within the floor. These are mostly two or three core flexible cables.

The "double ended" (standard coaxial) cables have a connection to the 230/240 V AC power supply, and the earth, at both the supply and return ends. It is now more common for "single ended" floor heating cables to be installed. These cables have two parallel heating wires that are joined at the end of the cable and an earth screen with an aluminum foil. This arrangement allows for simpler connections to the 240 V AC power supply at the supply end, allowing a faster and easier installation. There is also a single ended, screened and neutral screened cable and a "mineral insulated metal screened" (MIMS) cable available. All floor heating cable joins are double insulated and sealed via glue lined shrink tubing.

The cables are of various lengths, diameters, internal capacitance, and resistance per linear metre. They are generally grouped according to installed location and heat output per linear metre, as shown in Table I.

TABLE I. COMMON TYPES OF FLOOR HEATING CABLES.

Location	Output (W/m)	Spacing (mm)	Installation Depth (mm)
In-Slab	30	200	50-150
In-Screed	15-20	75-120	20-75
Under Tile	10-12	50-75	In Glue – 25
Under Tile Mat	10-12	Fixed	In Glue

The cables are laid out in loops, depending on the recommended spacing, and mostly embedded in cement or a cement-based screed. The Under Tile Mat is a variation of the standard layout. The heating cable is attached to an open weave mat in a series of 450 mm cable loops. The mat is rolled out across the floor and the matting is then cut to allow the cable to continue. This "cut and turn" continues across the floor. Matts are installed over sheeting floors with no adjacent earthed floor. Due to this, upstairs bathrooms are rarely found to have failed due to lightning. When found, it has appeared the earth screen has been too close to the A conductors, allowing lightning to arc across the small gap. There is often a wax present within these failed junctions.

When electric floor heating cables are installed, and the work is complete, the cables are firmly embedded within the floor and should never fail. However, there are numerous trades, and others, coming and going on the site and there is a low-level risk of damage. Cable failure numbers are relatively low and mostly they have been found to be due to impact damage. When located and repaired they operate as designed. There have been instances where cables have operated for several years and then failed following a nearby lightning strike. Previous low level impact damage to the cable has also been found at the point, or points, of failure.

III. LIGHTNING INDUCED CABLE FAILURES

Severe lightning storms are common in Australia, and as droughts and dry periods continue the number of recorded floor heating cable failures has increased. When nearing the end of the Australian millennium drought (1997-2009), failures implicating lightning were approaching one per month across Australia. When the rains came, failure numbers dropped noticeably. There have since been several droughts, with following rains, and similar numbers were observed. Severe storms near Adelaide during the winter of 2020 showed 11 out of the 21 cables tested had failed due to lightning. This failure rate was across several different brands of cables.

Early observations of lightning induced failures were mostly on MIMS cables (double-ended) installed within a concrete floor. These were the most common floor heating cables installed prior to thermoplastic cables taking over the market. The Cold Tail Junctions (CTJ), joining the non-heating supply section of the cable to the heating element located in the floor, would fail. This was mainly due to the construction of the MIMS cable and the relatively short distance for the high voltage to arc within. It was also noted that if the lightning strike was during the summer months, when the Active of the power supply was normally disconnected, the failure was mostly at the permanently connected Neutral CTJ. There was often a further breakdown of the cable at approximately ¼ to ⅓ of the total cable length from the failed CTJ. If the lightning strike was during winter, it was then found that both CTJs had failed and the ¼ to ⅓ distance to the additional breakdown could be at either end of the cable. At this breakdown point, the outer plastic insulation of the MIMS cable would be blackened with a rough surface texture due to overheating. If the lightning strike was extremely close, the copper tube earth screen could be partially melted, and the outer plastic insulation reduced to carbon. A thermoplastic cable will show similar patterns of failure to the MIMS cable, with other points of failure also often at ¼ to ⅓ the length of the cable. It should be noted that where in one case, a tree had fallen across the 11 kV aerials in the street, and onto a house. The 11 kV introduced into the floor heating cable produced a very different and noticeable failure to those found following a known lightning strike.

When a floor heating system is turned "on" at the start of winter, and one or more cables fail to operate, lightning could be the cause. The system may have operated successfully at 240 V for over 10 years. When the damage is located in a twin active conductor cable (single ended), there is often a noticeable colour difference in the two internal heating wires, as shown in Figure 2. One of the pair will show signs of overheating of both the "Teflon" insulation and the copper conductor. As both conductors are of the same resistance, length and insulation they would be the same colour. When removing the Teflon, to further test the cable, the copper conductor will break down and disintegrate. This conductor is usually found to be connected to the Neutral of the supply. It is suspected that the Multiple Earth Neutral (MEN) connection, along with the standard 6 mm^2 main earth conductor, cannot fully divert the incoming short-duration, high-voltage, high-current transient. A "weak spot" in the cable, due to minor impact damage, will allow lightning to pass from the Active conductor to the Earth Screen and to the surrounding earthed floor.

Figure 2. Colour difference after damage to heating wires.

As an example, a lightning strike was reported to have severely damaged a Main Distribution Board (MDB) and an attached standby generator. The MDB supplied a fruit packaging plant and a separate domestic residence. Two single-ended, 30 W/m, in-slab heating cables in the residence failed along with a 20 W/m upstairs bathroom single-ended floor heating cable. The upstairs bathroom in-screed cable failed at approximately 8% of its length from the end junction. The point of failure was at a horseshoe shaped loop in the cable which was blackened and burnt. The blackening only extended a short distance either side of the loop with the remainder of the cable testing OK. On the ground floor, there were three identical in-slab 125 m cables installed within a large area. All three cable connections to the supply were at the same location. Initial testing showed both cables had failed at the end junctions. The third cable tested OK.

When the end junctions were located, and the concrete removed, there were signs of arcing from the end of the junction to the metal reinforcing mesh, as shown in Figure 3. Analysis of the junctions showed both to be well constructed with a crimp lug and two layers of glue lined shrink tubing. The cable earth screen was well clear of the crimp connection and did not show signs of arcing. There was wax present within the earth screens and one of the two active conductors showed discolouration on both cables. The failed junctions were replaced, the cables fully tested and all three operated as designed. Two years later, it was advised that the third cable had failed following another known nearby lightning strike. There was no other electrical equipment damage reported at this time. A similar end junction failure, with arcing to the metal reinforcing mesh, was found. The cable was repaired, tested and operated OK. Other instances of cable failures, following a known lightning strike have been recorded, but only on cables of 125 m or 150 m length. Shorter lengths of cables have been installed in larger numbers with lower numbers of junction failures recorded as due to lightning.

Figure 3. End junction failure.

IV. LIGHTNING PROTECTION

Lightning protection in Australia is covered by AS 1768 [1]. While lightning storms are common in Australia, Surge Protection Devices (SPDs) are not often found in domestic housing. When found, they are most likely to be a basic 20 kA MOV device mounted within the main electrical distribution board. Lightning protection devices rely on the MEN connection and the main 6 mm^2 earth connection cannot carry the short-term high voltage and current of a lightning strike. These are diverted, mainly via the neutral connection, to the floor heating cables and then to the earth. It appears that the I^2t rating of a 6 mm^2 cable is inadequate, as there have been several cases of a breakdown of the main earth stake connection, along with discolouration.

The current rating of the main earth cables is designed to auto-disconnect the supply to a safe value and duration. It is not designed to protect against lightning. The higher currents and frequencies present during a lightning strike will create effects such as earth potential rise and associated potential differences. These are transferred to the floor heating cables via the neutral and the earth connections with the resulting breakdowns. Here it should be noted that the floor heating cables are mostly fully embedded within the building earth.

Where lightning surge protection was installed on the active cables at the electrical distribution board and a floor heating cable had failed, with typical lightning strike damage. The layout of the failed cable was traced, and the cable loops were found to be installed at right angles to the other adjacent rooms with undamaged cables. The floor heating cable layout was then noted to be of a similar layout to a roof-mounted, high-gain, television antenna, as shown in Figure 4 [2]. On a number of occasions, the cable layout, such as the one shown in Figure 5, had pointed directly at a severely damaged tree in the garden. Many papers [3,4,5,6]. have addressed the radiative and reception properties of antenna models in relation to the electromagnetic effects of lightning discharges.

Figure 4. Typical television antenna (Yagi-Uda).

Figure 5. Typical floor heating installation.

When a report is submitted to an insurance company, stating that the most likely cause of the cable failure is a nearby lightning strike, they often send out a local electrician to verify this diagnosis. Most electricians have reported that "since nothing else had failed, the cause cannot be lightning". Until approximately 10 years ago, such an explanation may have been correct. It was common then for several plug-in phone chargers to fail along with other control systems. These could be electronic thermostats, Clipsal Cbus, HPM lighting control systems or similar. When the failed items were inspected, the internal low voltage power supplies were found to be transformer based. Several components would be missing and there would be arc marks on the printed circuit board. Low voltage power supplies and mobile phone chargers have since changed to a pulse, or switched mode, electronic system of voltage control and the heavy transformer was no longer required [7]. Hence the smaller size of plug-in phone chargers. These power supplies are now rarely affected by lightning.

V. Creation of Wax

Following a known lightning strike, it is common to find a wax like substance in the earth screen within the shrink tubing at the damaged CTJ or end junction. The short-term, high-voltage and high-current transients, sealed within the shrink tubing, recreate the high temperatures and pressures used to manufacture the thermoplastic insulation. The plastics are partially converted back to the waxes from which they were created. An example is shown in Figure 6 [8].

VI. Discussion

Initial investigations into the problems outlined in this paper started with AS/NZS 1768-2007 [1]) and AS/NZS 3000 [9]. The Australian Power Quality and Reliability Centre at The University of Wollongong[1] was then approached for advice.

[1] Prof. Sarath Perera, PhD, SMIEEE and Mr. Sean Elphick, Research Coordinator, at University of Wollongong.

Further research showed there have been numerous studies and models used to understand and simulate electromagnetic effects on cables during a lightning strike. This work has included The Ferranti Effect [6] on underground cables.

Due to the wide range of floor heating cables, the cable characteristics, installation methods, and location, there has been so far no research found that has sufficiently answered the questions raised. Hence, further studies are required and this will form the basis of the next paper on this topic.

Figure 6. Creation of wax as a result of lightning strike damage.

VII. Conclusions

This paper has provided qualitative field observations of damage to floor heating cables where lightning discharges have been the most likely cause.

It is clear that the extremely high voltages and currents, both direct and induced, from a lightning strike, can cause an insulation breakdown within floor heating cables. The broad range of high frequencies present in a lightning strike may contribute to the cable damage. The large currents and high voltages may be imposed due to effects such as earth potential rise and associated potential differences, inductive coupling effects from indirect strikes, and possible also "standing wave" effects created within the cable. The latter mechanisms are possibly magnified due to the cable layout itself, as it may act as a "high gain, directional, receiving antenna" within the floor. The MEN system itself may add to the number of failures by creating a voltage divider network.

All of the above possibilities, as well as other mechanisms that may contribute to the failures, are currently being investigated using modelling and calculations. The findings will be reported in a subsequent paper.

However, it is expected that, in many cases, correct design of the MEN and earthing system, along with the use of appropriately located surge protection devices, will reduce the number of lightning induced failures.

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