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C4-306

Session 2004

HIGH FREQUENCY GROUNDING PERFORMANCE OF METAL SHEATHED DISTRIBUTION CABLES

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Power systems often use coated and/or uncoated metallic sheathed cables for medium and low voltage distribution. The metallic sheaths of such cables are connected to the grounding systems and may have significant grounding effects. In case of uncoated metallic sheathed cables they act as extended grounding electrodes while coated cables connect different grounding systems at transformer stations and customer premises. This usually improves the grounding conditions at the source transformer station but potentially dangerous voltages might be transferred to other locations. Such effects are well understood for 50/60 Hz but high frequency analysis is also of interest, for example in lightning protection, EMC, telecommunications, and power quality studies. This paper presents simulation based parametric analysis that reveals trends in the frequency dependent grounding performance of metal-sheathed distribution cables. A practical case in a rural environment is also analyzed.

Keywords: Power Distribution – Grounding – Power Cables – High Frequencies – Lightning

1. INTRODUCTION

Recently a number of papers have been devoted to the grounding effects of uncoated and coated metallic sheathed distribution cables at industrial frequency [1,2,3]. Uncoated cables, such as, paper insulated lead sheathed cables (PILC) are no longer manufactured in many countries, but many of them are still in operation. The steel armor and the lead sheath of such cables usually come in direct contact with soil after a period of use. In many cases such cables behave as extended ground electrodes overtaking considerable portion of the ground fault currents. On the other side, today in distribution networks in wide use are cross-linked polyethylene (XLPE) or polyethylene (PE) insulated polyvinyl chloride (PVC) coated cables. Their metallic shields are insulated from the soil but are bonded to the grounding systems of the source and consumers transformer stations (TS) all along the cables. This usually improves the grounding conditions at the source TS but potentially dangerous voltages might be transferred to other TS and consumers' premises. These effects are well understood at 50/60 Hz.

However, high frequency performance of grounding systems is also of interest, for example in analysis of power systems transients due to lightning [4], EMC [5], power quality [6] or power line telecommunications [7]. Another recent problem was related to coupling between the high (HV) and low voltage (LV) systems due to radio base stations that are often placed in poles of power transmission lines [8]. To analyze the protection measures, and especially the lightning current stress for the protective devices that separate the HV and LV systems, better knowledge of the lightning current distribution

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was required. This problem motivated detailed study of high frequency and transient behavior of grounding systems connected to a complex network of metallic sheathed cables [9-13].

This paper presents simulation results that reveal trends in the high frequency grounding effects of coated and bare metallic sheathed cables bonded to grounding systems in a distribution network.

2. MODELING OF COATED AND BARE METALLIC SHEATHED CABLES BONDED TO GROUNDING SYSTEMS

Rigorous electromagnetic field theory approach has been applied for modeling complex network of conductors formed by different grounding system electrode arrangements and connected metal-sheathed cables in [9-13]. This choice has been made since 3D analysis was required that takes into account mutual electromagnetic influences between complex configurations of grounding electrodes and cables. Applied rigorous model is based on a computer model developed in antenna theory [14] and details for its application for high frequency analysis of complex grounding systems are available in [15]. Reference [15] also includes validation of this method by comparison with field measurements. The same method is further extended for bare and coated cables with metallic sheath and iron tape armor [9,13]. It is worth noting that analysis in [9] and [13] has shown that although detailed modeling of the armor and sheath is important at 50 Hz, at higher frequencies it has less influence since external impedance dominates and at 10 kHz it is one and at 1 MHz two orders of magnitude larger than the internal impedance. This completes a computer model for a network of connected or separated grounding electrodes and bare and coated cables in arbitrary position. Interested reader may find details in [9-12] and more complete account in [13].

3. SINGLE CABLE BONDED TO GROUNDING SYSTEM

We first consider several simple cases to analyze trends in high frequency grounding performance of cables bonded to grounding systems. Figure 1 illustrates cases considered. Figure 1a shows grounding system (GS1) consisted of four 12 m vertical rods at 10 m distance connected with horizontal wires at 1 m depth. Current that is discharged to the ground through the grounding system is injected in one of its corners. This case (Fig. 1a) is designated as CASE ‘A’.

CASE ‘B’ is illustrated in Fig. 1b. Steel armor and lead sheath of 100 m long PILC cable is bonded at its both sides to grounding systems GS1 and GS2. (Please note that the construction of the grounding system GS2 is the same as GS1.) The considered 10 kV cable with 5 cm diameter has 2 mm thick lead sheath and total of 1 mm steel tapes over the lead sheath in direct contact with soil. For unsaturated steel we assumed relative permeability of 450.

CASE ‘C’ is similar to ‘B’ only the cable is 500 m long.

CASE ‘D’ is again similar to ‘B’, but the cable is coated. The considered cable is with 5 cm diameter over 1.6 mm thick copper sheath with 5 mm thick dielectric coating.

CASE ‘E’ is similar as ‘D’ only the cable is 500 m long.

All these cases are considered in three types of soil: ‘high resistive’ with resistivity $\rho = 1000\ \Omega$m, ‘medium resistive’ with $\rho = 100\ \Omega$m and ‘low resistive’ with $\rho = 10\ \Omega$m. For all cases soil relative permittivity of 10 is assumed.

Harmonic current in a frequency range up to 1 MHz is injected at the same corner of GS1 (Fig. 1) in all cases. The assumed injected current was with low intensity so non-linear phenomena related to soil ionization typical for high intensity currents were not taken into account.

Figures 2, 3 and 4 show simulation results that illustrate frequency dependent grounding effects for the considered cases. The part (a) of Figs. 2, 3 and 4 is frequency dependent impedance to ground computed by dividing the potential at the injection point with the injected current. The part (b) for Figs. 2, 3 and 4 is the percentage of the total current injected carried by the cables away from GS1.

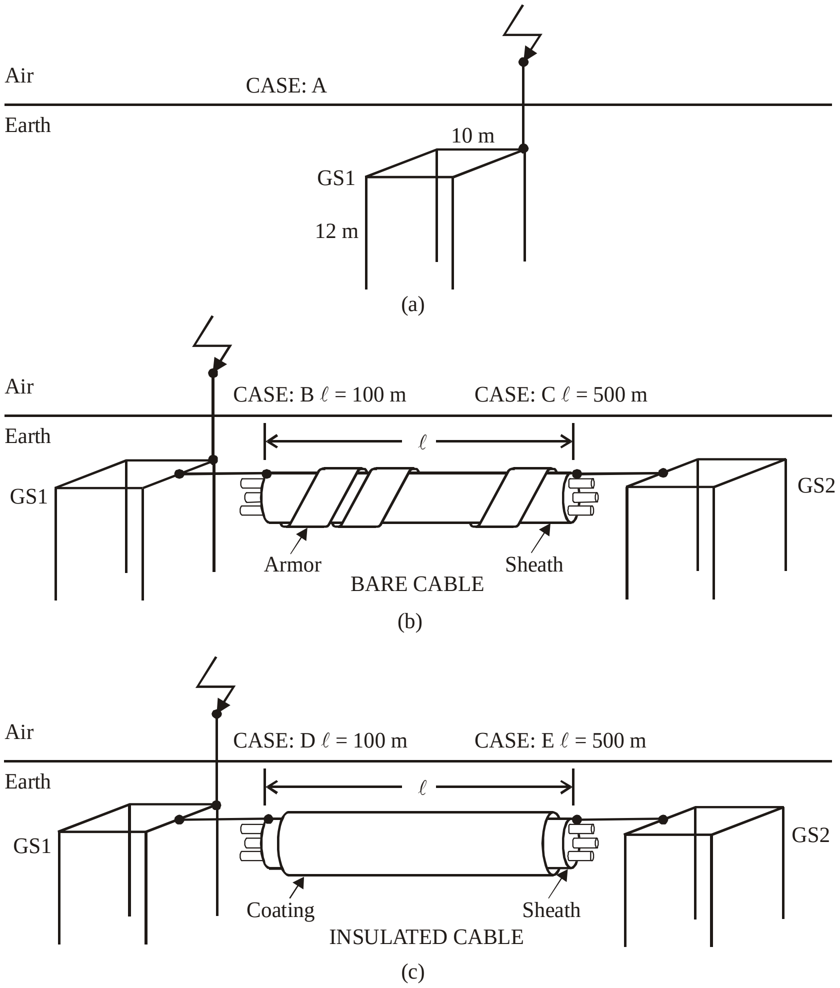
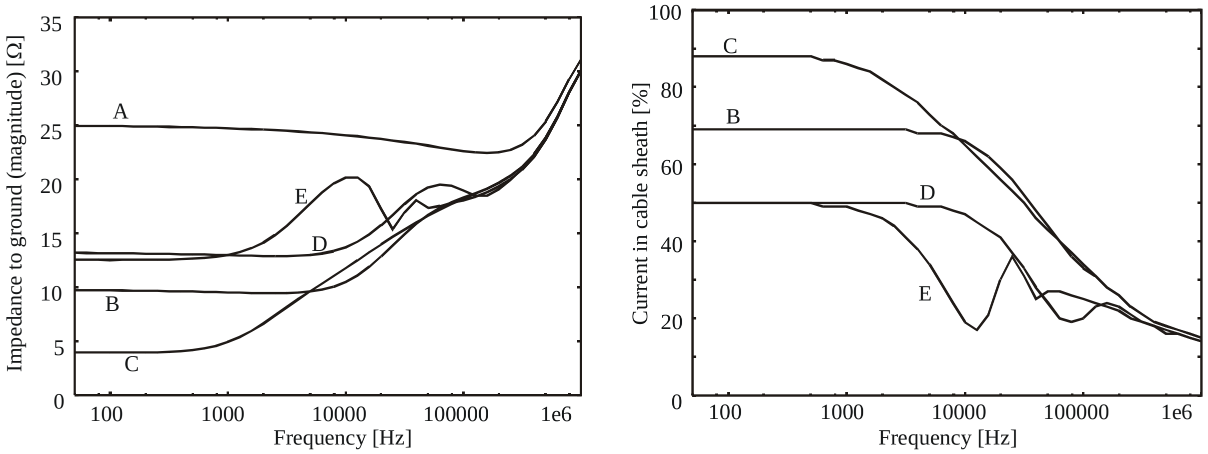


Fig. 1. (a) Grounding system GS1. (b) Bare cable (PILC) with armor and sheath bonded at both sides to grounding systems GS1 and GS2. (c) Coated cable with armor and sheath bonded at both sides to grounding systems GS1 and GS2.

Figure 2 shows results for low conductive soil with resistivity 1000 Ωm. In Fig. 2a curve ‘A’ is the magnitude of the frequency dependent impedance to ground of the grounding system GS1 alone (Fig. 1a). Its form is typical; it is nearly frequency independent up to certain ‘characteristic frequency’ [16] after which it rises with frequency.

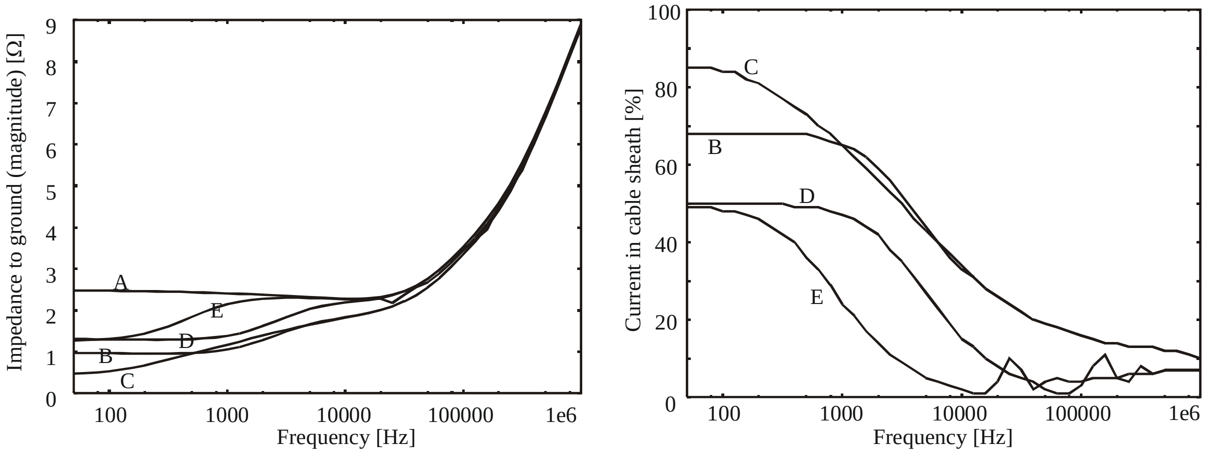
Bare cable bonded to the GS1 has large influence on grounding performance at lower frequencies; 500 m long cable reduces the impedance for about 5 times (‘C’ in Fig. 2a) and carry about 90% of the total injected current away from the feed point (‘C’ in Fig. 2b), while 100 m cable reduces the impedance for about 2.5 times (‘B’ in Fig. 2a) and carries about 70% of the total current (‘B’ in Fig. 2b). For 100 m long cable the characteristic frequency is at about 10 kHz, while for 500 m cable it is at about 1 kHz. It is worth noting that 500 m long cable performs the same as 100 m cable after 10 kHz, which means that at that frequency only 100 m of the cable is effective. This effective length becomes smaller with the rise of frequency and above about 500 kHz cable influence on the performance of GS1 is negligible.

Coated cables with metallic shields bonded to GS1, at lower frequencies connect in parallel grounding systems GS1 and GS2. Impedance to ground is reduced to one half and 50% of the total injected current is carried away (‘D’ and ‘E’ in Fig. 2a and 2b). For frequencies above the characteristic frequency cable performance reduces and its influence becomes negligible above about 500 kHz. It is worth noting that the characteristic frequency depends on the length of the cable but is same for bare and coated cables of same length.



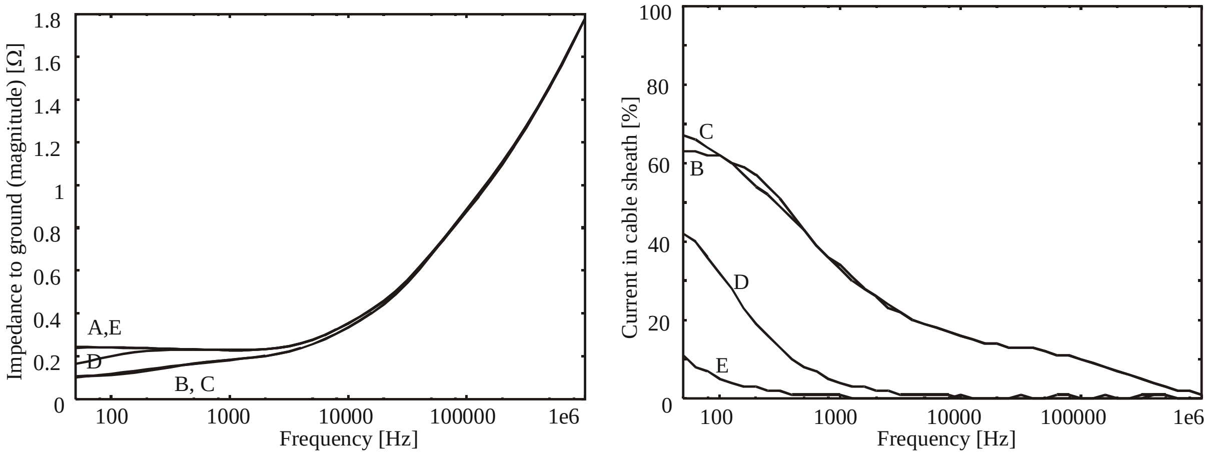
(a) (b)

Fig. 2. (a) Impedance to ground at feed point (b) Percentage of the total current injected in GS1 discharged to ground through the cable and GS2. Soil resistivity ρ = 1000 Ωm. (Designation of cases A, B, C, D and E is illustrated in Fig. 1)



(a) (b)

Fig. 3. (a) Impedance to ground at feed point (b) Percentage of the total current injected in GS1 discharged to ground through the cable and GS2. Soil resistivity ρ = 100 Ωm. (Designation of cases A, B, C, D and E is illustrated in Fig. 1)



(a) (b)

Fig. 4. (a) Impedance to ground at feed point (b) Percentage of the total current injected in GS1 discharged to ground through the cable and GS2. Soil resistivity ρ = 10 Ωm. (Designation of cases A, B, C, D and E is illustrated in Fig. 1)

Figure 3 gives results for 100 Ωm resistive soil. At low frequencies ratio amongst impedances (Fig. 3a) for the same cases are similar as for 1000 Ωm soil (Fig. 2a) with values 10 times smaller. Also characteristic frequencies are lower for a decade in the frequency logarithmic scale. This moves frequency dependent behavior to lower frequency ranges. This is clear from Fig. 3b where percentage of the current carried away by the cables is nearly the same as for 1000 Ωm soil at low frequencies (Fig. 2b), but frequency dependent reduction of the cable grounding performance starts already at 1 kHz for 100 m cable and even at 100 Hz for 500 m cable. Long cables have influence on the grounding performance in much lower frequency ranges in comparison to 1000 Ωm soil; 500 m bare cable perform as 100 m cable already at 1 kHz and the performance of the 500 m coated cable is completely negligible at frequencies higher than 10 kHz.

The trends noticed in Fig. 3 continue in Fig. 4 for low resistive soil with resitivity 10-Ωm. Characteristic frequencies are again moved by a decade to lower frequencies on the logarithmic scale and some are out of the range of Fig. 4. Bare cables still have significant influence on the grounding performance, which can be seen from Fig. 4b where they carry away more 60% of the total current at 50 Hz but their performance reduces constantly with frequency rise. Cables longer than 100 m are not effective already at 50 Hz. Long coated cable has negligible influence on the grounding performance while 100 m cable perform only up to 1 kHz (‘D’ and ‘E’ Fig. 4b).

4. NETWORK OF CABLES CONNECTED TO GROUNDING SYSTEM

Next we consider a practical case in rural environment of a network of coated and bare cables connected to HV line grounding. This is a case of a radio base station mounted in the HV line tower, which is powered by a LV cable [8-13]. Figure 5 gives an illustration of the problem.

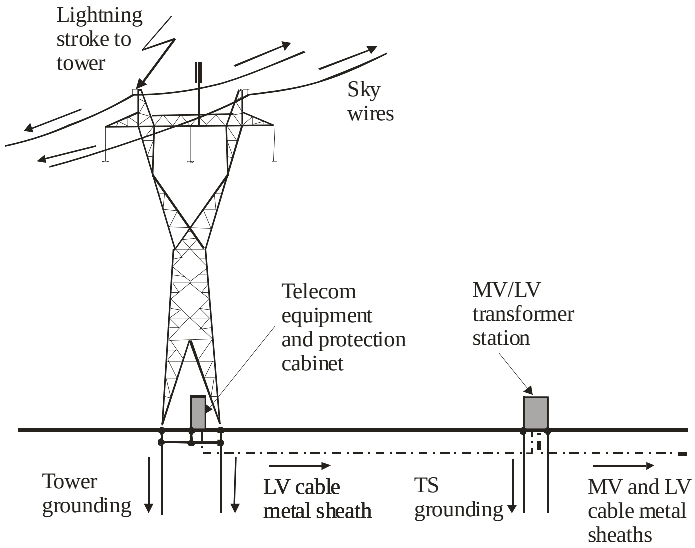


Fig. 5. Lightning strokes a tower with radio base station (arrows point to possible lightning current distribution) [13].

Lightning stroke at the line may induce flashover of the high-voltage (HV) insulators and a subsequent phase to ground fault. The resulting currents usually distribute to ground through the tower grounding and over the sky wires. However, if the radio base station is powered by a LV cable, a fraction of the power frequency fault current might flow through the LV cable towards the medium voltage / low voltage (MV/LV) transformer station (TS), Fig. 5. This may cause dangerous voltages at other customers’ premises served by the same TS. Appropriate measures could guarantee safety, for instance by installing an isolating transformer to separate the faulted HV and the LV network [17]. Special attention is paid to the protection of the isolation transformer, which is usually taken care of by suitable over-voltage arrestors. Such arrestors should withstand the power frequency over-voltage between the tower grounding and the rest of the LV network, but could pass some part of the lightning pulse current. To analyze the protection measures, and especially the lightning current stress for the overvoltage arrestor that protects the isolating transformer, better knowledge of the lightning current distribution is required.

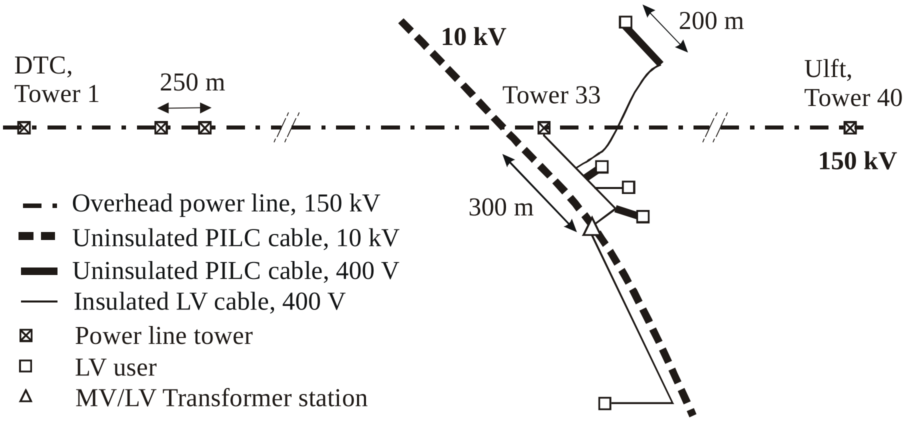


Fig. 6. Overview of the situation of the high voltage line and the LV/MV cable network. (Tower 33 is with radio base station system) [13].

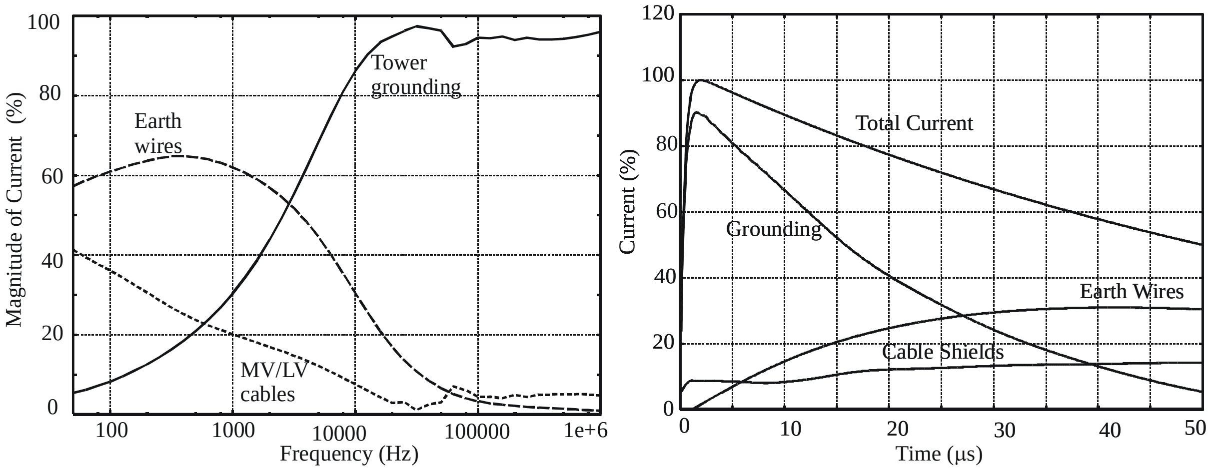
Figure 6 gives an overview of the situation. The measurements at 50 Hz have been carried out on the 10.3 km long double circuit 150 kV link between the substations Doetinchem (DTC) and Ulft in the province Gelderland, which in the area served by the NUON power distribution company [8]. At 8.3 km distance from DTC, tower 33 carries a radio base station. In the substation Ulft, tower 40 is directly connected to the local grounding grid. Two ACSR sky wires interconnect all towers. A 10 kV / 400 V TS at about 300 m distance from tower 33 feeds the radio base station. The LV XLPE insulated cable towards the radio base station also feeds several customers; two other LV cables serve further customers. Some of the LV cables and the MV 10 kV cable are PILC cables. Their metallic shields are in good contact with the soil and they are practically uncoated (or bare) and act as grounding electrodes. All cable shields at 10 kV / 400 V TS are connected with the grounding system of the TS of about 3 Ω resistance to ground. Therefore, all connected grounding systems and cable metallic shields act as a spatially extended grounding electrode arrangement.

Current distribution between the sky wires and the grounding system connected to the cable network is computed for current injected at the top of the tower. Results in frequency domain are in Fig. 7a and in time domain for standard double exponential current pulse with T_1 / T_2 = 1 μs / 50 μs in Fig. 7b. Results are for soil resistivity 100 Ωm.

At low frequencies about 60% of the total current is distributed to the ground through the sky wires, about one third through shields of the connected network of MV/LV cables, and only small part through the tower grounding, which is in agreement with the measurements [8], Fig. 7a. However, the situation is changed in the kHz range, where above about 50 kHz nearly all current is guided to ground through the tower grounding system. The current distribution between the tower grounding system and the shields of the connected network of MV/LV cables is very frequency dependent. With the rise of the frequency the part of the current through cable shields is diminishing rapidly. Similarly the part through the sky wires is diminishing, but more slowly, leaving nearly all current (more than 90%) through the tower grounding system above about 30 kHz.

The first conclusion from the results in Fig. 7b is that the performance of the grounding of the tower with the radio base station is very important in the first period after the lightning stroke when the most of the lightning current is discharged to ground through it. After few tens of microseconds (for the analyzed impulse), the tower grounding performance becomes nearly negligible in comparison to sky wires that take about two thirds and the cable network that takes about one third of the total current.

These conclusions are consistent with the experimental study [18] where horizontal counterpoises carried the bulk of the total lightning current away from the strike point while ground rods performed better for higher frequency components in the current.



(a) (b)

Fig. 6. Total current distribution between sky wires, tower grounding and metal shields of MV/LV cables. (a) Frequency domain. (b) Time domain for standard double exponential current pulse with T_1 / T_2 = 1 μs / 50 μs [13].

5. CONCLUSIONS

Metallic sheathed cables bonded to grounding systems tend to carry away the most of the lightning or fault current injected in the grounding system at low frequencies, while the most of the current is discharged through the grounding system at high frequencies. The same conclusion in time domain is that the most of the current is discharged through the grounding system in the first moments of the pulse but later the cables carry the most of the current away.

Frequency dependent grounding performance of bare and coated metallic sheathed cables may be considered in two parts: frequency independent part at low frequencies, characterized by dominant grounding performance and frequency dependent part at high frequencies characterized by decreasing performance with the frequency rise.

The key parameter is the switch frequency between the low and high frequency parts, so called ‘characteristic frequency’. It is higher for low conductive soil and shorter cables and it does not depend on the coating.

While longer bare cables might perform the same as shorter ones, longer coated cables might perform much worse than shorter ones, especially in high conductive soil.

Soil ionization effects related to high intensity lightning currents that are neglected in this study might significantly improve performance of the grounding system alone, but will not change the conclusion that the bonded cables will tend to carry away the most of the current at low frequencies or in other words after the first moments of the lightning pulse.

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