Appendix

The Elimination of Static Discharges on the Stays of High-Power Antennas

1. Introduction

The most common type of transmitting antenna for use in the long and medium wavebands comprises a vertical steel mast, insulated and driven at its base and kept in an upright position by means of steel stay ropes. The height of the mast is between 0.1 and 0.65 of the transmission wavelength, depending on the desired vertical radiation pattern and the radiated power. Towards the lower end of the MF band, antennas may therefore be up to 300 m high if they are to have vertical radiation patterns having so-called "anti-fading" properties. In the LF band, anti-fading antennas are not feasible and the tallest LF antenna built so far is 500 m high. All base-insulated masts require stays and those more than a few tens of meters high must be stayed at several levels.

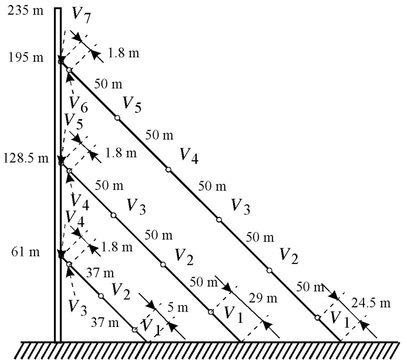

Fig. 1. The configuration of stays and insulators in the MF antenna at Radio Belgrade.

In order to suppress induced radio-frequency (RF) currents in the steel stays, and thus to prevent unwanted radiation from these stays, they are normally divided into short sections by a number of insulators; Fig. 1 shows the configuration of stays and insulators in the MF antenna at Radio Belgrade. Sectionalized stays are also used with other types of LF and MF transmitting antennas such as T or inverted-L wire antennas or shunt-fed mast antennas.

The stay insulators are subjected to two kinds of voltages:

- induced RF voltages due to the RF currents flowing in the mast; and
- electrostatic voltages caused by atmospheric electrostatic fields in the vicinity of the antenna.

Whereas the induced RF voltages are practically constant in time and depend on the radiated power, the electrostatic voltages are variable and can reach very high values. Immediately before, and during a thunderstorm, electrostatic voltages as high as 200 kV to 300 kV may occur across an insulator and values even as high as 400 kV are possible. These voltages are the result of very strong atmospheric electrostatic fields between the clouds and the earth: maximum field-strengths of 5 kV/m to 10 kV/m have been quoted [1]. Despite the use of very expensive and bulky stay insulators, such high voltages can produce flashovers between the metal fittings at either end of an insulator and these can lead to severe damage.

This problem of static discharge across stay insulators plagues many high-power LF and MF transmitting stations with tall stayed mast antennas. Although the problem was observed and described as early as 1939 [2], it is gaining increasing importance at the present time with the steady increase in the powers of these transmitters which are often in excess of several hundred or even one thousand kilowatts. Therefore greater attention has been paid to the problem in recent years and a number of articles about the influence of electrostatic and RF fields on stay insulators have been published in the specialized press [3] to [8]. An accurate method of computing the electrostatic field in the surroundings of a stayed mast, and the electrostatic voltages across the stay insulators, is presented in [5].

The static voltages across stay insulators mentioned in the previous paragraph were calculated using this method. The static voltages and the flashovers they cause are not, in themselves, particularly dangerous when the transmitter power is low. Problems do arise, however, in the case of high-power transmitters. Once the static voltage has caused a breakdown of the insulator spark gap, the induced RF voltage can maintain the arc even if the voltage is much less that needed to trigger a flashover.

If the arc occurs at the insulator, which connects the stay to the mast structure, there will be an appreciable change in the antenna feed point impedance and the transmitter's reflectometer protection system will momentarily interrupt the transmission thus extinguishing the arc. The only fault in this case will be a very short break in transmission.

In contrast, a flashover across an insulator, which is not in contact with the mast, will not activate the reflectometer and RF energy from the transmitter will maintain the arc; in high-power transmitters the power in the RF arc can be considerable and the resulting thermal stresses may damage the insulator (Fig. 2). In the absence of a system serving to extinguish such arcs, the safety of the mast can be jeopardized. In particular, prolonged arcing can cause catastrophic damage to strain insulators in which the fittings are not interlinked. In any event, the replacement of a broken insulator is time-consuming and costly.

Fig. 2. An old ceramic stay insulator damaged by RF arcing.

Contrary to what might be expected, a lightning strike which touches the mast directly or which falls in the immediate vicinity represents an incomparably smaller risk as regards antenna safety than a flashover triggered by the general level of the electrostatic field. A direct strike will cause flashovers on all the insulators on a stay and this, in turn, will trigger the reflectometer, interrupting the transmission.

2. Methods for protecting a mast antenna from atmospheric static discharges

In order to avoid annoying or even dangerous consequences caused by the static atmospheric electricity, several methods have been suggested and developed.

The oldest and most commonly used method for avoiding static discharges and accompanying RF arcs is the use of high-resistance static leak resistors connected in parallel to each insulator, except to those which connect the stays to the antenna mast structure [2]. These resistors leak the electric charge from the stays to the earth, thus preventing the accumulation of static voltages. Although this may seem to be an ideal solution of the problem, it is far from being perfect in practice: a direct or near stroke may destroy the resistor, so that the insulators remain unprotected with no visible indication.

In recent times special arc detectors, sensitive to the ultraviolet radiation or RF noise emitted by an arc, have been developed. Another interesting form of detector measures the RF currents in the lowest section of the stays by means of current transforms and compares them. When an arc occurs, these detectors activate protection devices, which interrupt the transmission for a short interval and extinguish the arc. If the system operates correctly, the number of these interruptions may be so high, during stormy weather and immediately before it, that listening to the program becomes unpleasant.

Since the arc detectors remove the consequences, but not the cause of arcs, some completely new technical solutions, which avoid the use of stay insulators, have recently been proposed and realized. Among these the most notable are:

1. The replacing the steel stays by plastic ones;
2. The use of self-supporting towers; and
3. The use of certain antenna types with steel stays without insulators.

Non-metallic stays are made of modern synthetic fibers. Although these have remarkable electrical and mechanical properties, there is still insufficient experience of their behavior over a long period of time. Also, the material is not resistant to high temperature and fire.

Self-supporting tower antennas have neither stays, nor insulators, so there are not problems regarding static voltages, but they have two serious shortcomings: high price, and a wide and varying tower cross-section, which makes it impossible to obtain a proper anti-fading vertical radiation pattern, if such pattern is required.

Attempts have been made in recent years to construct stayed antennas without insulators [5], [13]. The main disadvantage of this approach is that they cannot provide an anti-fading radiation pattern owing to the strong RF currents in the stays.

The shortcomings of the various technical solutions described above reaffirm (at the present state of technology and particularly in the case of tall anti-fading antennas) the preference for slender mast with insulated steel stays, provided that an effective system can be devised for eliminating static discharges.

That solution, efficient and simple, was proposed and realized by professor Surutka in 1977 [9], [10], during the reconstruction of the antenna of the main MF transmitter of Radio Belgrade.

3. The new anti-static system on the MF antenna of Radio Belgrade

Ever since the antenna for the main MF transmitter of Radio Belgrade (684 kHz) came into service, during 1949, there have been difficulties when transmitting during thunderstorms owing to the build-up of static charges on the stays. In fact the problems were considerably less common at first when the transmitter power was only 150 kW, but when it was increased to 400 kW, and more recently to 2000 kW, the problems became more frequent.

The MF antenna of Radio Belgrade is a steel lattice mast 235 m high; it is of triangular cross-section with sides of 2.2 m. The mast is held in vertical position by nine steel stays, arranged in three levels (three stays in each level). The stays are divided into sections with stay insulators; the configuration as it was prior to the reconstruction work done in 1975 is shown in Fig. 1.

During the preparatory work for this reconstruction, theoretical studies were conducted concerning the static as well as RF voltages on the stay insulators. The static voltages, assuming an electrostatic field of 10 kV/m, are calculated using already mentioned method described in [4]. The numerical results are shown in Table 1.

As far as the RF voltages are concerned, professor Veličković in his Ph. doctoral dissertation (Ref. [6]) proposed an efficient method for evaluating these voltages. By using this method the RF voltages on the stay insulators, corresponding to a radiated power of 2000 kW, are calculated and presented in Table 1. These theoretical values agree very closely with the experimental data.

By comparing the static and RF voltages shown in the Table 1, it is evident that the former are predominant and very large.

In order to ensure adequate RF insulation for the 2000 kW radiated power, coupled with an adequate mechanical safety margin, the contractors (Firm Continental Electronics, Dallas, USA) proposed an arrangement of

Table 1. Calculated static and RF voltages, in kV,
across stay insulators for static field strength of 10 kV/m,
and RF power of 2000 kW.

Top stay						
	V_1	V_2	V_3	V_4	V_5	V_6 and V_7
Static	322	306	268	177	144	958
RF	1.1	2.7	2.9	3.1	4.5	21.6

Middle stay				
	V_1	V_2	V_3	V_4 and V_5
Static	308	222	12	543
RF	4.0	4.5	4.2	7.4

Bottom stay			
	V_1	V_2	V_3 and V_4
Static	126	62	188
RF	4.0	11.6	26.0

four fibre-glass rods in parallel for each insulator (Fig. 3). This form of construction was chosen primarily because of its lightweight: the contractor's experts believed that the mast (more then 27 years old) could not support the increased weight of conventional ceramic girdle-band insulators for the increased RF voltages. Another advantage of the fibre-glass insulators was their relatively low cost, although this was not a decisive factor.

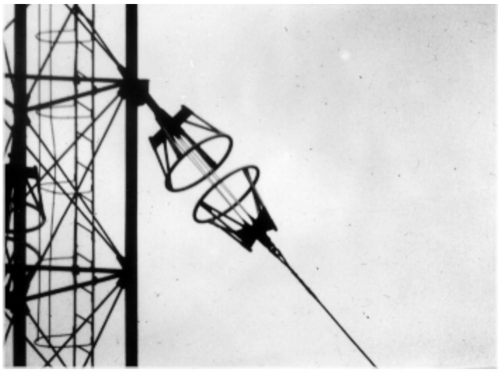

Fig. 3. One of the new fibre-glass insulators with field grading rings.

Unfortunately, the chosen insulators had two serious shortcomings, which had a direct bearing on the problem of static discharge and mast safety. The first was the poor resistance of the fibre-glass to the high temperature that can occur during arcing. To keep the arc as far as possible from the rods, two field-grading rings were placed around the rods, each being connected to the metal fittings at one end of the insulator. The second shortcoming, which affected mast safety, stemmed from the constructional design of this form of insulator. The rods are under tension and the metal parts at either end are not interlinked as in the case with conventional ceramic girdle-band insulators. Consequently, in the event of mechanical or thermal destruction of an insulator, the corresponding stay will be severed completely and the entire mast will fall to the ground. After the insulators had been installed and the transmitter power had been raised to 2000 kW, problems with static discharges increased to such an extent that transmissions became impossible during thunderstorms: static flashovers and RF arcs were so frequent that the transmitter had to be closed down in such conditions. Although these interruptions were unpleasant and inadmissible, the worst consequence of the static discharges was a constant fear in the minds of the station staff that the stability of the mast might be jeopardized.

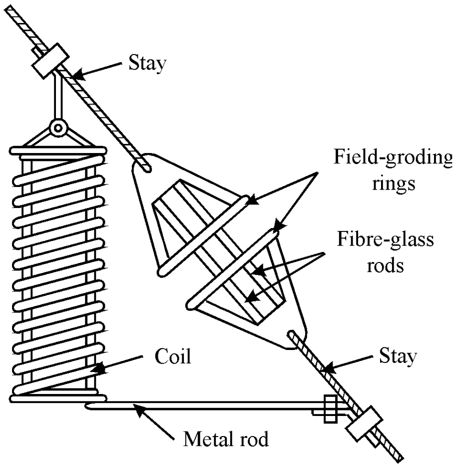

Fig.4. Sketch of the static drain coil connected in parallel with the stay insulator.

Confronted with a serious situation requiring a rapid solution, professor Surutka set about solving the problems. Experience to date suggests that his solution was indeed a good one. Not only is it very effective, but it has the added merit of being extremely simple: it involves the connection of static drain coils in parallel with all stay insulators, except those immediately adjacent to the mast (Figs. 4, 5 and 6). The coils act in a similar manner to static leak resistors, draining static charges to earth. The coil inductance was calculated so that a parallel resonant circuit would be formed with the insulator capacitance at the transmitter carrier frequency. Not only does this eliminate the accumulation of static charges, it also results in an appreciable increase in the RF impedance between the stay sections.

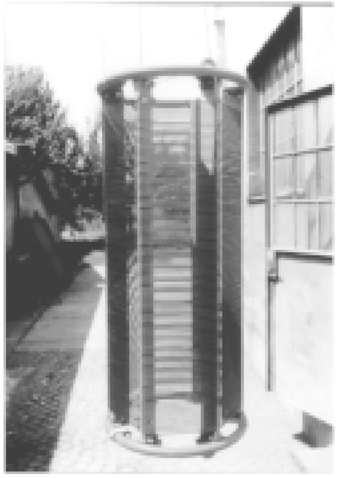

Fig. 5. A static drain coil on the ground.

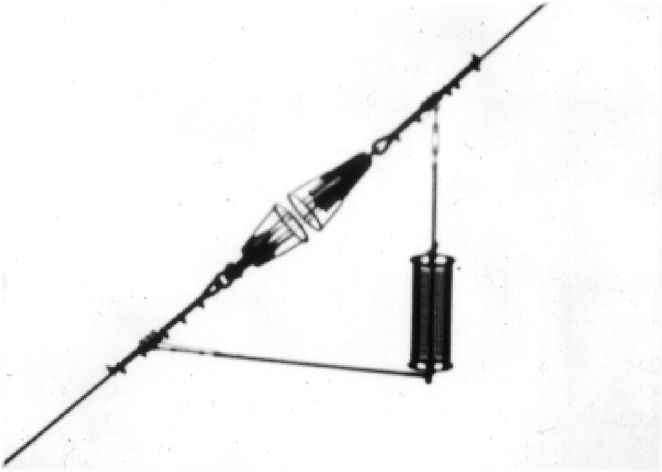

Fig. 6. An insulator and its static drain coil installed on the stay.

The system was put in operation in April 1977 and since that time there has been no recurrence of the problems experienced earlier as result of atmospheric electrostatic fields. The references [9,10], concerning the new anti-static system, are also cited in CCIR Report 943, XVIth Plen. Ass., October 1986.

4. A novel approach to the design of insulators in MF tower broadcast antenna stays

The elimination of dangerous static voltages forming on stay insulators leaves only relatively small, steady and predictable RF voltages. This fact changes the basic philosophy on the insulator design. Instead of expensive and bulky insulators designed for high voltages, the draining coils enable much cheaper and lighter insulators to be used, which are designed to withstand only relatively small RF voltages. The novel design approach was first applied in the design of stay insulators of the new MF broadcast antenna of Radio Podgorica (1987) [11].

The design procedure then required a suitable method for evaluating these RF voltages with sufficient accuracy.

In [11] a new and very precise method for the evaluating these RF voltages on stay insulators has been proposed. The antenna mast, stays and insulators are considered as an integral wire structure. Thus, the influence of the stays on the antenna radiation pattern and the input impedance, as well as the mutual influence of the stays are properly taken into account. For the analysis of the wire structure, the method described in Reference [12] was adopted, which was modified for the present purpose. By including the analysis technique into an optimization procedure it is possible to design a complete system of stay insulators.

The method was applied in the design of the stay insulators of the mentioned new MF antenna of Radio Podgorica. The antenna operating frequency is 882 kHz, and the unmodulated carrier power is 600kW. The mast height is about 185m. The mast has four levels of stays, which are arranged in the three vertical planes, symmetrically placed at 120° angles. In Fig. 7 only stays in one plane are shown.

5. A quarter-wavelength transmitting monopole antenna supported by no insulated stay ropes

As mentioned in Section 2, one of the ways for avoiding the atmospheric static discharges and their consequences is in the use, if possible, of certain

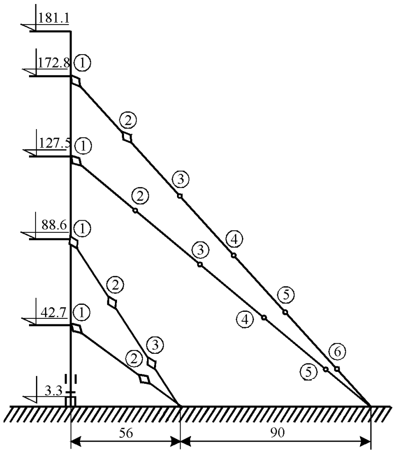

Fig. 7. The configuration of the stays and insulators in the MF antenna of Radio Podgorica (f =882 Hz, P =600 kW).

antenna types with steel stays without insulators.

Recently we have had the opportunity to develop and construct a new transmitting monopole without stay-rope insulators [13]. The antenna is conceived as a vertical quarter-wavelength monopole, insulated and fed at its base, and kept in the upright position by means of three non-insulated stay ropes. At the upper end the ropes are directly connected to the antenna mast and earthed at the lower end (Fig. 8). The antenna can also be treated as a kind of distorted folded monopole, without skirt, the stays of which play the role of the earthed conductor. The tower and stay ropes cross-sections are determinated by mechanical considerations.

In order to reduce losses in the ground, the mast base as well as the three anchoring points of the stay ropes must be supplied with their own radial grounding systems. A detailed analysis has shown that the main grounding system at the mast base should be similar to that of usual monopole antenna (for example, 120 wire conductors, each half wave long, but those at the anchoring points can be much smaller).

The theoretical analysis was performed by using general method presented in Reference [12].

Since the antenna was intended to serve as a stand-by antenna for the main MF transmitter of Radio Belgrade (2000 kW), radiating on 684 kHz, the height of the antenna mast of 110 m has been adopted ($\lambda/4$). In order to properly design the position of the anchoring point of the stay ropes to

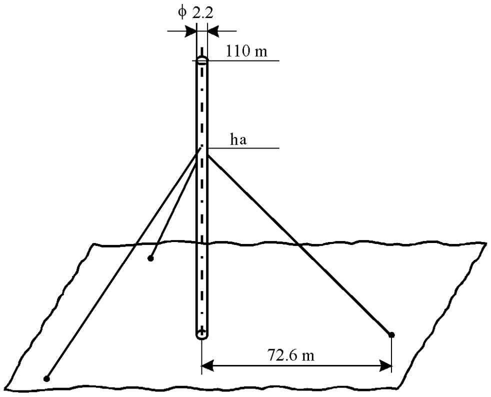

Fig. 8. Sketch of a monopole antenna with no insulated guy ropes.

the tower, the height h_a (Fig. 8) was varied between 60 m and 100 m. In this range, the antenna input impedance varied within the limits of ±5 % about 140 Ω, while the reactance varied within the limits of ±20 Ω about 100 Ω. Since these variations were relatively insignificant, it was adopted h_a =79.2 m, since this height is optimal from the mechanical standpoint. On the other side the input impedance has a very convenient value (about 140 Ω), which enables easy matching to the open-wire feeders.

Due to the lack of expensive and bulky stay rope insulators and accompanying problems with the electric discharge and arcing, such an antenna is very suitable for extremely large powers. The only disadvantage for larger application of the antenna in the MF broadcasting is that it cannot provide the anti-fading radiation pattern. The vertical and horizontal radiation patterns of this antenna are very close to those of a quarter-wavelength monopole. In those cases where sky-wave broadcasting to moderately distant areas is needed, this antenna is very convenient.

Owing to its good characteristics, the described new antenna has been adopted as the stand-by antenna for the main MF transmitter of Radio Belgrade (2000 kW).

6. The protection of the ends of the synthetic fibre stay ropes against strong electric fields

The up-to date technology of synthetic fibres offers the fibre-glass ropes having valuable electrical and mechanical characteristics. Being an excellent dielectric and having better resistance to breaking than the standard rope of the same diameter, the synthetic-fibre rope seems to be an almost ideal for staying large-power MF an LF mast antennas. With this kind there are no problems with RF arcing.

Though all these advantage have been known for several years, synthetic fibre ropes did not find adequately large application in the construction of large-power MF and LF transmitting antennas. The reason for that is, it seems, to be sought in the low resistance of fibres to high temperature.

Except a direct strike of the lightning into the rope, which is very little probable, the sole sources of high temperature and thermal damages can be long-term discharges and creeping at the rope end, caused by the strong static and RF fields on the sharp edges of inadequately shaped heads of ropes. Such a head, produced by manufacturer of ropes is shown in Fig. 9. The shortcoming of this head was viewed by Gregorač [14], who proposed a new form of the head, where the field in the vicinity of the rope's surface is considerably reduced (Fig. 10). The new head is patented and accepted from rope's manufacturer.

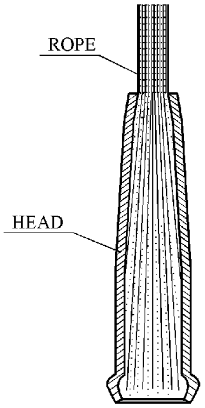

Fig. 9. A typical metallic head of a fibre-glass rope.

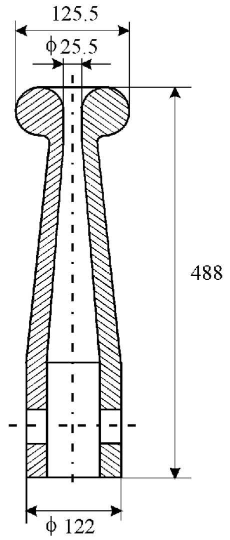

Fig.10. The new form of the head proposed by Gregorač.

In a relatively recent paper [15] a further attempt was made for improving the protection of the ends of the synthetic-fibre ropes for staying mast antennas against strong electric fields. In addition to the suitable shaping of the metallic head terminating the rope, very significant reduction of the field strength on the head and rope end can be achieved by putting a thoroidal protecting electrode coaxially to the head (Fig. 11). The thoroidal electrode is mechanically as well as conductively connected to the metal head and has the same potential. The dimensions defining geometry of the thoroidal electrode are: R - the mean radius of the thorus, r - the radius of its crosssection, and z_0 - the height of the center of thorus above the head bottom.

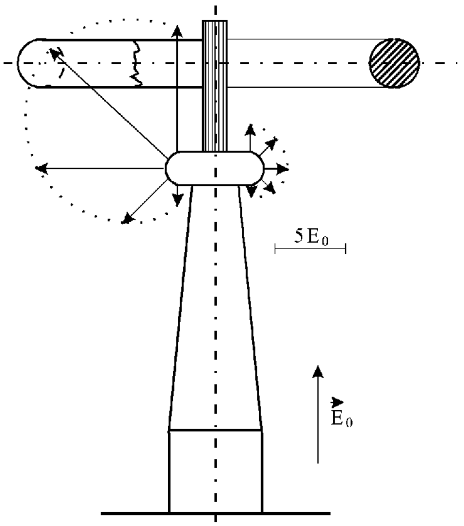

Fig. 11. Very significant reduction of the field strength on head rope end can be achieved by putting a thoroidal electrode coaxially to the head.

Using a numerical procedure, based on the charge simulation method (CSM) [16], the effect of the thoroidal electrode on the electric field intensity at the head's critical points and on the surface of the rope in the vicinity of the head was investigated. A rope having diameter 25 mm and corresponding head proposed by Gregorač were taken as a base.

The protective influence of the thoroidal electrode was investigated by putting the head, together with synthetic rope and protecting electrode (and without it) into homogeneous electric field, of intensity E_0, normal to the conducting plane (Fig. 11).

In order to determine the optimal dimensions and the position of the thoroidal electrode, the evaluations of the field intensities in a large number of points on the surfaces of the head, rope and thorus were performed for 36 combinations of parameters R, r and z_0. The following set of values for R, r and z_0 has been selected:

$$\begin{aligned} R &= 0.200\text{ m} \quad 0.300\text{ m} \quad 0.260\text{ m} \\ z_0 &= 0.550\text{ m} \quad 0.700\text{ m} \quad 0.625\text{ m} \\ r &= 0.025\text{ m} \quad 0.040\text{ m} \quad 0.035\text{ m} \end{aligned}$$

Only a small part of the obtained results concerning the field strengths on the thoroidal crown of the head and along the rope, is presented here.

On the left side of Fig. 11 the polar diagram, drawn by dotted line, represents the electric field strength on the crown of the head in the absence of the thoroidal protecting electrode (a measuring scale for the field strength is presented in Fig. 11). On the right side of Fig. 11 the polar diagram (also drawn by dotted line) represents the filed strengths on the crown of the head in the presence of the protecting electrodes defined by parameters

$$R = 0.200\text{ m},\ r = 0.040\text{ m} \quad \text{and } z_0 = 0.550.$$

These parameters provide the lowest maximum field strength on the crown. The largest ratio of the maximum values of the field strengths on the crown of the head without and with protecting thoroidal electrode is 5.74.

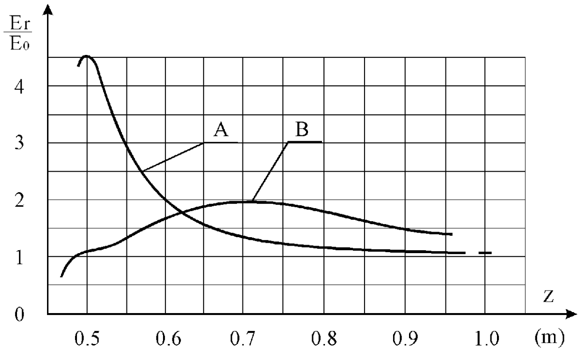

Fig. 12. The ratio of the tangential component of the field strength along the rope, E_r, and the impressed field, E_0, in the two particular cases:
(a) without the thoroidal protecting electrode;
(b) in the presence of the protecting electrode the geometry of which corresponds to the largest protection ratio on the crown of the head.

The protecting electrode has an appreciable reducing effect on the tangential component of the field strength on the surface of the rope, too. The two diagrams in Fig. 12 represent the ratio of the tangential component of the field strength along the rope, E_r, and the impressed field, E_0, in the two particular cases:

(a) Without the thoroidal protecting electrode; and

(b) The protecting electrode is present and its geometry corresponds to largest protection ratio on the crown of the head (5.74).

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