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A New Warning Sphere Design with Side Emitting Optical Fiber Technology on Transmission Lines

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Abstract
Conventional warning spheres (WSs) on high voltage lines cannot be detected adequately by air or military vehicles in the dark, foggy, closed, or misty weather and environments. This situation causes accidents from time to time. In recent years, fiber optic lighting has become very common, and side-emitting optical fibers (SEOFs), which is a type of fiber optic, have also increased. In this study, conventional high voltage WSs were illuminated using SEOFs with voltage generation based on Ampere’s circuital law. The developed system can be mounted on the WSs currently in use, and it also prevents the existing spheres from falling into an idle state, thus not causing economic losses. The system in the study was compared with another warning lamp, which is not based on fiber optic but has similar voltage acquisition, and it was found to be 81% more economical. Since it is fiber optic-based, it is not affected by disturbances such as corrosion and magnetic field. At the same time, the developed WS structure is domestic, and this is another very crucial feature of this system.

Key Words
“High voltage lines, Warning spheres, Side-emitting optical fibers, Fiber optic lighting, Ampere’s circuital law”

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1. Introduction

The interconnected system consists of three main parts: electricity generation, transmission, and distribution. Electric transmission plays a crucial role in this system with many transmission elements such as poles, transformers, breakers, separators, surge arresters, and transmission lines up to thousands of kilometers in length. In addition to issues such as corona, ice load, and voltage drops in electrical transmission lines, the safety of the lines has become extremely important because it causes both loss of life and economic losses.

A warning sphere (WS) or warning ball is equipment made of aluminum and polyethylene with a diameter of around 60 cm, mostly in red-white or orange-white colors (Gündüz, 2017). Efforts to spread the WSs on the lines continue around the world, so there is a need for a large number of WSs. In one study, it was stated that 3000 new WSs were needed only in the Minais Gerais state of Brazil (Campos et al., 2017). Therefore, WS assembly robots were designed (Campos, et al., 2017; Ruaux, 1995).

The primary purpose of the WSs is to enable vehicles such as low-flying aircraft and helicopters near the transmission line to detect these lines. However, especially in foggy, cloudy weather and at night, the perception of these spheres becomes difficult, resulting in severe aircraft or helicopter crashes. There are different national laws in different countries regarding the use of WSs. In our country, the criteria for the use of WSs were determined in the Electric Power Current Installations Regulation on February 8, 2007 (Resmi Gazete, 2007). Accordingly, it has been made mandatory to use bi-colored (white and orange) WSs every 120 m on lines with a height exceeding 30 m (Resmi Gazete, 2007). However, despite this, a military helicopter crashed into the Uludere-Beytüşşebap high-voltage line in 2017, resulting in the death of 13 soldiers (Habertürk, 2017). In addition, such events continued to occur in the following years (Gazetevatan, 2006). Experienced events show that the visibility of the WSs is not sufficient despite all the precautions taken. For this reason, this problem in transmission lines is tried to be resolved through periodic tenders (Yatırımlar, 2020).

WSs are located in an area of transmission lines that have difficulty accessing and mounting due to their height from the ground and in an environment where current flows due to high voltage and strong electromagnetic fields exist. For this reason, the illumination of these line elements with traditional methods is a complicated method and may cause other problems such as short circuits in the transmission line.

A fiber optic lighting system (FOLS) is the transmission of a light source based on the principle of transporting it over a path that will guide the light. The first studies in this area were started by John Tyndall, an Irish physicist, in 1870 (Tyndall, 1870). The original fiber was first produced for voice communication in the early 1970s, and the first commercial optical fiber telephone system was commissioned in 1983 (Li, 1983). While the applications of fiber optic principles in the field of communication are rapidly becoming widespread, on the other hand, fiberoptic lighting applications have started to be applied in many different areas. Examples of these areas are display and exhibit, water lighting, architectural lighting, ambient lighting, side-emitting optical fibers (SEOFs) applications, signage and visual guidance, tunnel and highway lighting, vehicle and automotive lighting, and decorative lighting (Sikkens and Ansems, 1993). Especially building lighting is among the detailed studies (Ghisi, 2002).

There is no study in the literature about the illumination of WSs to increase their visibility. Although the WS was not directly illuminated (Eldar, 2013), an attempt was made to create a warning system with LEDs using the magnetic field on the line. However, no information was given about the visibility of the system, and it was not specified how the LEDs could work in outdoor conditions such as rain and humidity over time. This study (Eldar, 2013) is presented as a concept study.

Although some warning lamps have been developed commercially (Delta Box, 2021), the main problems with these lamps are:

- Their visibility is low due to their size and shape,
- Low availability due to costs,
- Essentially, they will leave the existing warning spheres on the current transmission lines inactive.

For all these reasons, it does not seem possible for these lamps to become widespread in a short time. Considering that there are approximately 100 thousand WSs in our 67,600 kilometers of energy transmission lines throughout our country as of 2021, but there is a need for 180 thousand more WSs, the replacement of existing warning spheres with these warning lamps will cause severe economic losses (Kamu Iktisadi Teşebbüsleri Komisyonu, 2021).

In this study, FOLS has been developed for the WSs already mounted on the transmission line, and a cost comparison with other alternative devices has also been made. Each component of the system has been studied in detail. As a result of the study, it was determined that the recommended WS with added fiber optic lighting system (WS-FOLS) was 81% effective compared to the warning lamps. Thanks to the system we propose, which is created by modifying the existing WSs, it is ensured that the WSs that will become inactive are brought back into the economy.

2. Materials and Methods

2.1. Ampere's circuital law

In Fig. 1, total current I flows through the area enclosed by the C path of radius r. The direction of current flow and the direction of rotation of the C path is determined according to the right-hand rule. Eq. (1) shows Ampere's circuital law. Accordingly, the magnetic flux density $\vec{\mathbf{B}}$ expresses that its circulation on any closed path is equal to the product of magnetic permeability (μ), with the total current flowing through the surface bounded by this path.

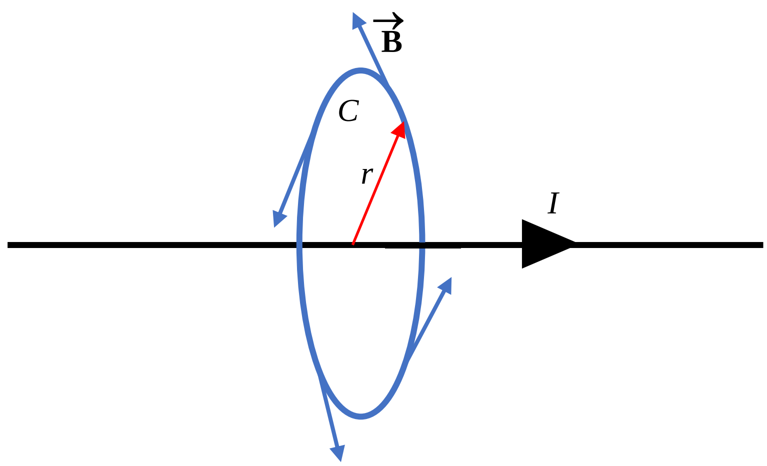


Figure 1. Ampere's circuital law.

In Eq. (1) $\vec{dl}$ line element becomes $\vec{dl} = \hat{\varphi} r d\varphi$ in cylindrical coordinates. At the same time, depending on the current flow direction, $\vec{\mathbf{B}} = \hat{\varphi} B_{\varphi}$.

$$\oint_C \vec{\mathbf{B}} \cdot \vec{dl} = \mu I \tag{1}$$

As $\vec{dl}$ and $\vec{\mathbf{B}}$ substituted in Eq. (1),

$$\oint_C \hat{\varphi} B_{\varphi} \cdot \hat{\varphi} r d\varphi = B_{\varphi} 2\pi r = \mu I \tag{2}$$

The magnetic flux density around the wire due to the current flowing through the wire is obtained as in Eq (3) (Liu et al., 2018),

$$B_{\varphi} = \frac{\mu I}{2\pi r} \ (\mathrm{Wb/m^2, T}) \tag{3}$$

where μ is written as magnetic permeability $\mu=\mu_0\mu_r$. Magnetic permeability consists of two components: the magnetic permeability of the cavity, μ_0 ($4\pi\times10^{-7}$ H/m), and the relative magnetic conductivity coefficient of the material used in the core, μ_r.

If it is considered that a toroid is placed around the conductor, as in Fig. (2), the magnetic flux that will occur inside the toroid can be given by Eq. (4).

$$\Phi = \oint_S \vec{\mathbf{B}} \cdot \vec{ds} \ (\mathrm{Wb, T \cdot m^2}) \tag{4}$$

According to the cylindrical coordinate system, the solution of Eq. (4) is as in Eq. (5).

$$\Phi = \oint_S \vec{\mathbf{B}} \cdot \overrightarrow{ds} = \int_S \left(\hat{\varphi} \frac{\mu I}{2\pi r} \right) \cdot (\hat{\varphi} dr dz) = \frac{\mu I h}{2\pi} \int_a^b \frac{dr}{r} = \frac{\mu I h}{2\pi} \ln(b/a) \tag{5}$$

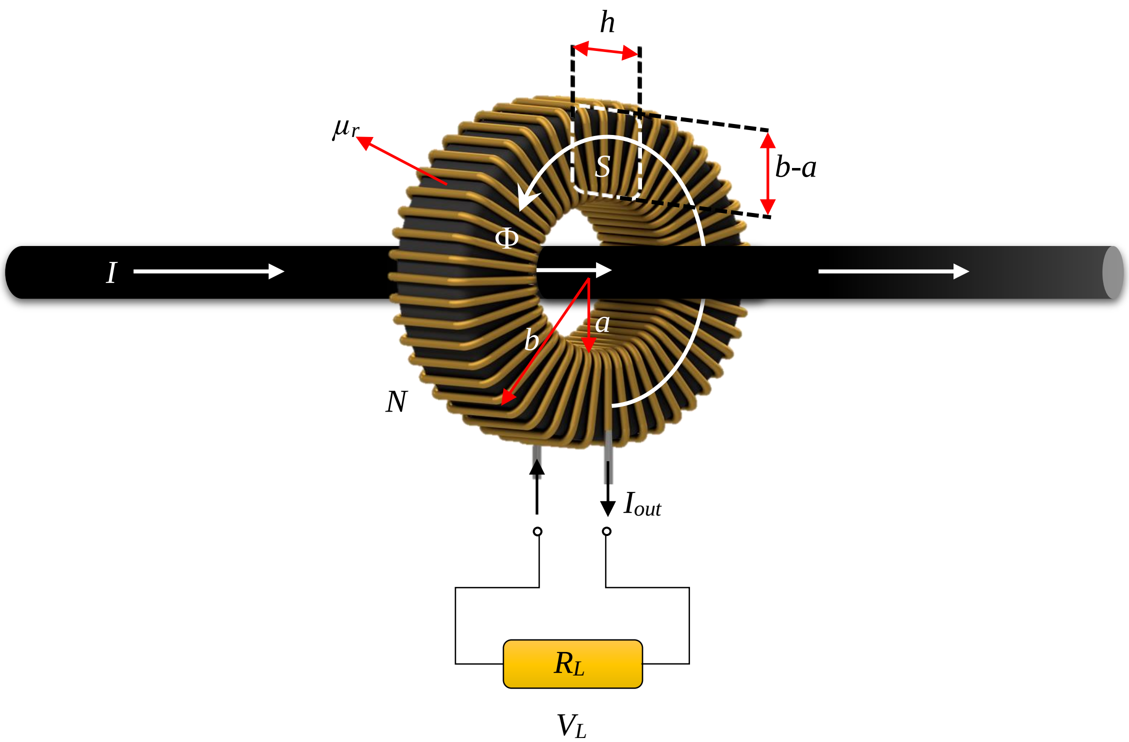


Figure 2. Placing the toroid around the conductor.

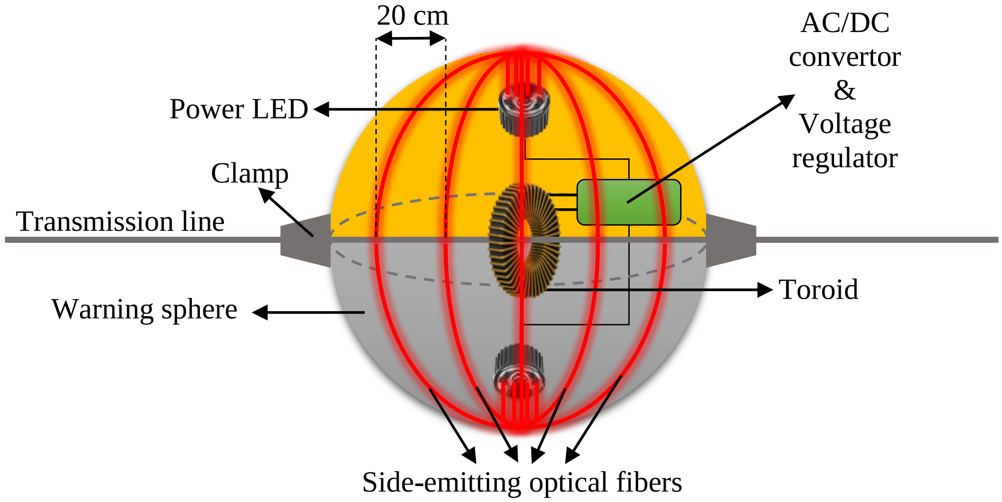
The current flowing through the conductor can be expressed as $I = I_m \sin(\omega t)$. From the Faraday's law of induction, the voltage drop on the load to be connected to the output of the toroid can be calculated as in Eq. (6)

$$V_L = -N \frac{d\Phi}{dt} = -N \frac{\mu h}{2\pi} \ln(b/a)\, \omega I_m \cos(\omega t) \tag{6}$$

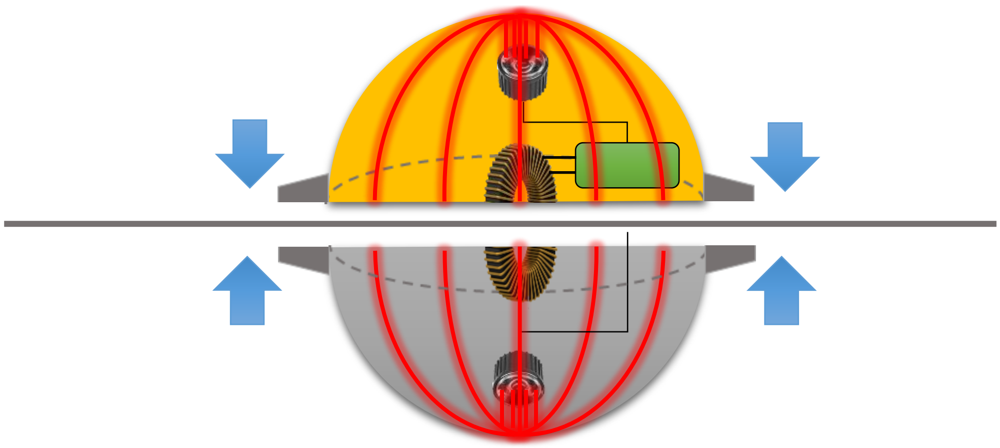
2.2. Warning sphere with added fiber optic lighting system (WS-FOLS)

When the development process of fiber optic technology is examined, the first thing that comes to mind is using these structures for communication purposes (Azadeh, 2009). Parallel to the development of optoelectronic systems, they have found an undeniable field of activity in the field of detection, thanks to their superior features such as not being affected by electromagnetic interferences, being light in weight, and enabling almost lossless data transmission (Zuckerwar, 2003). In addition, these structures have started to show themselves in different lighting applications. SEOFs have been used in many different areas, from lighting works of art to medical electronics and security systems, and have been developed (Spigulis, 2005).

The WS-FOLS handles the processes from obtaining the voltage from the current in the high voltage lines and then lighting the SEOF. A schematic representation of that WS-FOLS is given in Fig. 3(a). A classical WS knitted using SEOF is shown in Fig. 3. The typical diameter of WS is 63 cm. As seen in Fig. 3, SEOFs with different step lengths can be fixed on the WS structure. In this study, 20 SEOF fragments were placed in the center of the WS with approximately 20 cm step length. The length of each SEOF piece is 50 cm. Accordingly, the SEOF length used per WS is approximately 10 m with inward turns. The aim of integrating SEOFs into WS is minimum length value but high visibility and perceptibility. Identical designs were made for the upper and lower hemispheres under the standard opening directions of the WSs (Fig. 3 (b)). Thus, a system has been developed that will not interfere with the routine maintenance of the WS.



(a)



(b)

Figure 3. (a) WS-FOLS, **(b)** Opening demonstration of WS-FOLS.

WS-FOLS generally consists of 6 components. These are shown in Fig.4. The first component is the 154 kV high voltage overhead line conductor. Typically, a current of $I = 100\sqrt{2}\sin(2\pi \times 50 \times t)$ flows through this conductor. The geometric dimensions of the toroid forming the second component are h=19×10^{-3} m, b=49×10^{-3} m, and a=31.8×10^{-3} m. The toroid material is CF197, and the relative permeability value of this material is μ_r=7000±20%. It is known that the network frequency value is 50 Hz. Considering these values, the output voltage for a toroid of 50 turns is obtained as $V_L = 25\cos(2\pi \times 50 \times t)$ using Eq. (6). Voltage drops are inevitable on transmission lines. In addition, changes in μ_r can be observed depending on the temperature. As a result, the toroid output is not stable due to voltage drops in the transmission line and changes in μ_r. For this reason, the fluctuation in voltage may vary between ±5 V. The third component is the AC/DC converter, which converts the AC voltage at the toroid output to DC voltage. Depending on the fluctuations in the input voltage, changes in the DC value at the output may also be observed. The fourth component is a DC regulator circuit that regulates these DC surges. Regulator circuit output is constant at 12 V. The fifth component is a high-power LED Chip on Board 3W Green. A total of 20 power LEDs, 10 each, were used in each LED driver circuit in the upper and lower hemispheres. An LED illuminates each SEOF part described above. The last component of the system is the SEOF parts. The LEDs in the driver circuits are coupled to the SEOFs with specially designed stabilizers. SEOF parts are fixed to the WS surface with mini clamps.

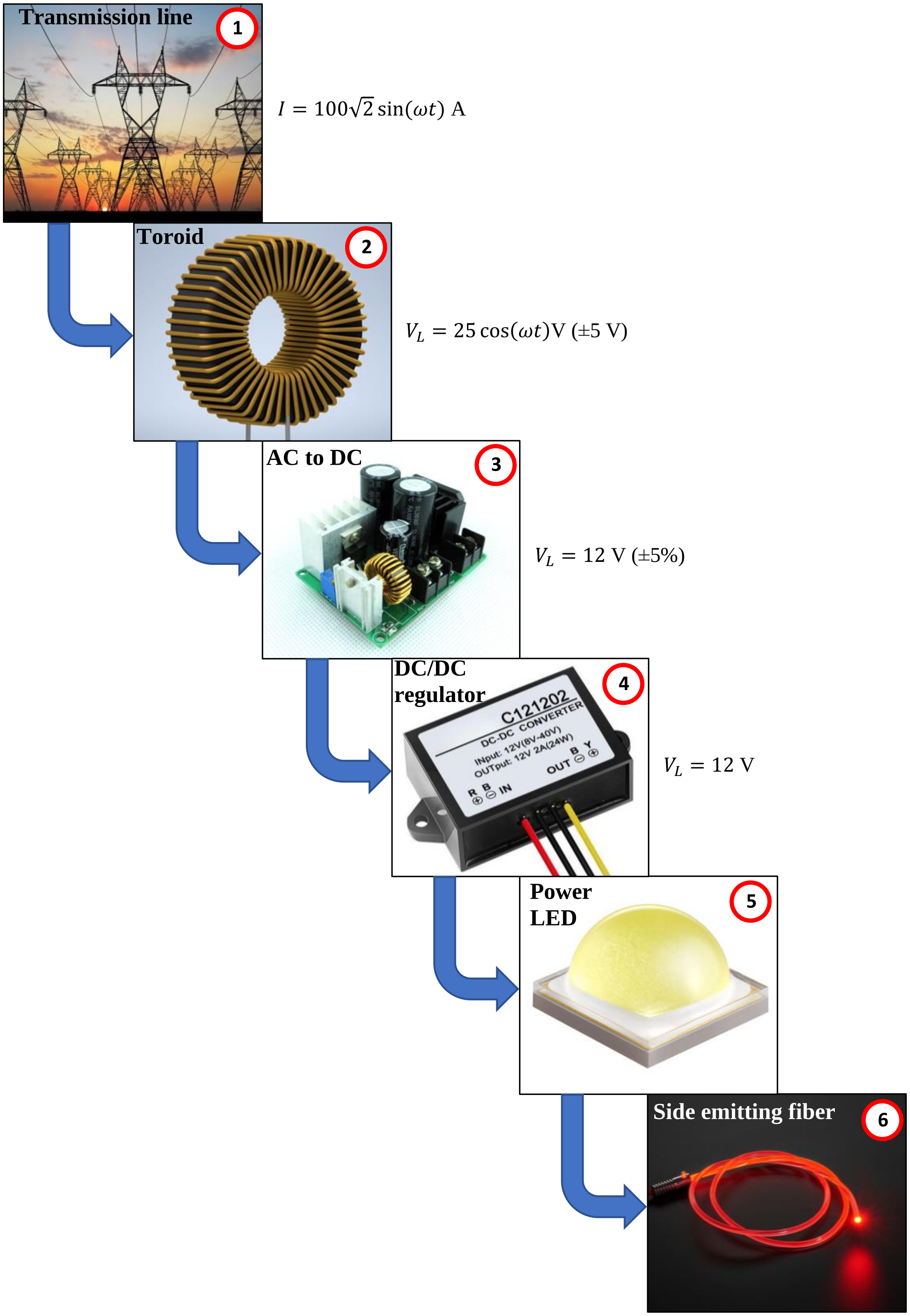
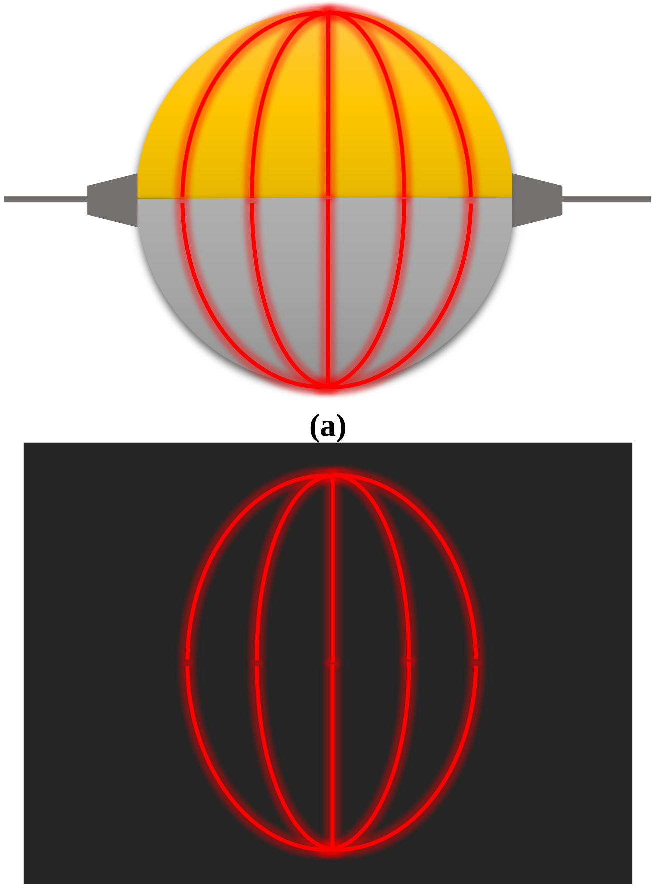


Figure 4. Components of WS-FOLS.

A schematic representation of WS-FOLS formed after production is given in Fig. 5(a). In addition, the control circuit that enables WS-FOLS to activate in the dark is integrated into the system. Fig. 5 (b) consists of a photocell driver circuit that detects light intensity in the environment and activates the system on cloudy days and at night. Thus, the service life is increased since the WS-FOLS is deactivated in bright weather with high visibility.



(a)

(b)

Figure 5. (a) WS-FOLS, **(b)** The night mode of WS-FOLS.

3. Results and Discussion

The cost of the developed WS-FOLS is given in Table 1. LED warning light for toroid-based high voltage lines, based on the same production method given in [13], costs 880 EUR. Luminous intensity is the most important parameter of this and similar warning systems. There are two types of products in the market, type A and Type B. Of these, the maximum lumen value for Type A at the most suitable angle is 125 lm, and for Type B, this value is 400 lm. These values may be lower depending on the point of view. However, since the developed WS-FOLS has spherical symmetry, the luminous intensity at every viewing angle is equal. Moreover, the light intensity of the system at each point is 600 lm. In a study conducted with a similar method, only the method was explained, and concepts such as light intensity and usability in high voltage lines were not examined (Eldar, 2013).

Table 1. WS-FOLS costs per sphere.

System Components	**Component Cost (EUR)**
Toroid	1.88
Toroid wire (1mm 50 m)	9.99
AC/DC converter (×2)	41.57
DC/DC regulator (×2)	39.84
Power LED (20 pieces)	13.28
SEF (diameter 2.5 mm length 10 m)	7.97
LED driver circuit (2 pieces)	15.48
Toroid enclosure	8.42
WS	18.54
Other system components	4.83
TOTAL	**161.8**

Thus, it has been calculated that the developed WS-FOLS can be easily mounted on existing WSs and is 81% cost-effective compared to other LED warning lights.

4. Conclusions

In this article, a warning sphere with added fiber optic lighting system (WS-FOLS) has been proposed and developed in order to ensure the visibility of high voltage transmission lines in the dark. Detailed analyses of all envisaged system components were made, and product performance and cost studies were also carried out. Thus, it is both high-performance and cost-effective compared to its equivalents. In addition, warning spheres (WSs) already in the transmission line are used in the study to impose no additional cost on the electrical system provider. The advantage of the infinite symmetry of the WSs in the system contributed to the visibility of this study, and it was ensured that the aircraft saw an equal light intensity from every point of view. Thus, the blind spot problem is also eliminated.

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