

Research of independent DC electric field sensor with wireless power supply circuit

eISSN 2051-3305

Received on 23rd August 2018

Accepted on 19th September 2018

E-First on 17th December 2018

doi: 10.1049/joe.2018.8549

www.ietdl.org

Jianzhong When¹, Zhanqing Yu² ✉, Chao Zhang¹, Ya Mou², Yaosheng Huang¹, Zhiming Zhen¹¹Jiangmen Power Supply Bureau of Guangdong Power Grid Co., Ltd, Jiangmen 529000, People's Republic of China²Department of Electrical Engineering, Tsinghua University, Beijing 100084, People's Republic of China

✉ E-mail: yzq@tsinghua.edu.cn

Abstract: The DC electric field strength is an important electromagnetic environment parameter of the high-voltage direct current (HVDC) transmission line. Measurement results of the space electric field are dramatically affected by the size and the potential of the sensor. In addition, the battery-powered solution of electric field sensor (EFS) is not feasible, for the reason that in the high-voltage electric field environment, the replacement of the battery will bring security risks to the power system and workers. The wireless energy supply solution not only solves the problem of potential isolation of the sensor, but also ensures that the sensor can work continuously. Various wireless power transmission systems (WPTSs) were compared. Microwave wireless power transmission system (MWPTS) was selected as the power supply of EFS. The key boundary conditions of MWPTS were determined. Two microstrip receiving antennas were designed in this article. A good performance antenna with high permittivity substrate was designed, realising 4.26 dB gain with the area of 1 cm² at 5.8 GHz. The antenna meets the energy requirements of the EFS which is 10 m far from the source.

1 Introduction

Effective monitoring of the electric field strength in the vicinity of the transmission line is one of the important measures to ensure the safe operation of the power system. In past years, the measurement of electric field strength has made great progress [1]. In 1983 years, P. Sarma Maruvada invented the electric field mill, which uses a grounded rotating electrode to periodically shield the sensing electrode to achieve ground electric field strength measurement [1]. Based on the bubble earwax effect, a photoelectric sensor is designed to measure the electric field strength [2]. Micro-electro-mechanical systems (MEMS) have the advantages of small size, low power consumption, and high integration. In 2003, the electrostatic-driven electric field sensor (EFS) based on silicon-on-insulator fabrication process technology was invented [3]. After that, Pockels device [4] and heat-driven [5] MEMS EFS were invented.

However, the drawback that sensors present require wired power supply [1] or battery power supply [2, 3] has significantly limited the progress of EFS. For the reason that wired access could not guarantee the potential isolation between small signal power and high-voltage transmission line, this method is an ineffective way of measuring space electric field. What is worse, replacement of the battery increases the cost of the economy, threatening the safety of the staff, and the safe operation of the power system. To solve these troubles, the WPTS is selected as power supply of EFS.

First of this paper, according to the requirements, microwave wireless power transmission system (MWPTS) was selected as the power supply of the EFS after comparing the advantages and disadvantages of each wireless power transmission system (WPTS). Then, we analyse the constraints of this programme, determine the boundary conditions, and identify project objectives. Finally, the design and simulation of the receiving antenna are completed.

2 Methodology

2.1 Selection of wireless power supply solutions

Wireless energy supply technology originated in the phenomenon of electromagnetic induction which was discovered by Faraday in 1831 [6]. So far, wireless power supply has been widely used in the world [7, 8]. The magnetic induction coupling programme has the

advantages of large transmission power and high efficiency at close range, but it has the disadvantages of large device size and inefficiency at long range. Magnetic coupling resonance programme also has the disadvantage of large device size. Microwave radiation programme, in the intermediate distance transmission, can realise high efficiency in small size. The laser mode has the disadvantage of difficult to realise the launch and receiving end alignment at long distance. In order to reduce the electric field distortion, the overall size of the sensor, and the space electric field, the sensor is placed in the air, so the distance between the sensor and the transmitting end is about several meters. Considering the size and transmission distance factors, the microwave wireless power supply can be the best.

2.2 Introduction of microwave power transmission system

Microwave power transmission system is mainly composed of transmitting antenna, microwave transmission medium, and rectifier antenna [9]. Microwave radio transmission system mainly consists of transmitting antenna, microwave transmission medium, rectifier antenna etc. As shown in Fig. 1, high-frequency signal produced by signal source is amplified by power amplifier at the first time and then is transformed into high-frequency electromagnetic waves and launched into atmosphere by transmitting antenna. Incident RF energy captured by the receiving antenna is transformed into specific amplitude and frequency of voltage and current to meet the energy requirement of the back-end load.

According to the equation of FRRIS [10], the received energy P_r by receiving antenna can be obtained as follows:

$$P_r = P_t e_r D_r \left(\frac{\lambda}{4\pi R} \right)^2 = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \quad (1)$$

where P_t is the power of transmitting antenna, G_t is the gain of transmitting antenna, G_r is the gain of receiving antenna, λ is the corresponding wavelength of the working frequency, and R is the distance between the power source and sensor.

From (1), conclusion that P_r is proportional to the P_t , G_t , and G_r can be obtained. The higher of operating frequency, the smaller of λ and P_r . The closer the distance between the transmitter and the

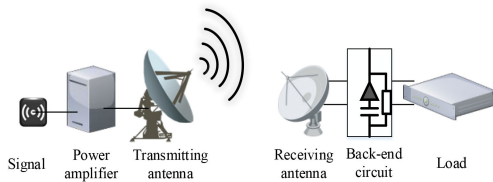


Fig. 1 Block diagram of wireless power transmission system

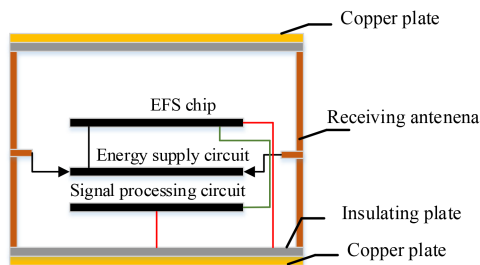


Fig. 2 Schematic diagram of the packaging structure

Table 1 Height of the HVDC transmission line from the ground

voltage	500 kV	800 kV	1000 kV	1100 kV
the average height (m)	12	16	22	28

receiver, the more energy is available. To decrease the transmission power, and lower the cost, a higher gain receiving antenna at small size is required. However, the size of antenna is related to working frequency. So, it is critical to choose proper type antenna and its working frequency.

2.3 Selection of receiving antenna

The package structure diagram for the EFS is shown in Fig. 2. The package is a complete symmetry rectangle. The upper and lower plates are made of copper, which are used to accumulate charges. The side walls of package are antennas for receiving the energy to supply sensor working. The middle ones between metal plates and the antennas are insulating materials for electrical isolation.

3 Determination of boundary conditions

As stated above, the determination of system parameters is of great concern to this project. Inappropriate parameters can cause an increase of the system costs, or result in failing to meet the power requirements of load. The parameters will be determined in this part according to the implication background and current industrial market.

3.1 Selection of receiving antenna

The object causes the distortion of the electric field when it enters into the electric field. In order to improve the measurement accuracy of electric field strength, the smaller sensor will be adapted in this programme. In addition to the detection portion to be smaller, the power supply part should be small and need to be easily integrated with back-end circuits. According to Formula (1), the power of the receiving antenna is proportional to the gain of the receiving antenna, and the gain of the receiving antenna should be as large as possible in order to satisfy the power demand of the back-end load.

A wide range of antennas, with dipole antenna, helical antenna, loop antenna, and logarithmic cycle antenna, have been widely applied in all kinds of industry [10]. Microstrip antenna with the superiorities of small size, light weight, low cost, easy to conformal, electrical performance diversification, easy integration with the circuit, is widely used in wireless local area networks and personal communications systems and other fields [11]. Therefore, microstrip antennas are ideal receiving antennas in this project.

Table 2 Frequency of the industrial, scientific, and medical use

Number	Frequency
1	6.78 MHz \pm 15 kHz
2	13.56 MHz \pm 7 kHz
3	27.12 MHz \pm 160 kHz
4	40.68 MHz \pm 20 kHz
5	915 MHz \pm 13 MHz*
6	2450 MHz \pm 50 MHz
7	5800 MHz \pm 75 MHz
8	24.125 GHz \pm 0.125 GHz
9	61.250 GHz \pm 0.25 GHz
10	122.5 GHz \pm 0.5 GHz
11	245 GHz \pm 1.0 GHz

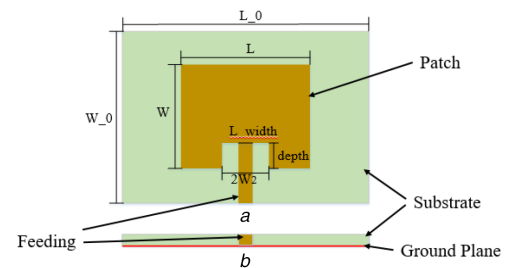


Fig. 3 Geometry of the receiving antenna

3.2 Determination of the distance between the power source and sensor

The chip based on micromechanical structure has the advantages of small size and low power consumption. The power consumption of the designed EFS is about 10 mw. According to (1), the closer the distance is, the bigger the power of receiving antenna will get. However, transmission lines have a certain height from the ground to ensure security of both power grid and the safety of life. It is impractical to place a power amplifier weighing a few kilograms in the air. So the distance between the transmitting antenna and the receiving antenna is conservatively estimated from the height of the HVDC transmission line from the ground, as shown in Table 1.

To meet the power demand of high-voltage situation, the distance R between the transmitting antenna and the receiving antenna is 10 m.

3.3 Determination of operating frequency

The higher the operating frequency, the shorter the wavelength and the antenna size. However, the higher the operating frequency, the greater the difficulty of the design of the back-end processing circuit and the lower efficiency. In 1979, the World Radio Communication Council divided the band into 11 narrow bands, which were designed for public health, industrial production, and scientific research (see Table 2 for details).

Microstrip antenna size is close to the length of half wavelength. The price of high-power amplifier is exponentially increased with the operating frequency, bandwidth, and the maximum allowable transmission power. To this end, in order to save the entire cost of microwave radio transmission system, the operating frequency is selected as 5.8 GHz.

3.4 Requirements analysis of the antenna performance

According to the production level of antenna manufacturers at home and abroad, first assume that the transmitter power of the launch antenna is 1 kW, which gain is 18 dB at 5.8 GHz. The relationship between the received power of the receiving antenna and the gain of the receiving antenna is shown in Figs. 2 and Figs. 3–5. When there is a need to receive antenna output power of at least 10 mw, the receiving antenna gain should be greater than or equal to 1.68, which is greater than or equal to 2.3 dB.

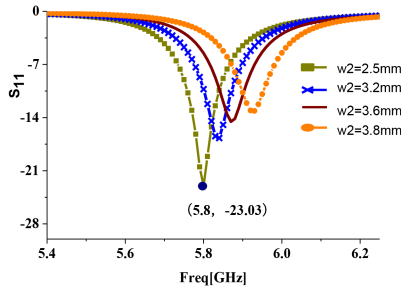


Fig. 4 Parametric study of S_{11} with w_2

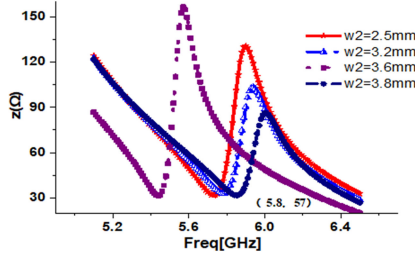


Fig. 5 Parametric study of input resistance with w_2

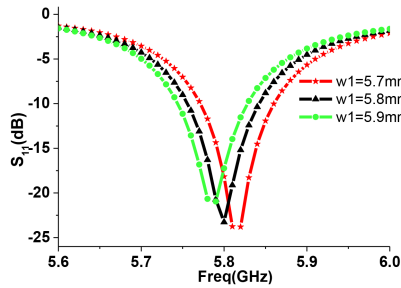


Fig. 6 Parametric study of S_{11} with w_1

4 Design of microstrip antenna

The microstrip antenna is consisted of a metal thin ground plate, a dielectric substrate, and a metal radiation patch over the dielectric substrate. The radiation of a rectangular microstrip patch antenna equals to an equal-amplitude co-directional binary array consisting of two gaps. The parameters of a rectangular microstrip patch antenna can be determined by the following empirical formula [10].

The width (W) of the patch is as follows:

$$w = \frac{c}{2f} \left(\frac{\epsilon_r + 1}{2} \right)^{-1/2} \quad (2)$$

The length (L) of the patch is as follows:

$$L = \frac{c}{2f\sqrt{\epsilon_e}} - 2\Delta l \quad (3)$$

where ϵ_r is the relative permittivity of the high-frequency dielectric material, c is the speed of light which equals to 3×10^8 m/s, f is the operating frequency, ϵ_e is the equivalent relative permittivity, and Δl is the equivalent length of the radiation gap.

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{w} \right)^{-1/2} \quad (4)$$

$$\Delta l = 0.412 \cdot h \cdot \frac{(\epsilon_e + 0.3)(w/h + 0.264)}{(\epsilon_e - 0.258)(w/h + 0.8)} \quad (5)$$

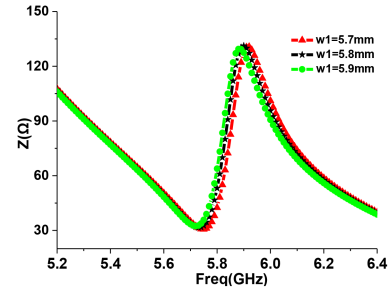


Fig. 7 Parametric study of input resistance with w_1

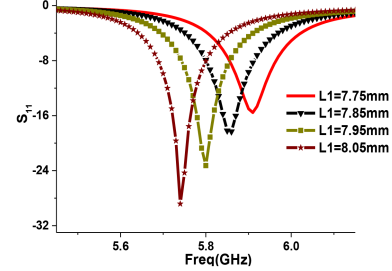


Fig. 8 Parametric study of S_{11} with L_1

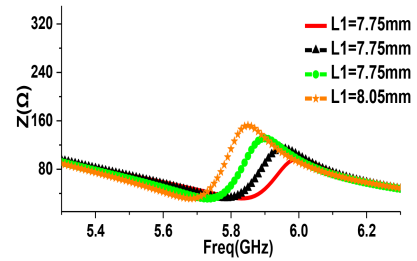


Fig. 9 Parametric study of input resistance with w_2

4.1 Rectangular microstrip antenna with high dielectric constant

The substrate material has great influence on the antenna material. According to (2) and (3), the equivalent relative permittivity increases when the dielectric permittivity of the substrate increases, resulting that the width and length of the antenna decrease, so the area of the receiving antenna decreases. To decrease the area of the antenna, a high dielectric permittivity substrate is used. However, the motion of electrons in high frequency will produce more heat, causing heat loss. The higher the dielectric permittivity, the larger the heat loss. Consequently, the balance between heat loss and area is what we should take into consideration. Finally, the material of Rogers RT/Duroid 6010 is chosen in this project.

As is shown in Fig. 3, the receiving antenna consists of a ground plane, a patch, and a feeding.

4.2 Parametric study

The size of the patch dramatically influences the resonant frequency. The location of the microstrip feeder has a great influence in the input resistance and therefore affects the energy transmission effectiveness. In order to achieve the optimal performance of the antenna, it is necessary to study the impact of each parameter on the antenna performance.

The influences of parameters of w_2 , w_1 , L_1 on the antenna are separately studied by using the control variable method. Initially, suppose the length of the reflector is 15 mm, the width of the reflector is 12 mm, the height of the antenna is 1.27 mm, the length of the patch is 7.95 mm, and the width of the patch is 5.8 mm. The results are shown in Figs. 4 and 5 and Figs. 6–9.

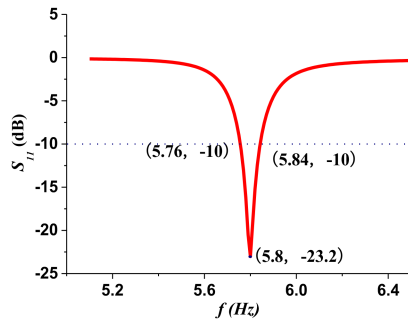


Fig. 10 S_{11} curve of the antenna

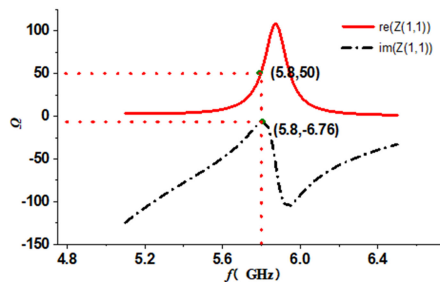


Fig. 11 Input resistance of the antenna

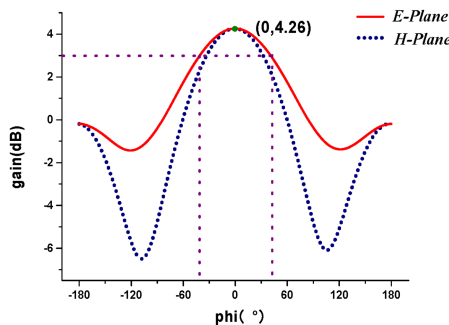


Fig. 12 Gain in the direction of E-plane and H-plane

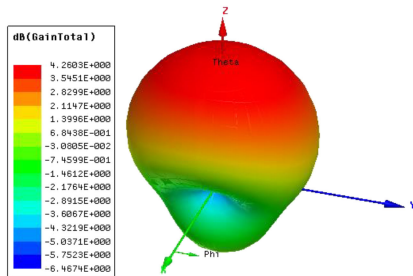


Fig. 13 Gain of the three-dimensional pattern

4.3 Results of simulation

Through simulation and optimisation of the high-frequency electromagnetic field simulation software, the antenna with optical performance is obtained. Finally, we choose the w_2 is 3.2 mm, the w_1 is 5.8 mm, and $L1$ is 7.95 mm.

Through the sweep analysis, the resonant frequency of microstrip antenna is 5.8 GHz. Fig. 10 shows the S_{11} parameter

changes as the frequency changes. As can be seen from Fig. 10, the bandwidth of the antenna is 80 MHz. Figs. 11 and 12 show the gain of this antenna. The gain of the antenna is high to 4.26 dB (shown in Fig. 13), and the area is small to 1 cm².

5 Conclusion

The wireless power supply of the EFS is necessary, which is used in the electric measuring of high-voltage transmission line. Microwave wireless power transmission is adopted for its merits of high efficiency at long distance and small size. After that, the boundary conditions of this project are determined: the distance between the power source and receiving antenna is 10 m, the energy required for the EFS is 10 mW, and the operating frequency of the MWPTS is 5.8 GHz. Finally, rectangular microstrip patch antenna with high dielectric permittivity is designed, simulated, and fabricated. The simulation results show this antenna has good performance. The rectangular microstrip patch antenna with the area of about 1 cm² achieves gain of 4.26 dB, VSWR of 1.15, and the input impedance of about 50 Ω . The wireless power supply system achieves a power supply with a load of 10 mW from the external power requirement of 10 m.

6 Acknowledgments

The project was supported by National Natural Science Foundation of China (51477089). The project was supported by Jiangmen Power Supply Bureau of Guangdong Power Grid Co GDKJQQ20152018 and National Natural Science Foundation of China (51477089).

7 References

- [1] Maruvada, P.S., Dallaire, R.D., Pedneault, R.: 'Development of field-mill instruments for ground-level and above-ground electric field measurement under HVDC transmission lines', *IEEE Trans. Power Appar. Syst.*, 1983, **102**, (3), pp. 738–744
- [2] Takada, T.: 'Acoustic and optical methods for measuring electric charge distributions in dielectrics', *IEEE Trans. Dielectr. Electr. Insul.*, 1999, **6**, (5), pp. 519–547
- [3] Riehl, P.S., Scott, K.L., Muller, R.S., *et al.*: 'Electrostatic charge and field sensors based on micromechanical resonators', *J. Microelectromech. Syst.*, 2003, **12**, (5), pp. 577–589
- [4] Hidaka, K., Kouno, T., Hayashi, I.: 'Simultaneous measurement of two orthogonal components of electric field using a Pockels device', *Rev. Sci. Instrum.*, 1989, **60**, (7), pp. 1252–1257
- [5] Wijeweera, G., Bahreyni, B., Shafai, C., *et al.*: 'Micromachined electric-field sensor to measure AC and DC fields in power systems', *IEEE Trans. Power Deliv.*, 2009, **24**, (3), pp. 988–995
- [6] Tesla, N.: 'Experiments with alternate currents of high potential and high frequency', *Electr. Eng. J. Inst.*, 2007, **21**, (97), p. 51
- [7] Alden, A., Ohno, T.: 'A power reception and conversion system for remotely-powered vehicles'. Sixth Int. Conf. on IET, Antennas and Propagation, Coventry, UK, 1989, **11**, (1), pp. 535–538
- [8] Xingming, F., Xiaoyong, M., Xin, Z.: 'Research Status and application of wireless power transmission technology', *J. China Electromech. Eng.*, 2015, **10**, pp. 2584–2600
- [9] Dickinson, R.M.: 'Performance of a high-power, 2.388-GHz receiving array in wireless power transmission over 1.54 km'. IEEE-MTT-S Int. in Microwave Symp., Cherry Hill, USA, 1976, pp. 139–141
- [10] Balanis, C.A.: 'Antenna theory: analysis and design' (Wiley-Interscience, Hoboken, 1982)
- [11] Mespaden, J.O., Chang, K.: 'A dual polarized circular patch rectifying antenna at 2.45 GHz for microwave power conversion and detection'. IEEE MTT-S Int. Microwave Symp. Digest, San Diego, USA, 1994, **11**, (3), pp. 1749–1752