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Design of a Microwave Radiometer for Mornitoring High Voltage Insulator Contamination Level

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***Abstract*— Microwave radiometry is a novel method for monitoring contamination levels on high voltage insulators. The microwave radiometer described measures energy emitted from the contamination layer and could provide a safe, reliable, contactless monitoring method that is effective under dry conditions. The design of the system has focused on optimizing accuracy, stability and sensitivity using a relatively low cost architecture. Experimental results demonstrate that the output from the radiometer is able to clearly distinguish between samples with different contamination levels under dry conditions. This contamination monitoring method could potentially provide advance warning of the future failure of wet insulators in climates where insulators can experience dry conditions for extended periods.**

***Keywords*— Insulators, Microwave radiometry, Insulator contamination, Pollution measurement**

I. INTRODUCTION

High Voltage insulators are employed extensively in overhead transmission lines and substations and form an essential component in power systems and networks. The build-up of surface contamination on the insulators can lead to an increase in leakage current and partial discharge which may eventually result in flashover. Most commercial contamination monitoring systems are based on leakage current measurements using either a current transformer or a shunt resistor with an electrode ring to intercept the leakage current. Such systems suffer from two drawbacks: (1) their physical installation onto insulator circuit would reduce insulation security, and (2) systems are only effective when the contamination layer has been wetted by rain, fog or condensation; under this condition flashover is likely to occur within a short time period [1].

In order to address these problems, a novel monitoring method based on microwave radiometry was presented [2]. Microwave radiometry is one of the basic techniques for measuring electromagnetic radiation and has been widely used in astronomy, meteorology, oceanography, geography and hydrology [3]. Electromagnetic radiation of a material will cover a very wide frequency band. The distribution of the spectrum is a function of material's emissivity and temperature. The emissivity ε of a material represents the relative ability of its surface to emit energy by radiation and is referred to as the brightness temperature T_B. Brightness temperature refers to the temperature of a blackbody that would radiate the same power [4]. A polluted insulator emits a different electromagnetic energy level compared to a clean insulator due to the contamination layer. Thus, a radiometer, or passive receiver that detects the input power in a specific frequency band using an antenna, has the ability to monitor pollution level on an insulator surface.

In the present paper, an X-band (8.0 to 12.0 GHz) radiometer with high sensitivity and stability with relatively low cost was designed especially for monitoring insulator surface. A laboratory experiment was implemented to verify the system performance.

II. THEORETICAL MODEL

Radiometers are widely used in remote sensing for soil moisture distribution and work has been published on models to provide the soil salinity from brightness temperature [5]. Brightness temperature is affected by several unknown parameters including moisture, salinity, bulk density, thickness and surface roughness. Obtaining Equivalent Salt Deposit Density (ESDD) on insulator might therefore be treatable in a similar manner to soil salinity detection problems. For a contamination layer on an insulator, the influence of thickness and surface roughness can be ignored when compared to moisture and salinity because the layer is relativity thin with a smooth surface. The bulk density is calculated based on the properties of the artificial contamination layer described in IEC standard 60507 [6]. Thus, the key parameters that need to be inferred are moisture and salinity.

Fig. 1 shows the structure of the proposed system model relating radiometer output to ESDD. Within this framework, the dielectric mixing model evaluates the dielectric properties of insulator contamination layer as a function of moisture, salinity, environment temperature and humidity by assuming it as salt and water affected soil. The brightness temperature model describes the relationship between dielectric properties, emissivity and brightness temperature of a contaminated insulator. Finally, the radiometer model converts input power to output voltage and is related to system design.

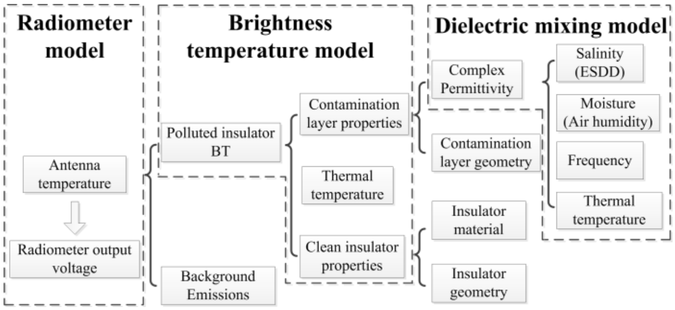

Fig. 1. Theoretical model of applying radiometry to monitor insulator contamination.

The detailed theoretical model is presented in [2]. Fig. 2 shows the relationship between salinity, frequency, moisture, angle of incidence and brightness temperature of a flat glass plane with varying levels of contamination. The brightness temperature increases with increasing salinity of the contamination layer at 0 ° angle of incidence. The sensitivity of the brightness temperature to salinity is higher at high moisture levels. Therefore, the radiometer will have better sensitivity to detect the ESDD of contaminated insulators under wet conditions than under dry conditions.

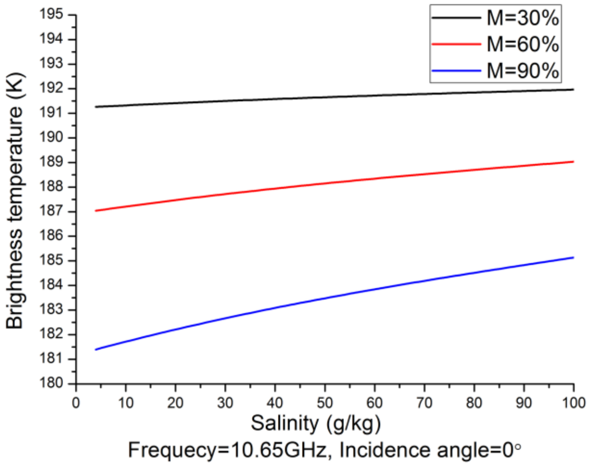

Fig. 2. Theoretical relationship between Brightness temperatures and salinity at different moisture level

III. RADIOMETER SYSTEM

The radiometer system developed for monitoring pollution levels on insulators is based on a Dicke radiometer with a superheterodyne architecture [3], as shown in Fig. 3. The radiometer system can be divided into five sections: (1) RF Input, (2) front-end, (3) downconverter, (4) back-end and (5) data acquisition (DAQ). The RF input signal to the radiometer systems is captured using a horn antenna with 20 dB gain, pointed towards the insulator sample. The system used in these experiments is a passive receiver with a centre frequency of 10.65 GHz and 1 GHz bandwidth. The output voltage of the radiometer is linearly proportional to the input power at the antenna. The design of the system has focused on optimizing accuracy, stability and sensitivity using a relatively low cost architecture.

A. Radiometer Design

The RF Input module detects the RF emission from the polluted sample and then compares with an external reference signal from a clean sample. The front-end circuit of the radiometer has two main tasks: selecting the input frequency band by filters and amplifying the signal by a low noise amplifier (LNA) to a proper level for the donwcoverter and the low-frequency circuit. The superhetrodyne circuit downconverts the X-band input signal to a 0-500 MHz signal. The back-end circuit again uses a LNA and a low pass filter to further improve the signal-to-noise ratio before a square-law detector provides a dc output voltage. After further amplifying and filtering, the dc output is captured by a DAQ card and a digital lock-in amplifier matched to the switching frequency between the input and reference signals.

The classical Dicke radiometer uses an RF switch to allow continuous comparison between the input power and an internal reference. The output of this Dicke radiometer can be expressed as [3]:

$$\begin{aligned} V_{out} &= c(T_A + T_{Ns})G - c(T_R + T_{Ns})G \\ &= c(T_A - T_R)G \end{aligned} \tag{1}$$

where c is a constant, G is the system gain, T_R is the equivalent antenna temperature of the internal reference signal and T_{Ns} is the system noise temperature generated by the thermal noise and instabilities of the individual components in the radiometer system. T_A is the antenna temperature which relates to the brightness temperature of the sample and background radiation and can be expressed as:

$$T_A = T_{AP} + T_{NPE} \tag{2}$$

where T_{AP} is the antenna temperature generated by the polluted test sample and T_{NPE} represent the contribution to the antenna temperature due to the background radiation of the surrounding environment of the test sample.

During initial testing of the Dicke radiometer on the insulator samples, the system was found to be very sensitive to external environmental conditions, such as changes in ambient temperature, background light and external RF interference. To address this issue an external reference signal from an antenna pointed at a clean sample was used to replace the internal thermal reference used in the classical Dicke radiometer system. Thus, T_R in Equation (1) can be replaced by:

$$T_R = T_{AC} + T_{NCE} \tag{3}$$

Since the polluted and clean samples have similar surrounding environmental conditions, these components will cancel out allowing Equation (1) to be expressed as:

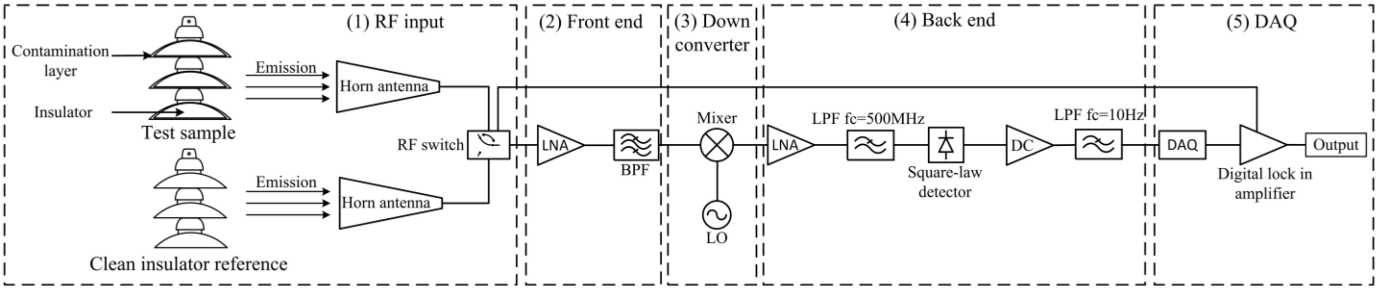

Figure 3. Block diagram of the X-band Dicke radiometer with external reference for monitoring contamination level on insulator surface

$$V_{out} = c(T_{AP} - T_{AC})G \tag{4}$$

The system output becomes dependent only on the brightness temperature differences between the polluted and clean insulator. The difference in the brightness temperature can be correlated to a change in ESDD levels.

The superheterodyne architecture utilizes a double balanced mixer and a 10.65GHz dielectric resonant oscillator to convert the observation frequency band 10.15-11.15GHz to a lower frequency band DC-500MHz, reducing system costs significantly. The local oscillator (LO) outputs +13dBm signal at 10.65GHz to drive the mixer. Both 500MHz bandwidth (10.15-10.65GHz and 10.65GHz-11.15GHz) sides of 10.65GHz are converted and compressed to DC-500MHz. The mixer has 5dB conversion loss on each side of frequency band.

In the back-end, two LNAs with 0.1 to 1000MHz bandwidth are connected in series amplify the downconverted signal for the square-law detector. A lowpass filter with 500MHz cut-off frequency is followed to remove unexpected noise. The square-law detector plays an important role in the radiometer system. Its output is a dc voltage which is linearly proportional to its input power. The employed detector can convert -40dBm to +20dBm input power in the frequency band 10MHz to 8GHz to an output voltage from 0.5V to 2.1V.

A 10Hz lowpass filter ensures DC voltage input to a DAQ card with 200MHz sample rate and 14bits resolution. To distinguish small dc voltage differences between clean and polluted insulators buried in noise, a digital lock-in amplifier was implemented. The lock-in amplifier couples the chopped input signal with 0.5Hz sine and cosine wave references, corresponding is the switching speed of the RF switch. I/Q demodulation is applied on 20 seconds coupled signals. The output is a dc voltage which is linearly proportional to the magnitude of the 0.5Hz signal. This digital lock-in amplifier also controls the system integration time.

B. *Radiometer Performance*

1) Sensitivity

The front-end LNA contributes to The system sensitivity is defined as the minimum change in brightness temperature that can be resolved and can be expressed as [3]:

$$\Delta T = 2 \cdot (T_A + T_{Ns}) / \sqrt{B \cdot \tau} \tag{5}$$

where B is the bandwidth of the radiometer, τ is the integration time. According to Equation (5), both the system bandwidth and the system noise have strong effect on sensitivity. The system noise temperature is expressed by:

$$T_N = (N_F - 1)T_0 \tag{6}$$

where N_F is the noise figure and To is the system temperature which is assumed to be 290K. The noise figure of each component was obtained from the datasheet. The system sensitivity is 0.016K with 20 seconds integration time as shown in Table 1 and can be calculated by using Equations (5) and (6).

TABLE I. RADIOMETER SYSTEM SENSITIVITY ANALYSIS

Components	Noise Figure (dB)	Total Noise figure (dB)	Noise temperature (K)	Sensitivity (K)
RF switch LNA Filter	0.25 3.5 0.2	3.95	855.5	0.016

Total Noise figure (dB)	3.95
Noise temperature (K)	855.5
Sensitivity (K)	0.016

2) Calibration

The calibration of a conventional Dicke radiometer uses two RF terminations with different, well-known noise temperatures to replace the antenna at the radiometer input. The relationship between antenna temperature and output voltage can be found from two data sets according to Equation (4). In our system, the external reference does not have a constant noise temperature compared to an internal reference. Thus, the system output voltages of two clean samples with the same material and geometry as the external reference but at different thermal temperatures are recorded to give the system equation:

$$V_{diff} = V_{offset} + 0.1021 \cdot T_{diff} \tag{7}$$

where V_{diff} is the output voltage after lock-in amplifier, V_{offset} = 21.01mV is the calculated internal voltage difference brought by RF switch and T_{diff} is the antenna temperature difference between sample and reference.

IV. EXPERIMENT

A. *Experimental setup*

To remove the effect of complex surface geometry of the HV insulators for the purpose of testing the concept, it was decided to use flat glass planes for the initial evaluation tests. The glass plane is 500 x 200 mm and 8 mm thick. The solid layer method recommended by IEC standard 60507 was employed to form an artificial pollution layer on the sample surfaces. This method involves uniformly spraying a pollution suspension on the sample surfaces to form a solid layer. The composition of the suspension used in tests comprised 6.5 g Kaolin, 150 g water and a suitable amount of NaCl to control the ESDD level. A 150 ml suspension was sprayed evenly on one sample surface and the sample. Four glass samples with 6 different contamination levels were tested. Table 2 lists the properties of the contamination layers on these sample pairs.

TABLE II. THE PROPERTIES OF THE CONTAMINATION LAYERS ON 6 SAMPLE PAIRS

Sample pair	NaCl (g)	ESDD (mg/cm^2)
1	3	0.0236
2	6	0.0436
3	9	0.0641
4	12	0.0827
5	15	0.1027
6	18	0.1176

The radiometer was allowed to stabilize for 1 hour before each test to achieve thermal stability within the system. Each sample was measured 40 times to remove errors generated by the impulsive noise lasting shorter than the switching time and to study the repeatability of the experiment. For each measurement, the radiometer outputs from the lock-in amplifier were recorded to provide a single dc value which is proportional to the average brightness temperature difference between the sample and the reference within 20 s time period.

B. *Results*

In order to verify the agreements between the experimental results and the theoretical model, the theoretical brightness temperature was calculated in [2] by using the particular parameters from the experiment and then converted to radiometer output voltages based on Equation (7). Fig. 4 shows the validation of the theoretical model by experimental results under dry condition of the glass samples.

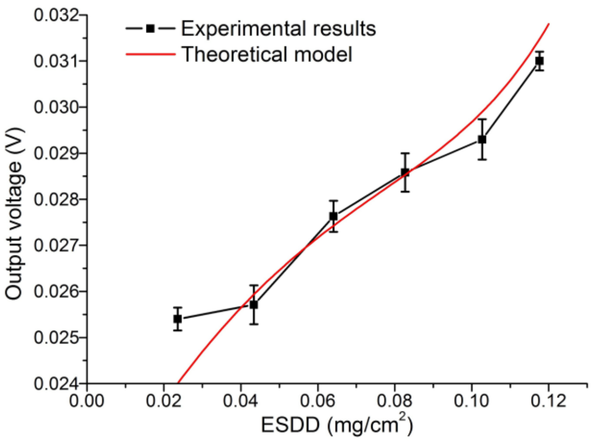

Figure 4. Output voltage from microwave radiometer system and theoretical model as a function of ESDD levels.

Fig. 4 indicates good agreement between the theoretical model and the experimental results for the output voltage from the microwave radiometer system as a function of ESDD levels on a glass substrate. The results show that the radiometer output voltage increases with the increasing of the ESDD levels on a glass sample’s surface. The error bars of experimental results show the range of values obtained across 40 repeat measurements taken for each sample. The disagreement of the first sample may be attributed to the variations in contamination level due to the particularly low concentration of NaCl in this case.

V. CONCLUSION

This paper has described the system design of an X-band radiometer for determining the ESDD levels on HV insulators surface. The system was tested under experimental conditions and the results demonstrated good agreement with system outputs and ESDD levels. This work provides a foundation for future investigations into the development of an on-line monitoring system for insulator pollution that is effective under dry conditions.

In future, the effect of complex surface geometry of insulator and Non-Soluble Salt Deposit Density (NSDD) will be studied. Because this novel method suffers very high external noise from surrounding environments, the study on further de-noising technology will be necessary for onsite testing.

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REFERENCES

[1] S. M. Gubanski, A. Dernfalk, J. Andersson, and H. Hillborg, "Diagnostic Methods for Outdoor Polymeric Insulators," IEEE Trans. Dielectr. Electr. Insul, vol. 14, pp. 1065-1080, 2007.

[2] Y. Jiang, S. G. McMeekin, A. J. Reid, A. Nekahi, M. D. Judd, and A. Wilson, "Theoretical Model of Applying Radiometry to Monitor Insulator Containimation", International Conf. Condition Monitoring and Diagnostics, Jeju, Korea, 2014.

[3] N. Skou and D. M. L. Vine, *Microwave Radiometer Systems: Design and Analysis*, Artech House, Incorporated, 2006.

[4] M. Z. Rahman, L. Roytman, and A. H. Kadik, "Refining environmental satellite data using a statistical approach", Proc. SPIE 8723 Conf., Sensing Technologies for Global Health, Military Medicine, and Environmental Monitoring III, Baltimore, Maryland, USA 2013.

[5] Y. Lasne, P. Paillou, A. Freeman, T. Farr, K. C. McDonald, G. Ruffie, *et al.*, "Effect of Salinity on the Dielectric Properties of Geological Materials: Implication for Soil Moisture Detection by Means of Radar Remote Sensing," IEEE Trans. Geosci. Remote Sens., vol. 46, pp. 1674-1688, 2008.

[6] IEC 60507, artificial pollution tests on high-voltage insulators to be used on a.c. systems, 1991.