DC FIELD SENSORS – UNUSUAL APPROACH

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ABSTRACT

We deal with several types of electric DC field sensors. Their operation is due to the movement of their sensing electrodes, which enables coupling of the sensor to the field sources in spite of the fact that the sources are DC ones. We show that the operation of most of the DC sensors is made explicable by appreciating that their electrodes movement creates a time varying coupling capacitance in their Thevenin equivalent. It is further shown that the latter Thevenin circuit, which possesses a DC source, can be converted to another Thevenin equivalent with an AC source. It enables a much simpler evaluation.

INTRODUCTION

Some recent works have demonstrated that DC field sensors can be accommodated under the wings of antenna theory [1], [2], [3], [4]. The relatively new approach is of value in letting sensors, which are usually regarded as an independent entity, to be treated using the highly developed machinery of antenna theory. A further advantage of the approach beside of letting better understanding of sensors is in paving the way for their systematic evaluation and design. Furthermore, the presently discussed methods, which have been developed in association with electric field sensors, can be extended to dealing with magnetometers [3], [4]. (The scenario is that of near field in spite of the fact that the sensor in absolute distances is far away from the sources).

The best known antenna perhaps is the dipole antenna. Dealing with sensors means that the corresponding dipole operates in its reactive mode and no radiation is taken into account. It is known, that in such circumstances the radiation resistance is much smaller than the structure resistance and it is completely ignored. The wavelength in such cases is much larger than the structure dimensions. Hence, the dipole relevant reactance is capacitive. The corresponding parameters, however, in the present work case tend to approach even more extreme values, since the sensing of DC fields is attempted. The capacitive reactance, when attempting to sense DC fields, tends to infinity. Hence, the sensor in such circumstances is not coupled to the measured sources. The remedy is the employment of time-varying sensor. Namely, when the field is steady or almost steady, the sensor becomes the varying entity [1], [3]. Many of the common dc field sensors are made explicable by appreciating that their performance is that of a modified time-varying dipole.

The main argument of the present work is that the mechanical movement in most of the DC field sensors leads the antenna capacitance to be time varying. The antenna capacitance is in fact the capacitance between the sensor electrodes in the external field. (It does not include the internal capacitance, which is due to the capacitance between the sensor electrodes in the internal field.) It can be shown, at least intuitively, that the latter antenna capacitance is also equal to the capacitance between the sensor electrodes and the far away electrodes that are regarded as generating the measured field. This intuitive approach may suggest that the movement of the electrodes causes the coupling between the sensor and the field sources to be time varying. As a result, the movement establishes a channel for sensing the field in spite of the fact that we deal with a DC case. The main approach developed in our work is rigorous and it relies on the Thevenin model. We show that the sensor system can be actually modeled by a time varying Thevenin equivalent. The time varying component in the model is the capacitance that connects the open circuit DC source of the model with the load representing the measuring device. It means that the previous intuitive approach is valid. We also show that the latter Thevenin model can be converted to a considerably more practical Thevenin circuit, where the DC source is replaced by an AC source. Furthermore, the time varying capacitance in the new model is replaced by a constant capacitance. The latter Thevenin model enables a practically simple evaluation of the sensor operation.

APPLYING THE METHOD FOR TREATING A DIPOLE LIKE DC SENSOR

A simple dipole can be employed for sensing ac electric fields. The dipole is shown in Figure 1. Its Thevenin equivalent is shown in Figure 2 [2].

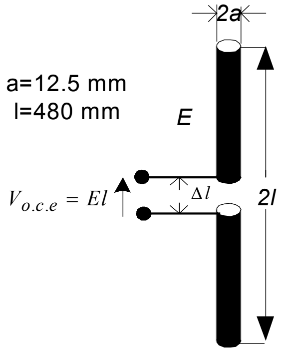

Fig. 1: A short electric dipole

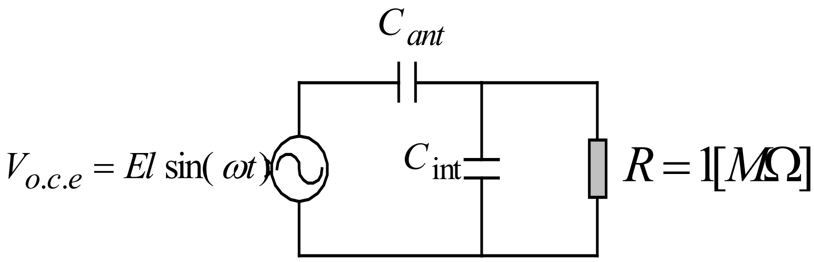

Fig. 2: Circuit Thevenin model for the sensor in Fig. 1.

Such a dipole, however, cannot serve to sense DC fields, since the reactance associated with C_{ant} in the Thevenin equivalent becomes very large at DC and low frequencies. C_{ant} is in fact the same as the parameter entitled as "antenna capacitance" when dealing with antennas. Its role in the Thevenin equivalent is well established in the literature on receiving antennas [5]. It possesses a similar role when sensors are dealt with. In the present sensor case, however, the "radiation resistance", which is of great importance for receiving antennas, can be completely ignored. We have investigated the sensor shown in Figure 1 [2, 4], and its series reactance is as large as $40 \; G\Omega$ at 1.0 Hz. It means that the system should be modified in order to be able to sense DC. The sensor is, therefore, modified to become time-varying. This is achieved by vibrating periodically one of its arms [4],which causes the antenna capacitance to be time- varying as well. Our investigation shows that the latter system can be represented by a Thevenin equivalent, which possesses time varying capacitances (both the antenna capacitance C_{ant} and the internal capacitance C_{int} are time varying). This is shown in Figure 3. The vibrating system is coupled mechanically to the antenna arm by a relatively long plastic rod. Sleeves are mounted [4] in the experimental system on the edges of the symmetrical electrodes. As a result, the vibration procedure does not change the overall length of the sensor. It merely changes the length of the gap in the middle.

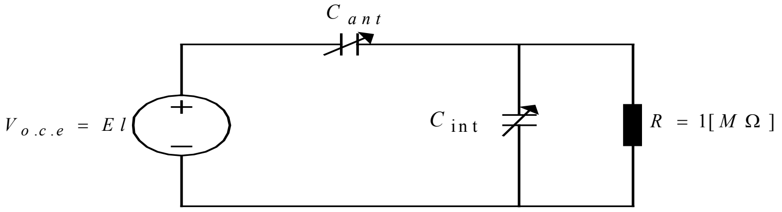

Fig. 3: The Thevenin circuit model describing the dipole with vibrating arms.

The resistor R represents the loading of the measuring device. The circuit model of Figure 3 can be solved by treating the related differential equation.

$$\dot{v}_R = -\left[\frac{\dot{C}_{ant} + \dot{C}_{\text{int}} + \frac{1}{R}}{C_{ant} + C_{\text{int}}}\right] v_R + \left[\frac{\dot{C}_{ant}}{C_{ant} + C_{\text{int}}}\right] v_{o.c.e} \qquad (1)$$

A solution of this equation will result the sensing signal v_R in terms of Thevenin open circuit voltage. The solution is made possible by substituting for the values of C_{ant} and C_{int} in equation (1). The latter values are known through our reported measurements and evaluations [4]. Their assumed sinusoidal time variation is a reasonable approximation, which is due to the mechanical movement being sinusoidal. An analytical solution of equation (1) is obtained by observing that the time varying parts of the related capacitances are much smaller than their average sizes, which enables an approximate solution. The final approximation is made simple by searching for the steady state solution of the sinusoidal output of v_R, namely for the amplitude $\hat{V}_R$ [3], [4],

$$\hat{V}_R = \omega\alpha R E l C_{0-ant} \qquad (2)$$

where C_{0-ant} is the average of the C_{ant}. α is the relative amplitude of the time varying portion of C_{ant}. This approximation relies also on the assumption that the average capacitive reactance of C_{int} is much larger than R in practical circumstances. It is, therefore, concluded that a relatively simple circuit can represent the steady state equivalent of the circuit in Figure 3. This equivalent circuit is shown in Figure 4. The latter equivalent circuit enables a simple description and understanding of the sensor operation. The evaluation of the measured field also becomes simpler through the latter equivalent.

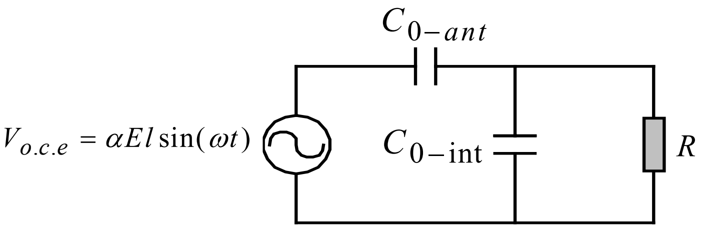

Fig. 4: simple circuit that represents the steady state equivalent of the circuit in Figure 3.

APPLYING THE METHOD FOR TREATING THE ROTATING COVERING FIELDMILL SENSOR

The rotating covering fieldmill is sketched in Figure 5. The system operation is usually interpreted in the literature as a sort of chopping device that converts the measured field DC displacement current to an AC current in the system electronics [3]. The chopping operation is due according to their explanation to the rotating disc of eight wings in relation to the stationary electrode. Our explanation is different and conforms to antenna theory. It is in fact similar to that of the previous dipole system. The evaluation of the open circuit $V_{o.c.e}$ in the present case is simpler than that of the previous system, since we can regard the disc like electrodes as coinciding with the field equipotential planes. It means that,

$$V_{o.c.e} = E\Delta Z\,, \tag{3}$$

Where E is the field intensity parallel to the sensor direction, and ΔZ is the distance between the rotating and the stationary electrode. In this case we can also distinguish between two types of capacitances. There exists there an obvious internal capacitance (in parallel to the load), which varies periodically eight times per rotation. However, there also exists an external capacitance that can be entitled as the antenna capacitance (C_{ant}) of the present system. The latter is also time varied, and is interpreted by us as responsible for coupling the sensor to the DC field sources. The present operation is, therefore, similar to that of the previous sensor and is represented by the time-varying Thevenin equivalent shown in Figure 6.

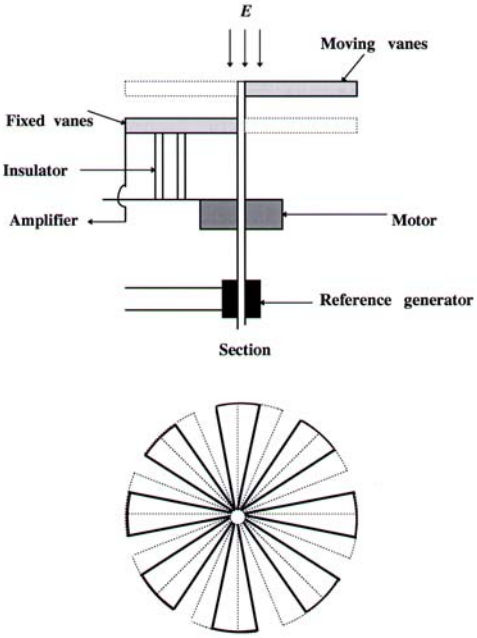

Fig 5: The rotating covering fieldmill

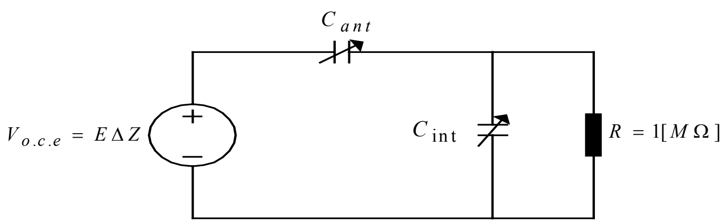

Fig. 6: The time-varying Thevenin equivalent that represents the system in Fig. 5.

The evaluation of the output signal in the present case is similar to that of the previous section. The result is also similar. The only difference is the additional 8, which is due to the effective frequency being eight times that of the rotational frequency, as is shown in equation (4),

$$\hat{\mathrm{V}}_R = 8\omega\alpha\,\mathrm{RE}\,\Delta Z\,\mathrm{C}_{0-a\,\mathrm{nt}} \tag{4}$$

Equation (4) leads to an AC Thevenin equivalent circuit model similar to that of Figure 4. The present AC equivalent possesses the same advantages as those explained at the end of the previous section.

OTHER RELATED ELECTRIC DC FIELD SENSORS

Some DC Field sensors, which are somewhat related to the previous ones, will be discussed in the present section. One of them is shown in Figure 7. It is similar in its operation mode to the rotating covering fieldmill (Figure 5). In both cases the so called sense electrode is stationary, while the so called shutter electrode is rotating in the fieldmill case and is vibrating in the present case. The great similarity, however, between the systems is due to the fact that the movement of the shutter in both cases is such that it is maintained in a plane parallel to the stationary electrode. As a result, the evaluation of the DC open circuit voltage is the same in this case as it was in the rotating covering fieldmill case. The Thevenin equivalent circuits in the present case are also closely similar to those related to the rotating covering fieldmill, and the resulted output signal evaluation should differ from that of Equation (2) merely by the missing 8 in the present case.

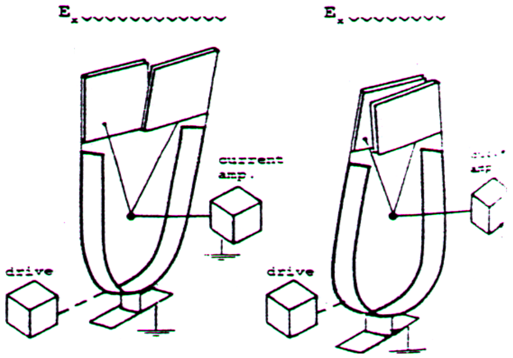

Fig. 7: An efork with parallel electrodes

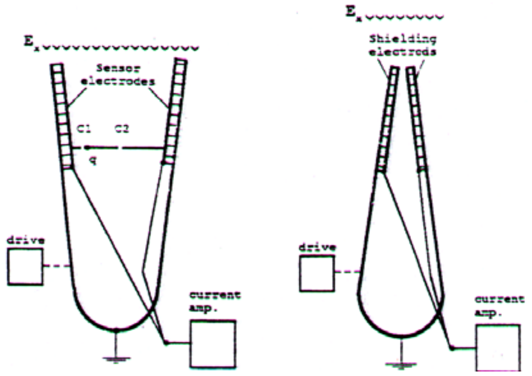

Fig. 8: An efork with an oblique movement of the electrodes

Another sensor is shown in Figure 8. It also possesses like the previous sensor two electrodes mutually mounted as a fork. The difference here, however, is that the mutual movement of the electrodes is not maintained in parallel. The electrodes in the present case move in front of each other as is shown in Figure 8. The evaluation of the DC open circuit voltage in the present case is more complicated than that of the previous sensor, since one cannot suggest that the planes of the electrodes here are always maintained in parallel and that they coincide with the equipotential planes of the measured field. Furthermore, the variation of the average distance between the electrodes as a result of their vibration in the present case is relatively large. Hence, the initial open circuit voltage in the present case possesses a relatively large AC component. As a result, the initial Thevenin representation in the present case includes time varying series capacitance as well as a mixed AC and DC voltage source. The final output signal evaluation is obtained by a superposition of a voltage similar to that of the previous paragraph sensor together with a voltage component that is due to the AC part of the open circuit voltage. The latter part of the output signal is similar to that generated in the cylindrical fieldmill [3]. We have shown that dual methods of analysis are also valid for some magnetic field sensors [1]-[4].

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