Study of Direct Energy Tapping From Electric Field

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***Abstract*- A method of extracting small amounts of power directly from the ambient electromagnetic field around a 50kV AC single phase line is described using a new approach to coupling capacitance. The amount of the power that may be extracted is limited. The proposed solution is vastly more cost effective than the alternatives of a transformer or a directly connected capacitive tap. The modelling and design limitations of the method are described and demonstrated on a scaled model.**

I. INTRODUCTION

The Sishen-Saldana (South Africa) railway line links the iron ore mines at Sishen to the harbour export facilities at Saldana bay. It is approximately 400km in length and often traverses large uninhabited areas of the Karoo. Traction power is supplied via an AC overhead line at 50kV. This power is used directly by the locomotive, and there is generally no other power source available to supply trackside services. Several sensor requirements along the track do however require small amounts of power at regular intervals.

In the absence of a low voltage ac supply the powering of these sensor applications is problematic. Tapping from the 50kV traction supply is not generally possible due to the high cost of a high voltage step down transformer. Capacitive tapping via the direct connection of a high voltage capacitor [1] is also relatively high in cost. Generally less than approximately 10 W of power is required. The possibility exists to supply this power through the use of a photo-voltaic panel and battery combination. However the problem with this solution is the high occurrence of theft of the panels. As the line is very remote, policing of it is impractical.

In this paper a low cost solution is proposed to tap small amounts of power directly from the ambient electromagnetic field around the line. The harvesting of small amounts of power has been attempted in the past by several methods. Normally the power required is very low in the µW or mW range [2,3] and use is made of piezoelectric transducers.

II. BACKGROUND

Capacitive coupling between two circuits is a well known phenomenon from the field of electromagnetic compatibility. Invariably this is a detrimental effect and ways are sought to minimize the influence of one circuit on another. In this investigation the capacitive coupling effect will be maximized to the extent that small amounts of meaningful power may be extracted from the coupling.

Two capacitors may be defined that are of interest. One is formed between the high voltage overhead line and the return current path through the track. This is a relatively small capacitance due to the large separation distance. However due to the high voltage of the line, a significant amount of energy may be stored in it. A second capacitor the harvesting capacitor is added to the system and consists of two conductive plates, one of which may also be referenced close to earth potential. This combination may be schematically described by the circuit in Fig. 1.

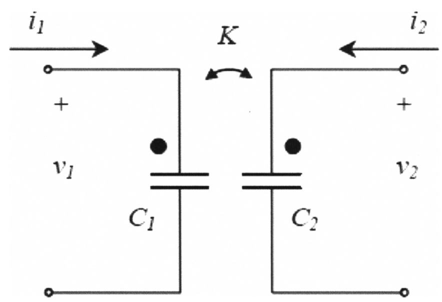

Fig. 1. Circuit description showing capacitive coupling

The behaviour of the coupling capacitance can be described by the equation of:

$$i_1 = C_1 \frac{dv_1}{dt} + K \frac{dv_2}{dt} \qquad (1)$$

with:

$$K = \frac{Q_2}{v_1} \qquad (2)$$

For analysis purposes the 4 conductor system previously mentioned will be considered. Two conductors each making up a conventional capacitor, and then the two capacitors coupled with each other. The equivalent structure is shown in Fig. 2. One capacitor is realized by conductors 1 and 2 and the other by conductors 3 and 4.

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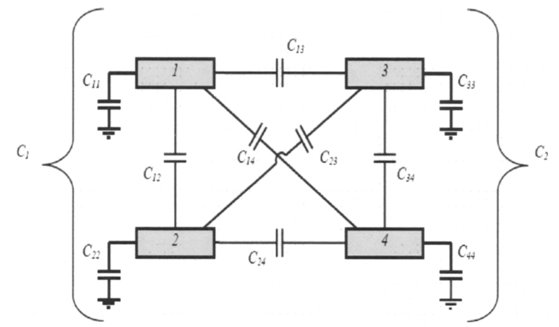

Fig. 2 Capacitive equivalent circuit of four conductors

The potentials on these four conductors can be described by the following expression:

$$\begin{cases} V_1 = p_{11}Q_1 + p_{12}Q_2 + p_{13}Q_3 + p_{14}Q_4 \\ V_2 = p_{21}Q_1 + p_{22}Q_2 + p_{23}Q_3 + p_{24}Q_4 \\ V_3 = p_{31}Q_1 + p_{32}Q_2 + p_{33}Q_3 + p_{34}Q_4 \\ V_4 = p_{41}Q_1 + p_{42}Q_2 + p_{43}Q_3 + p_{44}Q_4 \end{cases} \quad (3)$$

where p_{ij} are the coefficients of potential.

The definition of the coupling capacitance between two conventional capacitors as defined in the previous section can be applied to the above equations. From where the equivalent circuit model of the "electric" transformer may be determined. The coefficients of potential may be determined via measurement as well as via finite element modelling methods.

A unit test charge Q_{test} and $-Q_{test}$ is placed on the conductors 1 and 2 respectively. Conductors 3 and 4 are short circuited and therefore their voltages must be equal. Further, the charges on conductors 3 and 4 must be equal and opposite, as the two are electrical neutral. Therefore:

$$\begin{cases} Q_1 = -Q_2 = Q_{test} \\ Q_3 = -Q_4 = Q_{ind} \end{cases} \quad (5)$$

Subtracting V_3 and V_4 in (4) and setting it equal to zero with the above constrains gives:

$$Q_{ind} = Q_{test} \frac{p_{31} - p_{32} - p_{41} + p_{42}}{-p_{33} + p_{34} + p_{43} - p_{44}} \quad (6)$$

Under these conditions, the voltage developed between the plates of the initial capacitor can be determined by subtracting V_1 and V_2 in (4) which gives:

$$V_{dev} = Q_{ind}(p_{13} - p_{14} + p_{23} + p_{24}) + Q_{test}(p_{11} - p_{12} - p_{21} + p_{22}) \quad (7)$$

Making use of the definition of the coupling capacitor and dividing the result of (6) by (7) gives the coupling capacitance of the system in farads.

When working with a practical system, it may be easier to work directly in terms of capacitance rather then going the route of potential coefficients (6) & (7). The individual capacitance of the four conductors systems is shown in Fig. 2. Generally, it may be possible to neglect the self capacitance of the structure and set $C_{ii} = 0$. The absolute voltages of the structure may not be of much interest and it is the differential voltages which are often more important from the circuit point of view.

The definition for the coupling capacitance may be applied to the remaining circuit. If the assumption is maintained that the one capacitor is defined between conductors 1 and 2 and the second between 3 and 4, then the coupling capacitance is given by:

$$K_{12} = \frac{C_{14}C_{23} - C_{13}C_{24}}{C_{14} + C_{24} + C_{13} + C_{23}} \quad (8)$$

The effective value of the two capacitors doing the coupling should also come under consideration. Considering Fig. 2, the main coupling capacitance is not merely that of C_{12}, as the presence of the other conductors modifies the field situation. The total "input" capacitance is therefore given by the capacitance seen between terminal 1 and 2 with terminal 3 and 4 short circuited. This gives:

$$C_1 = C_{12} + \frac{(C_{13} + C_{14})(C_{23} + C_{24})}{C_{13} + C_{14} + C_{23} + C_{24}} \quad (9)$$

$$C_1 = C_{34} + \frac{(C_{13} + C_{14})(C_{23} + C_{24})}{C_{13} + C_{14} + C_{23} + C_{24}} \quad (10)$$

It is now possible to correctly predict the behaviour of two coupled capacitors and the circuit equations that can be used are:

$$i_1 = C_1 \frac{dv_1}{dt} + K \frac{dv_2}{dt} \quad (11)$$

$$i_2 = C_2 \frac{dv_2}{dt} + K \frac{dv_1}{dt} \quad (12)$$

The coupled capacitors could be modelled by the simplified transformer network given in Fig. 3. This network is the dual

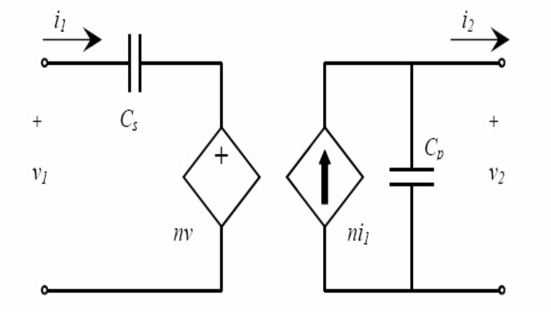

Fig. 3 "Transformer" representation

of the common two windings magnetic transformer model. The parameters of the model can be determined from (11) & (12). Cs is numerically equal to C1. The coupling factor *n* (or current gain under short circuit conditions) can be determined as:

$$n = K / C_1 \tag{13}$$

The value of the parallel capacitor (C_p) is given by:

$$C_p = \frac{C_1 C_2 - K^2}{C_1} \tag{14}$$

III. Proposed Solutions

In order to draw a small amount of power from the electric field and based on capacitive coupling, two possible practical solutions are proposed in this study:

- An isolated wire running parallel to the main line.
- An isolated metal plate in the vicinity of the main line.

A. *Isolated wire*

This solution consists of running an isolated wire parallel to the main line between two poles. Fig. 4 shows such model. This shows the overhead support structure of the line with the floating conductor of the pick-up capacitor mounted very close to the supporting structure and the HV cable; in this figure, the HV cable has three components: one for the contact with the pantograph and another two for carrying the main current, thus reducing the losses.

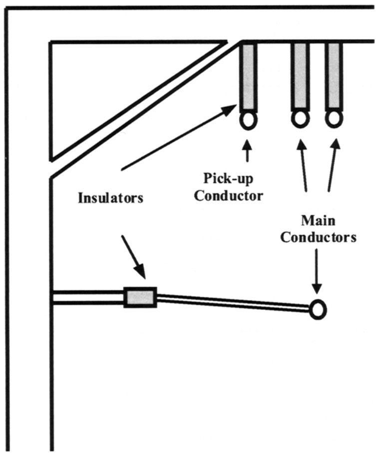

Fig. 4 Isolated pick-up wire

B. *Isolated plate*

Fig. 5 shows a plate isolated from a railway pole. As can be noticed, the isolated wire is replaced by a metal plate as armature of the pick-up capacitor.

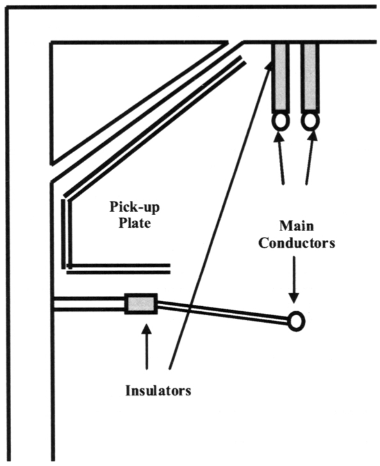

Fig. 5 Isolated pick-up plate

C. *Simulation results*

The result of finite element for the modelling the isolated wire is shown in Fig. 5. This simulation gave a capacitance of 3.72 pF/m. This can represent a short circuit power of 182 VA/m.

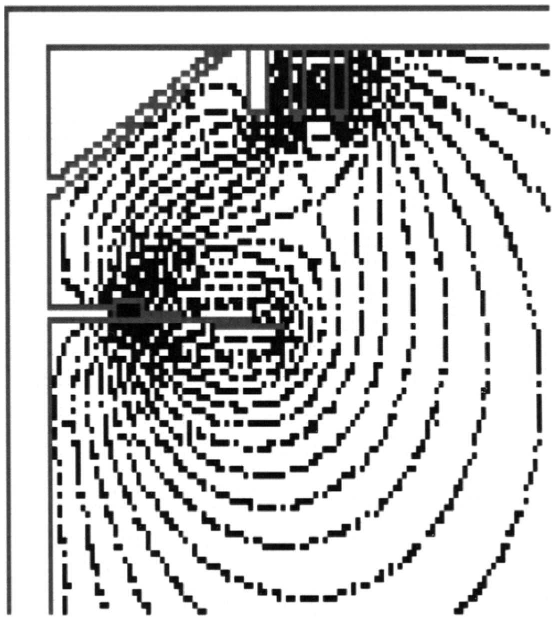

Fig. 6 Isolated pick-up wire: electric field distribution

The results of finite element for the isolated plate are shown in Fig. 7. From this simulation the equivalent capacitance is 1.63 pF/m, which represent a short circuit power of 127.9 VA/m of the given plate configuration.

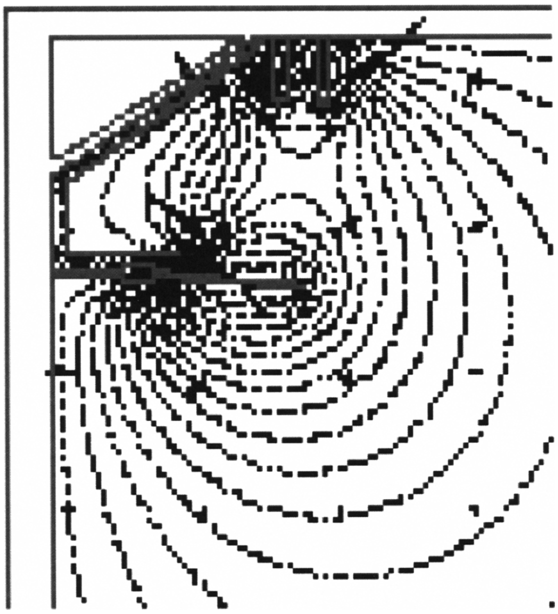

Fig. 7 Isolated pick-up wire: electric field distribution

IV. Experimental Results

In order to validate the simulation results and the feasibility of such tapping two experiments have been performed.

A. *Isolated wire experiment*

One experiment was concerning a conductor parallel with the high voltage line as presented in Fig. 8.

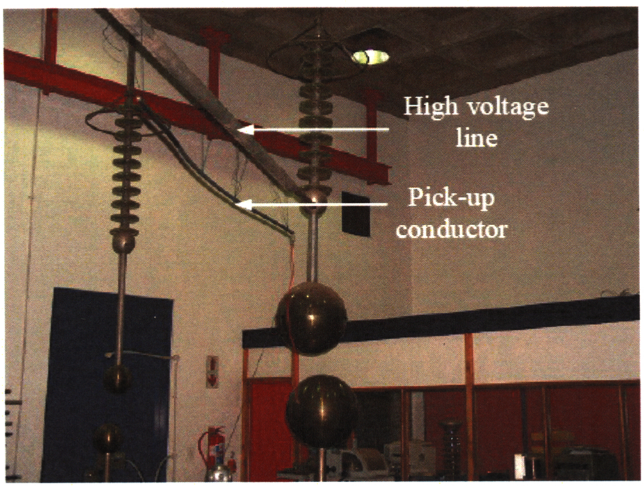

Fig. 8 Setup for isolated wire experiment

The pick-up conductor of 2.7 m, which was placed at 30 cm below the high voltage line, has been shorted to ground and the short circuit current measured while the high voltage has been varied from 40 to 100 kV in order to get significant current. The results are presented in Table I and Fig. 9 and the equivalent capacitance determined from this experiment is 4.71 pf/m. The above setup and for a voltage of 50 kV represents a short circuit power of 3.52 VA/m of pick-up conductor.

TABLE I
ISOLATED WIRE EXPERIMENTAL RESULTS

V (kV)	40	50	60	70	80	90	100
I (mA)	0.15	0.19	0.22	0.26	0.30	0.35	0.39

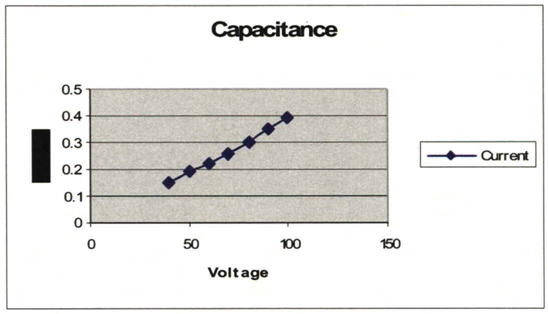

Fig. 9 Experimental results for isolated wire

B. *Isolated plate experiment*

The experiment has been repeated for a metallic plate whit the length of 915 mm and width of 455 mm. The plate has been placed on isolated support at 30 cm below the high voltage line as presented in Fig.10. The plate was shorted to ground and the short circuit current measured while the high voltage was varied between 15 and 55 kV. The results are presented in Table II and Fig. 11.

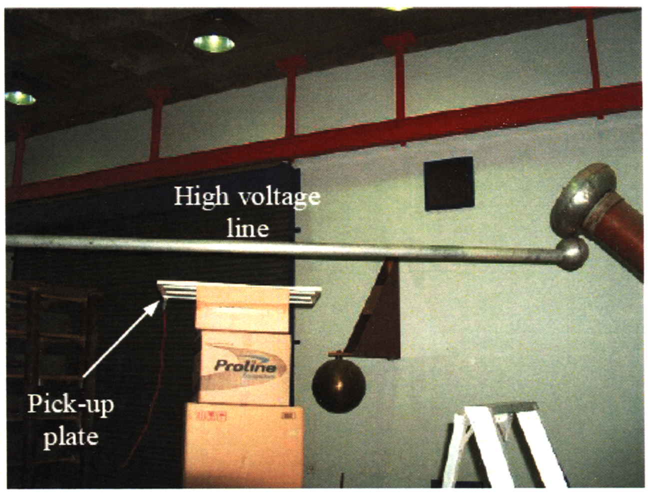

Fig. 10 Setup for isolated plate experiment

TABLE II
ISOLATED PLATE EXPERIMENTAL RESULTS

V (kV)	15	20	25	30	35	40	45	50	55
I (mA)	0.1	0.13	0.16	0.2	0.23	0.27	0.3	0.34	0.37

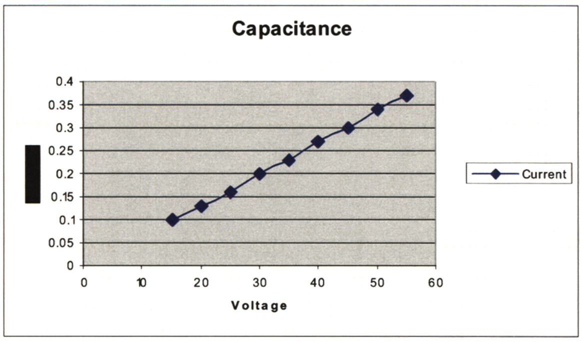

Fig. 11 Experimental results for isolated plate

For the experimental plate and for a voltage of 50 kV, the short circuit power was 40.8 VA/m^2.

V. CONCLUSIONS

In this paper has been studied the possibility of direct tapping from the electric field. Two possible tapping solutions have been investigated with simulation and experimental results presented. As can be noticed, the parallel isolated wire installed between two consecutive poles can deliver the necessary power but practical solution represents the hazard of wire braking. The isolated plate can capture a little bit more power.

The study has shown that is a real possibility of harvesting a small quantity of power directly but contactless from the electric field.

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