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Measurement of Voltage and Current in Electric Power Systems

Michael Davis

MEASUREMENT OF VOLTAGE AND CURRENT IN ELECTRIC POWER SYSTEMS

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INTRODUCTION

A. B. Chance Company of Centralia, Missouri requested a study of the latest state-of-the-art technology to measure voltage and current on a normal distribution power line. (4kV - 35kV)

The particular device that A. B. Chance needs must be relatively inexpensive, $200.00 per measurement, reliable, and capable of being manufactured by them.

Four types of power line measurement techniques were investigated; electrooptics/magnetooptics, present day measurement devices, the Raychem Line Monitor, and remote voltage and current sensing (RVCS).

The remote voltage and current sensing idea is the basis of the following report.

THEORY

One common type of voltage and current measurement technique used in power systems is voltage and current transformers. This type of measurement, while still effective, has just about reached its developmental maturity. Also, the devices have some draw backs. For instance: they are quite large and heavy, have the potential for catastrophic failure, and have low dynamic range.

Another possible way to perform power line measurements is with the use of optical sensors, meaning electrooptics and magnetooptics. The theory behind optical sensors is beyond my knowledge. However, the literature mentions that this technology needs much more research and development. Also, projected costs for the device are very high and the major application for these devices appears to be limited to the transmission level where voltages exceed 100kV.

Third, there is a device called the Raychem Line Monitor developed by the Raychem Corporation. The basic design is a coaxial capacitor that has a high voltage tap to measure the line voltage and a low voltage current transformer for measuring the line current. Even though the device has already been developed and does work, some development work would still be necessary to perform voltage and current measurement. Also, the projected cost of this device is about $400.00 for both measurements.

Finally, an idea was proposed by Dr. Todd Hubing to use remote sensing to measure the voltage and current of a power line. The basic theory behind this device is that if field sensors are placed near power lines the electric and magnetic fields could be measured. With this information, using electronics and a inexpensive digital signal processor the voltage and current on each line of a three phase distribution power line could be calculated. Also, the cost of such a device would be about $200.00 per measurement, which is within the limits set earlier, and is capable of being produced by A. B. Chance.

REMOTE VOLTAGE AND CURRENT SENSING

Dr. Hubing's proposal is to place field sensors near the three phase distribution power line to detect the respective electric and magnetic fields produced. Figure 1 shows a possible arrangement of the field sensors around the power lines. Depending on how the sensors are arranged, a constant and unique 3×3 matrix of coefficients for each configuration can be developed. Calculation of the matrix coefficients will be explained later.

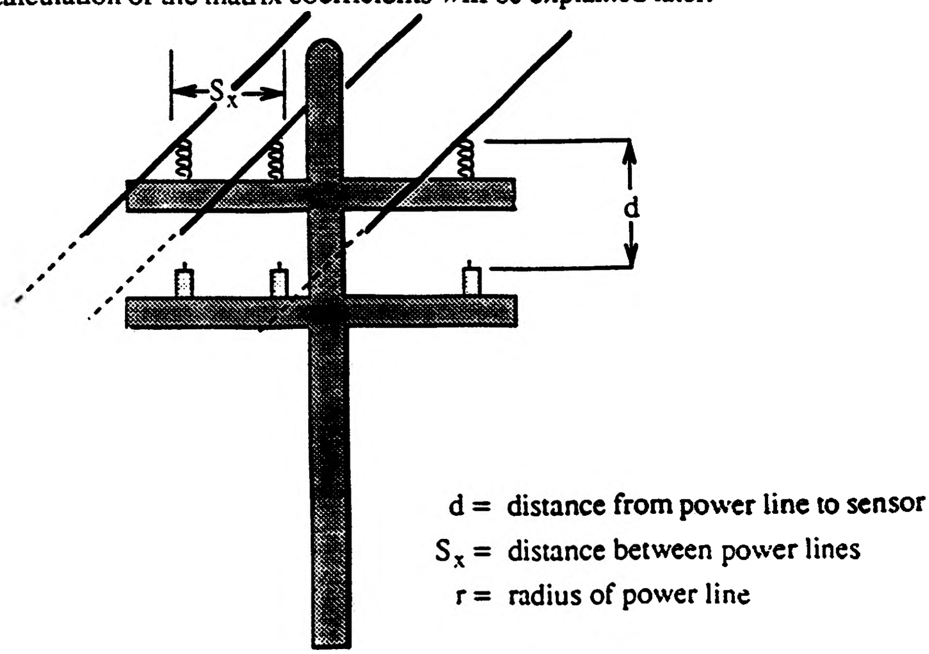

Figure 1:
Remote Voltage and Current Sensing

Assuming the matrix coefficients are known, Equation 1 shows the relationship between the electric field, line voltages, and the matrix coefficients. It should be noted that the same equations can be related to magnetic field and line current. The only changes are to substitute magnetic field for electric field and line current for line voltage.

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (1a)$$

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^{-1} \times \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (1b)$$

Electromagnetic theory was employed to determine the matrix coefficients. Appendix A contains two lists of matrix coefficient equations. The first list of equations are valid for sensor configurations similar to Figure 1. The second list of equations is an approximated version of the first that assumes an infinite ground plane and considers the effect produced by the image. For this approximation to be valid there must be strong electric fields present and the distance between the power lines should be small compared to the distance of the sensor from the line. The approximated version will not be considered further. Dr. Hubing developed the matrix coefficient equations which are explained as follows:

Figure 2 shows a two dimensional view of a possible sensor configuration with electric field lines.

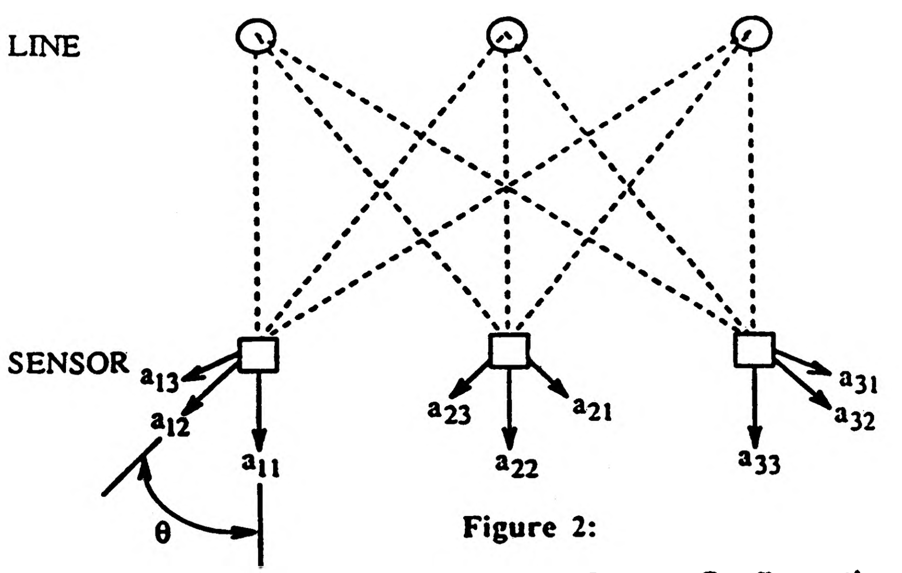

Figure 2:

Electrical Field Lines for Sensor Configuration

$$a_{xy} = \frac{\cos\theta}{z \times \ln\left(\sqrt{z} / r\right)} \tag{2a}$$

$$a_{xy} = \frac{2 \times \cos\theta}{z \times \ln(d / r)} \tag{2b}$$

Equation 2a & 2b show the basic form of the equations for the first and second list in Appendix A, respectively. The 2 in the numerator of Eq. 2b came from assuming an infinite ground plane and θ in Figure 2, is the angle that a_{12}, a_{13}, a_{21}, etc. makes with the vertical.

The theory behind the techniques is that each probe would be a single mono-pole that can detect the vertical component of the total electric field from each power line. However, a fault of some sort on one of the lines would cause a change in the voltage level and the resultant electric field. Since this would be detected by the field sensors, the calculated line voltages would reveal the fault.

With this in mind, initial development of the electronics to perform the matrix calculations for the device began under the guidance of Professor Herrick. The electronics development began on the TMS32010 Digital Signal Processing Development System. However, initial progress was slow, partly because of the need to learn Assembly Language programming and also due to limitations in the commands on the chip. Because of this, development was moved to the Computer Research Lab CRL25 Development System for the TMS320C25 DSP chip in the UMR computer lab. This system used the Fourth programming language. Converting a program from Fourth to Assembly language is relatively quick with only a few differences in the list of commands. Since the TMS320C25 is a higher member of the DSP family, the assembly language program can be performed by the TMS32010 chip with the only difference being that some commands on the TMS320C25 have to be two separate commands on the TMS32010.

The program was developed on the basis that there was a 60 Hz signal that could be sampled 32 times per period. This sample rate is high enough to catch most fault conditions; however, definitely not quick enough to detect faults from a lightning strike. A listing of the program is provided in Appendix B and deserves further explanation.

The program was written on fifteen screens of Fourth starting with screen #33 (SCR #33), screen #34 (SCR #34), etc. SCR #33 and #34 each contain a look up table for a 1.25 period sinusoid. The true values in the table are scaled for peak values of 1 and -1; however, the numbers listed in the table are between 32767 and - 32767 to make entering hexadecimal constants easier. SCR #34 differs from SCR #33 by a 5.625 degree phase shift. This was done to determine the error caused by not being able to represent +1 on SCR #33. SCR #34 eliminates this error. Further calculation for this program have been done with SCR #33. SCR #35 is a program that involves the electric field signal with the sinusoid look up table to produce the real and imaginary components of the measured signal along with their relative phase, for each A/D channel. An interesting feature of this is the fact that it extractes the 60 Hz component of the signal by taking the Fourier Transform, thereby eliminating the second and third harmonics. SCR #37 is used to plot sample waveforms to a printer. SCR #36 and #38 are used to derive three sample signals given the first three values of each waveform. Again, the amplitude of the waveforms are scaled to ±1. The formulas used to calculate the first three values of the waveform are shown in Equation 3.

$$u_K = 2 \times 2^{15} \times \cos[(2 \times 3.14)/32] \qquad (3a)$$

$$n_{Y2} = 2^{15} \times \sin[(2 \times 3.14)/32 + \phi]; \quad \phi := \text{phase shift} \qquad (3b)$$

$$n_{Y1} = 2^{15} \times \sin(\phi) \qquad (3c)$$

$$n_{AMP} = \text{magnitude of electric field} \qquad (3d)$$

SCR #39 is used to display the waveform on the monitor. SCR #40 was used to determine the worst case conditions. These calculations provided the overflow limitations on the output. SCR #41 solves the three simultaneous equations shown in Eq. 1b. SCR #42 outputs the result on the monitor. The output includes scaling factors for the matrix coefficients and the line voltages. SCR #43 is the main program and it links all the necessary programs together. Screen #44 thru #48 provide a list for matrix coefficients of different configurations and test cases to go along with them. The first matrix configuration is for a symmetrical situation where the sensors are about three meters away, called MATRIX1. A second matrix configuration is for the unsymmetrical case about three meters away also. This one is called MATRIX2. Finally, the third matrix configuration is for the sensors close to the lines, only about .3 meters away, called MATRIX3. For the matrix coefficients, MATRIX1, the test cases that go along with it are; TEST1 - TEST4. For MATRIX2, the test cases are; TEST5 - TEST8. For MATRIX3, the test cases are: TEST9 - TEST12.

The type of tests they perform is, assuming there is a three phase, 30kV distribution line, Eq. 1a was used to calculate the electric fields generated. If phase A, B, or C were down, then this would result in different electric field calculations. After the electric fields are calculated, Eq. 3a - 3d are used to determine the first three points and the magnitude of each waveform. From these points, SCR #38 of the program generates the hypothetical electric field waveforms. The process just mentioned determines the theoretical signals detected by the field sensors for each A/D channel. Since the matrix coefficients are known, SCR #41 performs the calculation of Eq. 1b resulting in a scaled version of the voltage on each phase.

CONCLUSION

After is was determined that the line voltages could be calculated, a discussion with Dr. Stanton of UMR about the possible applications of such a device took place. Several comments from him were quite interesting and some appear below.

Such a device could be implemented in three ways. One way would be for it to simply detect if each individual line is energized or not. Even though this method is possible, it is quite primitive and will not be considered further.

Another possible application would be for it to actually reveal the calculated line voltage. If the actual line voltages were known, along with some detailed information about the line, it would be possible to determine the exact location of the fault, either direction from the measurement site. While this method might be used in the future, further developments of such an application are too sophisticated to be considered now.

The third way to implement the device would be to place the sensors at various locations along the distribution line and have the device compare measured conditions to normal conditions. From this it would determine if each phase had normal voltage, no voltage, or some useful intermediate voltage range. For instance, if a fault occurred on phase C, then normal voltage would be detected on phase A & B, but the voltage detected on phase C would vary according to the impedance of the line. The same approach can be made for current measurement using a coil sensor. If voltage and current measurements were available, fault currents on each phase could be detected and combined with line voltages to provide even more information.

The results of this project showed that a Digital Signal Processing chip can easily perform the computational aspects of this technique. Also, using the TMS32010 DSP, which is about $6.00 per chip, along with additional digital logic and circuitry make the projected cost for such a device to be about $200.00 per measurement.

Finally, the next step would be to build a prototype and make tests and design changes as necessary.

ACKNOWLEDGEMENT

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