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Innovative Modeling and Simulation of Electric Power Systems

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Abstract: In the last decades many papers and textbooks devoted to the computer modeling and analysis of large power system network have been written. For the most part the models and analysis techniques have been developed for large interconnected transmission systems (TS) and synchronous generators. Little, relatively, attention was devoted to the distribution systems (DS) and its major components. As a result, the distribution engineer has not had the same number of tools as the systems engineer to analyze the distribution system under steady-state (power flow) and fault (short circuit) conditions. Without these tools the distribution engineer has been left in the dark (no pun intended) as to the operating characteristics of distribution feeders. Line segments in distribution systems are inherently unsymmetrical. That is, the spacing distances between phases are not equal and the lines are not transposed; as is typically done on high voltage transmission lines. The non-symmetry results in unequal self and mutual impedances. Couple this with line currents that are typically unbalanced and a potential for severe voltage unbalances can occur along with additional line power losses. For a four wire grounded Wye line, the unbalanced operation leads to currents flowing in the neutral and dirt. Original literature uses the term “dirt current”. In other literature, the reader will also find the terms “ground” or “earth dirt”. This presentation will develop a method for the computation of the “neutral” and “dirt currents” and the power losses that are a result of these currents.

Keywords**:** Smart Grids, Carson's Equations, Wave Propagation, Overhead Wires with Ground Return, Neutral and “Dirt” Currents, Real Power Losses, Protection of Power Systems.

1. INTRODUCTION

It has been written many papers and books focusing on numerical modeling and analysis of large energy systems, however most of it is designed for the interconnected transmission system (Neuman, 2011), (Neuman and Jirkovsky, 2015). Relatively little attention was paid to the distribution system (DS) and its main elements. The result is that the distribution engineer does not have the same number of tools for simulation and analysis of the distribution system as transmission system engineer; e.g. PLF - power load flow at steady state and Failure and transients (short circuits). The paper touches the issue of dynamic models of distribution systems and the possibility of "smart" automatic control (Neuman, 2014).

This paper fits into the upcoming celebrations of IFAC’s 60^{th} anniversary, which will be held at the 20^{th} World Congress of the IFAC 2017, Toulouse, France.

Distribution feeders are inherently unbalanced. That is loads are generally unbalanced and lines are not transposed. The analysis of the operating conditions for a distribution feeder must model the line segments as accurately has possible. The application of the modified Carson’s equations allows for a very accurate model of the line segment and does provide a means for computing the current flowing in the neutral conductor and “dirt”. The term “dirt” is used to distinguish it from “ground” current which usually is the sum of the phase currents without any regard to the return path for the “ground” current.

2. Celebration 2000, and THE CONTINUITY OF THE 21ST CENTURY

2.1 The most Important Work and Publications Past Century

The passing of the year 2000 into history, and the recognition of the roll-over of the calendar to 21^{st} century has not occurred without reminiscence of the past and wonderment for the future. The use of digital controls, and computer operations in many elements of modern life. Power engineering has a considerable number of accomplishments that should be acknowledged at this time. Major publications of the 21st century were not quite deliberately considered.

The 39 + 1 nominated high impact papers appear in Table 1. (Heydt et. al., 2000). The 39 nominated papers were identified by National Academy of Engineering of the United States, invited participating profesional engineering societies (ASME, IEEE, ANS, and others), members of the Power Globe, and some students. Another paper is added to the context of this paper (G. Kron, 1952).

2.2 The Neutral and Dirt Currents and Power Losses

For more applications of „Phase Impedance Matrix for Overhead Lines“(J. Carson, 1926), the primitive impedance matrix needs to be reduced to a matrix consisting of the self and mutual equivalent impedances for free phases. One standard method of reduction is the Kron reduction. The Kron reduction method applies Kirchhoff’s voltage law to the circuit.

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Table 1. Nominated high impact papers of 1900 – 1999 / five high impact

Final 4+1 papers (positive / total votes)	**Nominated high impact papers of 1900-1999**				
	1	W. Lyon	Problems in Electrical Engineering Alternating Currents	McGraw Hill, NY	1908
1 (47/73)	2	C. Fortescue	Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks	Transactions of the AIEE, vol. 37, p. 1027-1140	1918
	3	C. Fortescue	Transmission Stability, Analytical Discussion of Some Factors Entering Into The Problem	Transactions of the AIEE, vol. 44, p. 984-994	1925
4 (19/73)	4	J. Carson	Wave Propagation in Overhead Wires with Ground Return	Bell System Technical Journal, vol. 5, p. 539-554	1926
2 (36/73)	5	R. Park	Two Reaction Theory of Synchronous Machines	Transactions of the AIEE, vol. 48, p. 716-730	1929
	6	C. Fortescue, A. Atherton, J. Cox	Teoretical and Field Investigations of Lightninig	Transactions of the AIEE, vol. 48, April, p. 449-468	1929
	7	E. Clarke	Simultaneous Faults on Three Phase Systems	Transactions of the AIEE, vol. 50, March, p. 919-941	1931
	12	E. Clarke	Problems Solved by Modified Symmetrical Components	General Electric Review, vol. 41, p. 488-494, 545-549	1938
	14	E. Clarke	Circuit Analysis of AC Power Systems, Symmetrical and Related Components	John Wiley, NY	1943
3 (19/73)	19	J. Ward, H. Hale	Digital Computer Solution of Power Flow Problems	Transactions of the AIEE, vol. 75, Pt. III, p. 398-404	1956
	27	G. Kron	Diakoptics	MacDonald, London	1963
	39	C. Concordia, J. Paserba	Opportunities for Damping Oscillations by Applying Power electronics in Electric Power Systems	CIGRE Symposium, Tokyo, report No. 38.01.07	1995
5		G. Kron	Tensorial Analysis of Integrated Transmission Systems	Transactions of the AIEE, vol. 71, Pt. I,	1952

Because distribution systems consist of single-phase, two-phase, and especially untransposed three-phase lines serving unbalanced loads, it is necessary to retain the identity of the self and mutual impedance terms of conductors and take into account the ground return path for the unbalanced currents. Carson's approach was to represent a line withthe conductors connected to a source at one end and grounded at the remote end. Fig. 1 illustrates a line consisting of two conductors (i and j) carrying currents (I_i and I_j) with the remote ends of the conductors tied to ground. A fictitious "dirt" conductor carrying current I_d is used to represent the return path for the currents.

Carson assumes the earth is an infinite, uniform solid with a flat uniform upper surface and a constant resistivity. Any end effects introduced at the neutral grounding points are not large at power frequencies, and therefore neglected.

It is assumed: ρ [Ω/m]… Earth resistivity, ρ = 100 [Ω/m].

2.3 Line Segment Model

A. The Modified Carson's Equations. The analysis of the unsymmetrical line with unbalanced currents starts with a model of the line where the impedances have been calculated using the modified Carson's equations. In order to apply these equations, it is important to understand how they are developed.

The development starts with the application of the general flux linkage equation (1), (2). This application leads to the general equations for the self and mutual impedances of conductors.

$$z_{ii} = r_i + j\,0.12134\ x\ ln\frac{1}{GMRi}\ [\Omega/\text{mile}] \qquad (1)$$

$$z_{ij} = j\,0.12134\ x\ ln\frac{1}{Dij}\ [\Omega/\text{mile}] \qquad (2)$$

where:

z_{ii}	self impedance of conductor *i*
z_{ij}	mutual impedance between *i* and *j*
r_i	resistance of the conductor *i*
GMR_i	Geometric Means Radius of the conductor
D_{ij}	spacing between conductors *i* and *j* [ft]

These equations can be applied to a one mile long line consisting of two conductors that are grounded at the remote end as shown in Figure 1.