A Time Domain Model for Flicker Analysis

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Abstract This paper presents a time domain model of an electric power system for the purpose of studying voltage magnitude variations due to the operation of an arc furnace. The time domain model of the arc consists of the nonlinear characteristics of the arc and the associated absorbed energy. The rms value of the voltage can be computed anywhere in the system. The voltage variation is compared to flicker threshold values as defined in standards. Typical results in a test system are presented in the paper.

1. Introduction

Operation of nonlinear loads cause distortion of the sinusoidal waveform of the voltage and current which are quantified with harmonics. If the nonlinear load is also varying with time, as is the case of arc furnace loads, the rms value of the electric load is also varying. Lighting, which is affected by the voltage variations, may flicker which cause a certain degree of unpleasantness. This phenomenon has been known since the early days of power systems. Advances in power system technology and interconnections resulted in large power systems and the minimization of flicker type behaviour of a power system.

2. Modeling of Power System Devices

Models of power system elements are derived in direct phase quantities (a, b, c, and n (neutral) for three phase neutrals or L1, L2 and NN (neutral) for secondary service systems). The modeling procedure starts from a set of algebraic-differential-integral equations which describe a power system element. These equations are transformed into (a) a quadratic state space model or (b) a quadratic frequency domain model. These models are used to obtain the overall network solution with a Newton type algorithm. Details of the model and network solution are presented next followed by examples.

2.1 Time Domain Device Model

Any power system device is described with a set of algebraic-differential-integral equations. It is always possible to cast these equations in the following general form:

$$\begin{bmatrix} i \\ 0 \end{bmatrix} = \begin{bmatrix} f_1(\dot{v}, \dot{y}, v, y, u) \\ f_2(\dot{v}, \dot{y}, v, y, u) \end{bmatrix} \tag{1}$$

where i : vector of terminal currents,
v : vector of terminal voltages,
y : vector of device internal state variables
u : vector of independent controls.

Note that this form includes two sets of equations which are named *external equations* and *internal equations* respectively. The terminal currents appear only in the external equations. Similarly, the device states consist of two sets: *external states* (i.e. terminal voltages, v(t)) and *internal states* (i.e. y(t)). The set of equations (1) is consistent in the sense that the number of external states and the number of internal equations equals the number of external and internal equations respectively.

Equations (1) are integrated using a suitable numerical integration method. Assuming an integration time step h, the result of the integration is approximated with a second order equation of the form:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \frac{1}{2}\mathrm{diag}(v(t), y(t)) \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \frac{1}{2}\begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \mathrm{diag}(v(t), y(t)) \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix} \tag{2}$$

where $b_1(t\text{-}h)$, $b_2(t\text{-}h)$ are past history functions.

2.3 Example: Arc Model

The arc model consists of a nonlinear relationship between the arc current and arc voltage, i.e.

$$i(t) = k_1(v(t)/v_{01})^{\alpha_1} + k_2(v(t)/v_{02})^{\alpha_2}$$

where i(t) is the arc current
v(t) is the arc voltage
k_1, α_1, k_2, α_2, v_{01}, and v_{02} are model parameters

3. Network Solution

The network solution is obtained by application of Kirchoff's current law at each node of the system. This procedure results in the set of equations (3). To these equations, the internal equations are appended resulting to the following set of equations.

$$\sum_k A^k i^k(t) = I_{inj} \tag{3}$$

internal equations of all devices (4)

where I_{inj} is a vector of nodal current injections, A^k is a component incidence matrix with:

$\left\{ A_{ij}^{k} \right\}$ =1, if terminal j of component k is connected to node i

= 0, otherwise

$i^k(t)$ are the terminal currents of component k.

The component k terminal voltage $v^k(t)$ is related to the nodal voltage vector v(t) by:

$$v^k(t) = (A^k)^T v(t) \tag{5}$$

Upon substitution of device equations (2), the set of equations (3) and (4) become a set of quadratic equations. These equations are solved using Newton's method. Specifically, the solution is given by the following expression.

$$\begin{bmatrix} v(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} v^0(t) \\ y^0(t) \end{bmatrix} - \left\{ \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} + \frac{1}{2} \mathrm{diag}\left[\begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \mathrm{diag}(v^0(t), y^0(t)) \mathbf{1} \right] \right.$$

$$\left. + \frac{1}{2} \mathrm{diag}(v^0(t), y^0(t)) \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \mathrm{diag}(v^0(t), y^0(t)) \right\}^{-1} \begin{bmatrix} B_1^0 \\ B_2^0 \end{bmatrix} \tag{6}$$

where :

$v^0(t), y^0(t)$ are the values of the state variables at the previous iteration, B_1^0, B_2^0 represents the mismatch of the system equations of the previous iteration, and $\mathbf{1}$ is a column vector with all entries equal to 1.

Note that at each time step, the quadratic device model is an approximation of the nonlinear device equations. For this reason, the above procedure utilizes an iterative algorithm which is applied at each time step. The algorithm is illustrated in Figure 1.

4. Applications

The proposed method has been applied to an example power systems with an arc furnace. The single line diagram of the system is illustrated in Figure 2. For this system we compare the harmonics and flicker at BUS10, BUS20, and BUS30. The computed flicker is compared to the allowable limits as described in [13]. For convenience the permissible flicker curves are presented in Figure 3.

Figure 4 illustrates the time wavform and the rms value (over a sliding window of 16.6667 mseconds) of the voltage at buses BUS20 and BUS30 (see Figure 2). Figure 5 illustrates the rms values of the voltages at the three buses of the system (BUS20, BUS30 and BUS32KV) as well as the variation of the electric real power absorbed by the furnace. Note that the power varies with a frequency of 5 Hz. The maximum power is 18.3 MW per phase and the minimum is 13.1 MW per phase. Note that in the model we can simulate any variation of the arc power, including random variations. However, for the simulation shown we elected to use a periodic variation with frequency 5 Hz. The rms values of the voltages vary in the ranges (61.2-64.3 kV), (58.8-62.7 kV) and (15.5-17.0 kV) for the buses BUS20, BUS30 and BUS32KV respectively. The percentage variations are 4.06, 6.63 and 9.68% respectively. It is important to note that the rms value of the voltage variation is high near the furnace and decreases for buses further away from the furnace. This is to be expected in a system that does not have capacitor banks. In systems with capacitor banks, however, the voltage variation profile may be different. With reference to Figure 3, the computed voltage variations will be noticed as flicker above the threshold of perception (at 5 Hz the threshold of perception is about 1.3%).

5. Summary and Conclusions

A time domain model for computing flicker due to changing electric loads, such as electric furnace loads, has been presented. The model is based on a quadratic equivalent representation of each element in the system and subsequent simultaneous solution of all equations. When there are nonlinear elements, such as an electric furnace, this approach yields a method with quadratic convergence characteristics. The result is an accurate and efficient computational method. The solution provides the waveforms of voltages and currents anywhere in the system. From the waveforms, any other desirable quantity can be computed such as rms values, real power, reactive power, distortion power, etc. Typical results have been presented in the paper. Our experience with this method indicates that the use of quadratic equivalent representation for each element of the system results in a robust real time simulation method.

6. References

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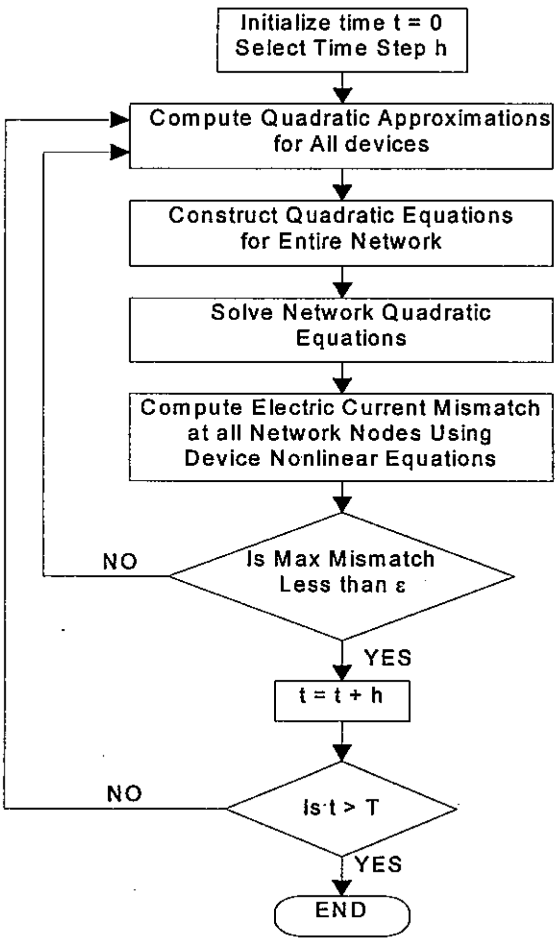

Figure 1. Network Solver Algorithm

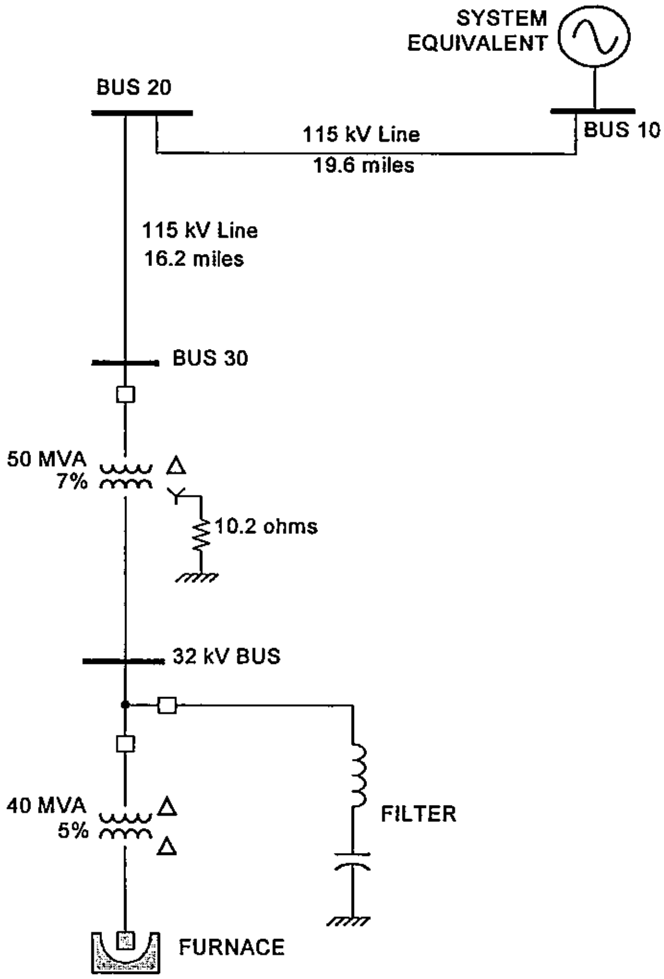

Figure 2. Example Test System

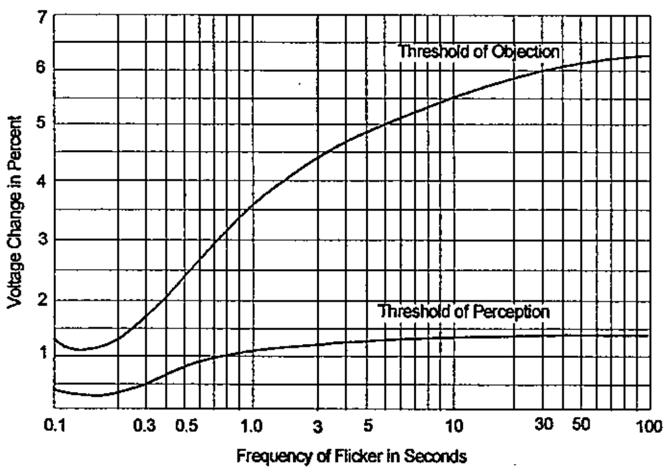

Figure 3. Range of Observable and Objectionable Voltage Flicker Versus Time (from reference [13])

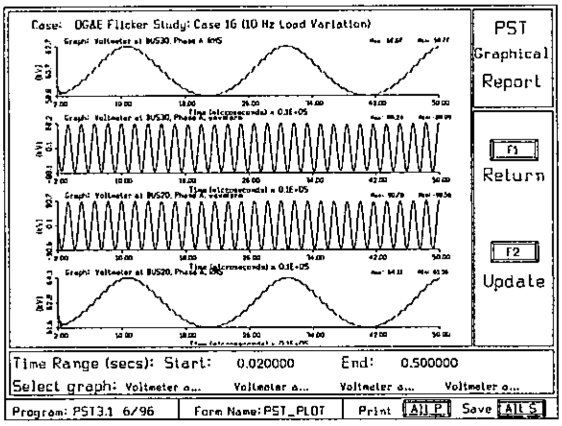

Figure 4. Waveform and RMS Variation of the BUS20 and BUS30 Voltage

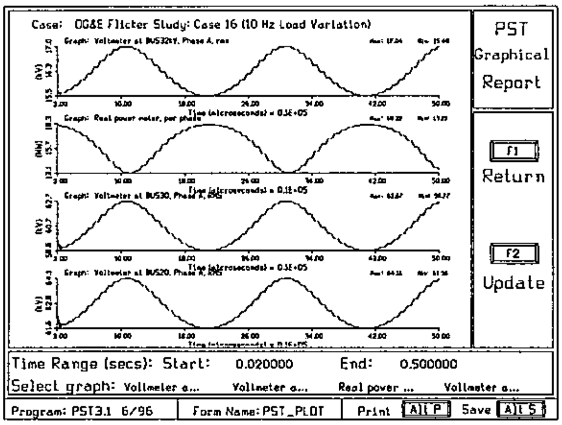

Figure 5. RMS Variation of the BUS20, BUS30 and BUS32KV Voltage and Furnace Real Power

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Biographies

A. P. Sakis Meliopoulos (M '76, SM '83, F '93) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, Power Systems Grounding and Transients, Marcel Dekker, June 1988, Ligthning and Overvoltage Protection, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993, and the monograph, Numerical Solution Methods of Algebraic Equations, EPRI monograph series. Dr. Meliopoulos is a member of the Hellenic Society of Professional Engineering and the Sigma Xi.

G. J. Cokkinides (M78). Dr. Cokkinides' interests include power system simulation and control, electromagnetic system modeling, measurement instrumentation, and CAD software development. Current research projects include the development of a power system ground impedance measurement device based on a custom microprocessor controlled multichannel data acquisition system, the development of a GPS synchronized measurement system for the estimation of the harmonic state of a bulk power transmission system, development of a CAD tools for characterization of microelectronic components, development of a comprehensive FEM based tool for dynamic structural analysis.