VOLTAGE FLICKER PREDICTION FOR TWO SIMULTANEOUSLY OPERATED AC ARC FURNACES

Le Tang
Member, IEEE
ABB Power T&D Company Inc.
Raleigh, NC, USA

Sharma Kolluri
Senior Member, IEEE
Entergy Services
New Orleans, LA, USA

Mark F. McGranaghan
Member, IEEE
Electrotek Concepts, Inc.
Knoxville, TN, USA

ABSTRACT - An EMTP-based arc furnace model was developed for evaluation of flicker concerns associated with supplying a large integrated steel mill as they go from one to two furnace operation and as system changes are implemented that will affect the short circuit capacity at the 230 kV power supply substation. The model includes a dynamic arc representation which is designed to be characteristic of the initial portions of the melt cycle when the arc characteristics are the most variable (worst flicker conditions). The flicker calculations are verified using previous measurements with one furnace operation. Flicker simulations were then performed to evaluate a variety of different possible system strengths with both one and two furnaces in operation. The primary flicker measure used for this study is the unweighted rms value of the fluctuation envelope, expressed as a percentage of the rms line-to-ground voltage magnitude.

Key Words: Arc Furnace, Voltage Flicker, EMTP Model

1. INTRODUCTION

Bayou Steel has a steel making facility supplied from Entergy's Little Gypsy 230 kV switchyard through a 2.5 mile 230 kV transmission line. This facility currently operates a single 57 MW ac arc furnace and a rolling mill. Bayou Steel plans to start up a second 57 MW furnace. In the meantime, Entergy is making changes in the system configuration to meet the 230 kV circuit breaker rating limitations and to improve system performance. The proposed alternatives reduce the equivalent system strength at the Gypsy 230 kV bus from the present 21576-18015 MVA to 13568-10196 MVA.

Flicker measurements were performed previously with the stronger system and one furnace in operation. The rms flicker levels were in the range of 0.2-0.3%. Flicker measured as the unweighted rms value of the fluctuations is generally considered to be a problem at about 0.5%, depending on the frequency of the fluctuations and the probability of occurrence. This is illustrated on the flicker limit curve in Figure 1, which was found to be the most common limit curve applied by electric utilities in the United States [1,2].

The study reported in this paper was designed to evaluate flicker concerns with the weaker system and both furnaces in operation to determine if remedial measures (e.g. a static var system) would be needed.

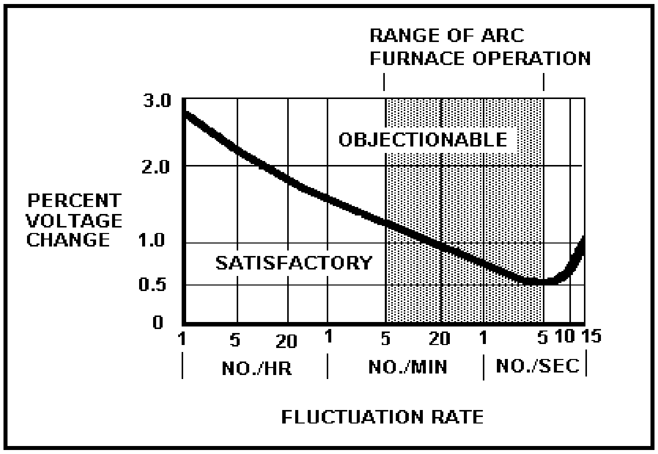

Figure 1. Flicker sensitivity curve showing limits for voltage fluctuations as a function of their frequency of occurrence.

2.0 CHARACTERIZING FLICKER

Many different methods are used around the world to characterize voltage fluctuations that cause flicker. IEC has standardized on a flickermeter that was specified by a UIE working group [3,4]. This flickermeter incorporates weighting curves that represent the response of the human eye to light variations produced in a 60 Watt incandescent lamp. The output of the meter is given as a per unit flicker voltage (P_{st}) where one per unit is the level that should cause noticeable light flicker.

The IEC flickermeter is not directly applicable to 60 Hertz systems where the secondary voltage is typically 120 volts. Lamps at 120 volts are less sensitive to voltage fluctuations than lamps at 230 volts. Sakulin [5] has performed tests that provide a basis for using the IEC flickermeter for 120 volt system applications. Results indicate that an acceptable level of P_{st} for North American systems should be in the range 1.2-1.35, instead of 1.0.

Until a standard measurement procedure for flicker concerns is developed in the United States, using the unweighted rms value of the voltage fluctuation envelope, along with information about the frequency content of the voltage fluctuation envelope, provides a convenient method of measurement which can easily be implemented in many different types of measurement equipment. This is the method adopted for the evaluations in this paper.

Measurements performed using this method should be evaluated in a statistical manner. For instance, a possible limit using this method might state that the rms value of the voltage fluctuation envelope should be less than 0.5% for 99% of the time.

3. PREDICTING FLICKER PROBLEMS

The results of measurements on furnace supply systems in Europe [6] have resulted in an empirical relationship for predicting flicker problems when the system supplies a single furnace:

$$P_{st}(99) = {}^{60}\!/_{SCR} \qquad (1)$$

where:

$P_{st}(99)$ is the P_{st} level that is exceeded 1% of the time.
SCR is the short circuit ratio at the point of common coupling.

An equivalent flicker level for multiple furnaces can be estimated using Equation 2:

$$P_{st\,total} = \sqrt[a]{\sum_i P_{st\,i}^{\;a}} \qquad (2)$$

where:

$a = 3$
$P_{sttotal}$ - total Pst resulting from all furnaces
$P_{sti} = P_{st}$ due to the i^{th} furnace

According to this empirical relationship, for two furnaces of the same size, the flicker level with both furnaces operating should be about 26% greater than the flicker level for one furnace. Other empirical relationships [7] have resulted in an exponent of 2 for this relationship which would yield a flicker increase of about 40%. In either case, the empirical results are from installations where the multiple arc furnaces are independent, and therefore seldom operate with both furnaces simultaneously at the initial melting stage.

Prediction of flicker levels associated with specific furnaces requires an accurate representation for the arc furnace loads. The major difficulty in the furnace modeling is to accurately characterize the electric arc. Even in the same stage of a melting cycle, the arc voltage and the equivalent arc resistance may change significantly, ranging from a momentary open circuit status to a momentary short circuit status. This arcing variation depends on the materials being melted and is highly random in nature. It has been found that the arc variations do not obey any uniform distribution.

In this study, arc furnace loads are represented using the Transient Analysis of Control Systems (TACS) modeling capability of the Electro-Magnetic Transient Program [8]. A variable arc length is characterized using the band limited white noise method [9]. The equivalent arc resistance varies continuously as a random function of time. The arc characteristics are also influenced by the electrode lifting and lowering controls. These variations are applied to an average arc voltage and furnace heating power which are controlled by a preset furnace operating voltage. Bandpass filters and random signal magnitude functions were used to characterize ac arcing resistance. A trial and error method was used to determine properties of the bandpass filters and magnitude functions for the arc characterization.

Once the model representing the arc variations was developed, the resulting voltage fluctuations can be evaluated against different system supply strengths, with either a single furnace operation or two furnace operation. In order to facilitate a sensitivity analysis, an EMTP TACS flicker meter module was also developed. This EMTP TACS flicker meter module reads a simulated voltage waveform at a specified system location during each time step of the simulation, performs the flicker calculation, and outputs instantaneous voltage flicker ($\Delta V(t)/V$) and unweighted rms flicker as a part of the simulation results.

4. EMTP MODEL DEVELOPMENT

The power circuit of the steel mill is schematically shown in the one-line diagram given in Figure 2. Bayou Steel is supplied by the Entergy system from the Gypsy 230 kV switchyard through a 2.5 mile 230 kV transmission line.

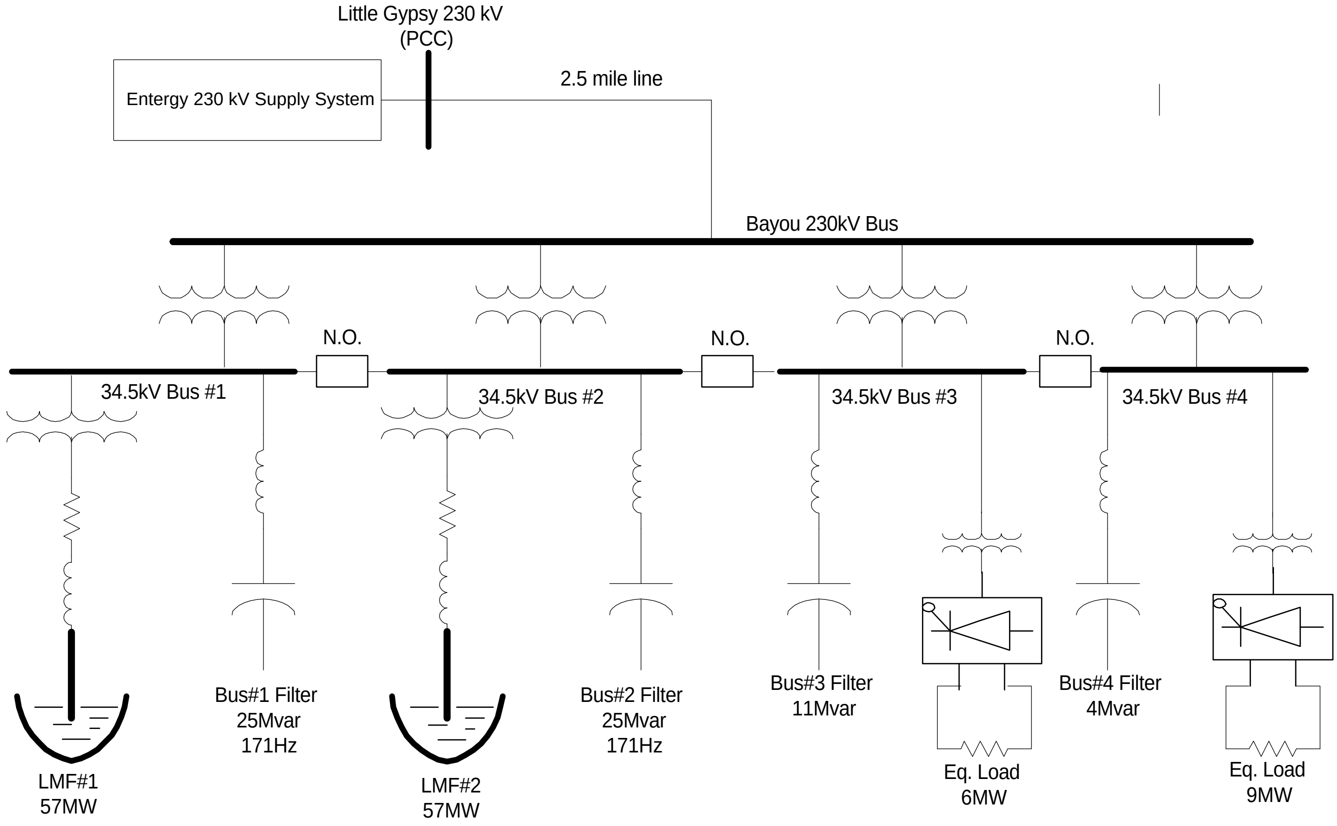

Figure 2. Bayou Steel power supply system one-line.

Two 60 MVA, 230/34.5 kV, Delta-Wye, power transformers are used to supply the melt shop that includes two 57 MW ac arc furnaces. Each of these furnaces has its own 60 MVA, 33 kV/728-240V, Delta-Wye step-down transformer and a 25 Mvar harmonic filter at the 34.5 kV bus. The filter is tuned at 171 Hz.

The melt shop auxiliary and rolling mill is supplied separately by two 20 MVA, 230/34.5 kV transformers with the same winding connections. The major loads of these transformers are SCR based dc drives supplied at either 500V or 600V. For simplification, these drives are grouped according to their supply voltages and are equivalently represented in the EMTP model by one 6 MW and one 9 MW drive. The drives are assumed to be operated at a 30 degree firing angle. The 4 Mvar and 11 Mvar power factor correction/ harmonic filter units are connected at 34.5 kV buses as shown.

The representation for the arc furnace, and the arc characteristics in particular, is the most crucial for evaluating flicker concerns. The models related to this portion of the model are described below.

4.1 AC Arc Furnace Model

In this study, the ac arc representation is a function of three major factors.

The first cause of variations is associated with the 60 Hz current zero crossings. For a constant arc length, the arc voltage $V_{arc}(t)$ changes with the magnitude of the instantaneous current, $I_{arc}(t)$. As described in [10], for a positive half cycle of the arc current, the arc voltage can be expressed by Equation 3.

$$V_{arc}(t) = V_{arco} + C/(D+I_{arc}(t)) \qquad (3)$$

where:

V_{arco} = a constant, unit length arc voltage threshold
C = a constant, in unit of Watts
D = a constant, in unit of Amps

The voltage shape for the negative half cycle is symmetrical to the positive half cycle with respect to the origin. The constants C and D are of different values for increasing and decreasing instantaneous current magnitude. This is a deterministic rule mainly responsible for characteristic harmonic distortion.

The second factor affecting the furnace arc is electrode lifting and lowering controls. It is also referred to as electrode voltage regulation. The principle of this ac voltage regulation is shown in Figure 3.

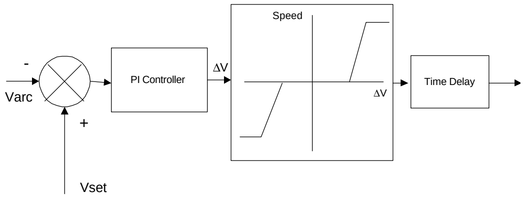

Figure 3. AC arc voltage control.

With a constant voltage across a unit length of arc, a desired total arc voltage is adjusted by changing the length of the arc. An appropriate operating voltage is obtained by lifting or lowering the movable positive electrode with respect to the fixed negative electrode. As a result, the distance between the tips of the electrodes changes, resulting in a different range of arcing voltage variation.

At different melting stages, the furnace heating power is adjusted by changing the arc voltage. With a constant supply system impedance, this voltage change results in arc current change and arc power change. A long arc operation tends to give a high operating power factor. A short arc operation results in a low power factor. For the electrode regulation, the rms value of the ac voltage is directly monitored at the electrode. The measured voltage is compared with a selected ac voltage setting.

The difference between the actual and setting voltages, δV, is processed through a PI controller. The output of the PI controller determines the direction and the speed of an electrode movement. Then, this control signal is amplified to operate a proportional valve to complete the arc length adjustment.

When the actual ac voltage is greater than the set voltage, δV is negative. If the magnitude of this negative voltage exceeds a dead band, the electrode will be lowered with a specified speed to reduce the arc length so that the ac arc voltage decreases. When the actual voltage becomes smaller than the setting voltage, a reverse action takes place. Dead bands are set on both sides of the zero point on the voltage error axis to prevent unnecessary electrode movement in response to small magnitude arc voltage fluctuations. The maximum lifting and lowering speeds are imposed by the limit of the mechanical proportional valve system. The time delay in the control diagram reflects the response time of the mechanical system. A typical mechanical system of this type can have a frequency response as fast as 2 to 3 Hz. For a flicker frequency range of 0.5 to 30 Hz, this mechanical system response should not be ignored.

The third factor applied is a random time variation of the arc length. For any given furnace arc voltage setting and distance between the tips of the electrodes, the actual arc length changes randomly with time.

The factors which directly affect this random change include the physical distance between the tip of the electrode and the melting materials, characteristics of the materials, status of melting, and many other factors related to furnace design and operating conditions. As a result, the magnitude of these random changes can be dramatic, ranging from a bolted short circuit to an open circuit.

According to previous studies over the past several decades, it is now commonly accepted that the variations of an electrical arc do not obey any standard distribution rule and the arc length changes in a completely random fashion. In this study, to properly represent such a random arc change, a band-limited white noise method is used [9,10]. The TACS realization in the EMTP simulation is illustrated schematically by Figure 4.

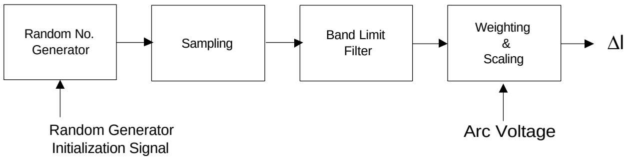

Figure 4. TACS representation of random variation of arc length.

The procedure to model the random variation portion of the arc length, ΔL, consists of four steps:

1. Generate a random number between 0 and 1 at each simulation time step.
2. Set up an appropriate sampling scheme so that the time step effects on the generated random signal are removed.
3. Process the sampled random signal through a 4 Hz to 14 Hz band-pass filter.
4. Apply proper scaling and weighting functions which characterize the different disturbance magnitude at different melting stages. In this stage, a pre-set ac arc voltage is used as an input to the weighting function.

The effective arc length obtained through this procedure can be expressed by:

$$L(t)=L_o(t)*(1-\Delta L(t)) \qquad (4)$$

where:

$L_o(t)$ is the desired arc length calculated by the electrode regulation control logic for a given ac voltage setting value.

With all of the above factors considered, the arc voltage can be structured as follows:

$$V_a=kV_{ao}(I_a) \qquad (5)$$

where:

V_{ao} is the arc voltage corresponding to the reference length, L_o.

The coefficient k is the ratio of the threshold arc voltage corresponding to a length L, $V_{at}(L)$, to that relevant to the reference length, $V_{at}(L_o)$.

Since the relationship between threshold voltage and arc length can be expressed as:

$$V_{at}=A+B*L \qquad (6)$$

then, with the random nature included, k is given by:

$$k(t) = (A+B*L(t))/(A+B*L_o(t)) \qquad (7)$$

where:

L = the arc length in cm.
A = a constant taking into account the sum of anode and cathode voltage drops (40 volts)
B =the voltage drop per unit arc length (10 volts/cm)

4.2 Flicker Meter Model

In this analysis, the actual voltage variations, ΔV, or "disturbance voltage", including all frequency components in the 0.5 to 30 Hz range, are defined as instantaneous flicker. The definition of ΔV and the method to separate it from its 60 Hz carrier voltage are given in [11]. To obtain the instantaneous voltage flicker from EMTP simulation, a sampled voltage is processed by TACS functions consisting of the following four steps:

1. Voltage signal full-wave rectification
2. 120 Hz notch filtering.
3. 30 Hz low-pass filtering
4. DC voltage removing

In the EMTP module, a minor modification on this procedure was made. As a result, the actual signal processing is illustrated in Figure 5. The denominator V in the output is the mean rms voltage within a 2 second rolling time window, which corresponds to the 0.5 Hz low limit of the flicker frequency. For easy reading, a factor of 1000 is used as a multiplier on the percentage disturbance voltage output. Consequently, a direct reading of 500 from the simulation corresponds to a flicker level of 0.5%. The EMTP TACS module for this flicker meter was tested with a known disturbance signal to verify performance.

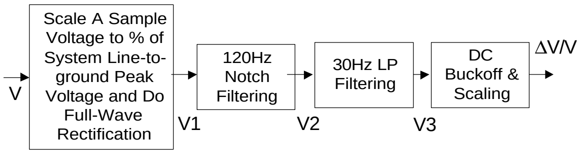

Figure 5. Flow chart for separating instantaneous voltage flicker from 60 Hz carrier voltage.

5. TYPICAL WAVEFORMS

Typical waveforms from the simulations of the Bayou Steel operation with one 57 MW arc furnace operating and the original source conditions are provided for reference. These are the conditions for comparison with previous flicker measurements. Figure 6 shows the simulated arc voltage within a 2 second time window. Figure 7 illustrates the voltage fluctuations at the Gypsy 230 kV bus. Figures 8 and 9 give the instantaneous voltage flicker at the Gypsy 230 kV bus and its frequency spectrum. Figure 10 is the percentage rms flicker at the same Gypsy bus.

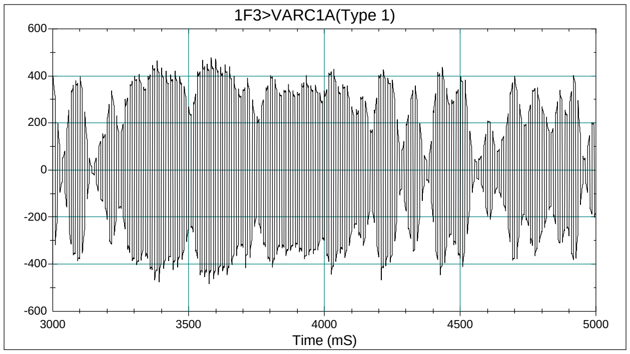

Figure 6. Arc voltage waveform.

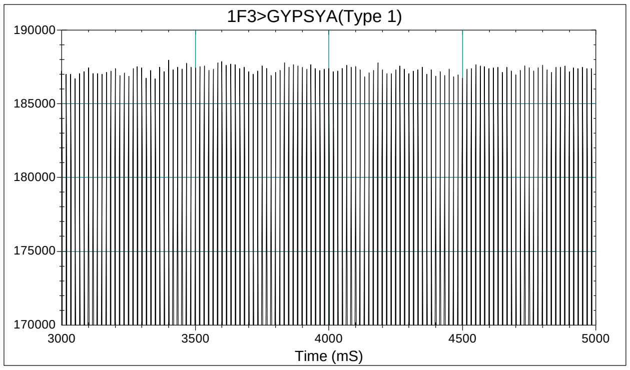

Figure 7. Gypsy 230 kV bus voltage fluctuation (magnified).

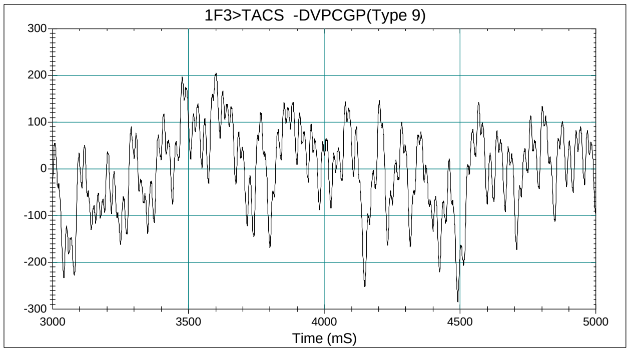

Figure 8. Gypsy 230 kV instantaneous voltage flicker DV/V in 1000 times percentage value.

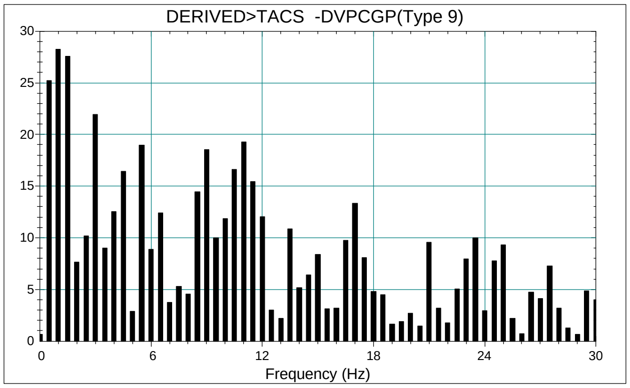

Figure 9. Frequency spectrum of Little Gypsy 230 kV instantaneous voltage flicker.

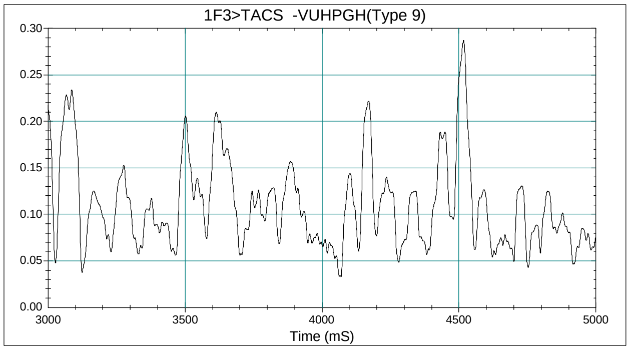

Figure 10. Gypsy 230 kV rms flicker.

The rms flicker calculations were found to have excellent agreement with previous flicker measurements. For these conditions, the previous measurements showed that the 99% probability point for the rms flicker levels was approximately 0.3% with primary frequency components in the range 2-7 Hz.

The following observations are worth noting from these waveforms and other simulations with two furnaces in service.

- The instantaneous and rms flicker plots show significant variations. The maximum value can be significantly higher than a value averaged over a 1 or 2 second period. The maximum flicker values have been used for evaluation in this study. This should be considered a conservative approach.

- The frequency spectrum of the flicker is concentrated in the 1-12 Hz range but it is difficult to pick out a dominant frequency. This means that the simplified calculation approaches for sine waves and square waves cannot be applied at all for these waveforms. The concentration below 12 Hz is typical of arc furnace variations without a static var system. These variations are in the range that has the most potential to cause complaints.

- The frequency spectrum of the flicker shifts somewhat with two furnaces operating. In this case, the dominant components are in the 8-12 Hz range, rather than the 1-5 Hz range for one furnace. This is still in the range that can cause problems but slightly higher levels may be acceptable.

6. SUMMARY OF EXPECTED FLICKER

There are three alternatives for the steel plant power supply. For each alternative, there are upper and lower available short-circuit capacities for different generation schemes. These system conditions combined with the possible arc furnace operating conditions resulted in twelve cases. The available short circuit level at Little Gypsy for each case is indicated in the first column of the summary in Table I.

Table I. Summary of flicker simulation results at the Little Gypsy 230 kV bus.

	One Furnace		**Two Furnaces**	
Available Fault MVA	**ΔV(t)/V (%)**	**Unweighted rms Flicker (%)**	**ΔV(t)/V (%)**	**Unweighted rms Flicker (%)**
21576	0.28	0.28	0.36	0.43
18015	0.26	0.29	0.41	0.49
15664	0.30	0.33	0.47	0.57
13568	0.35	0.39	0.60	0.75
12203	0.38	0.43	0.68	0.75
10196	0.45	0.52	0.76	0.92

The calculated flicker at the PCC (Little Gypsy) is presented in two formats: the maximum magnitudes of the instantaneous flicker (peak value of the ΔV/V) and the unweighted rms flicker. The field measurements at Little Gypsy with the original strong system supply showed unweighted rms flicker levels in the range 0.25-0.30%. These results correspond with one furnace in the first row of the table. The simulations include a 2 second window with arc variations designed to represent the worst part of the melt cycle. Therefore, the cases with two arc furnaces operating simultaneously are actually simulating two furnaces both operating in the initial melting period when the arc is the most unstable.

The values given in the table for the ΔV/V are in percent of the peak line-to-ground voltage. That is, they represent the maximum deviation in the fluctuation divided by the nominal peak line-to-ground voltage. The unweighted rms flicker values are based on a 30 Hz reference frequency (in other words, the rms is calculated as a moving 0.033 second window) and are rms values expressed in percent of the nominal rms line-to-ground voltage. The maximum rms value over this time period is presented in the tables.

If the primary frequency components of the flicker are in the 1-10 Hz range, a flicker level less than 0.5% is generally considered to be acceptable. The results at Little Gypsy indicate that flicker levels should be acceptable for one furnace operation almost all the way down to the worst case short circuit level simulated.

For two furnace operation, the worst case rms flicker levels are acceptable as long as the short circuit level at Little Gypsy is about 16000 MVA. The strongest source alternative nearly provides this short circuit capacity. Lower short circuit capacities at Little Gypsy could result in unacceptable flicker levels for worst case furnace operating conditions (two furnaces in the initial bore down period of the melt).

It is interesting to evaluate the effect of the second furnace on the flicker levels. Table II summarizes the results of the simulations as a ratio of the flicker with both furnaces operating to the flicker with only one furnace operating. The average value of this ratio if 1.61 for ΔV/V and 1.73 for the unweighted rms flicker. These ratios are significantly higher than predicted by Equation 2 but this is explained by the fact that both furnaces are operating in the worst part of the melt cycle for the simulations. Statistically, the average impact of the second furnace will be less than the impact predicted in the simulations.

Table II. Effect of second furnace on expected flicker levels at the Little Gypsy 230 kV bus.

Available Fault MVA	**Instantaneous Flicker Ratio**	**rms Flicker Ratio**
21576	1.29	1.54
18015	1.58	1.69
15664	1.57	1.73
13568	1.71	1.92
12203	1.79	1.74
10196	1.69	1.77
Average	**1.61**	**1.73**

The simulation results indicate that flicker levels could be unacceptable with two furnace operation. However, the simulations are conservative and the recommendation from the study was to permit initial operation in a two furnace configuration with monitoring of the flicker levels. If objectionable flicker levels are encountered, the optimum solution (e.g. static var system, furnace controls, etc.) can be developed in cooperation between the utility and the customer.

7. CONCLUSIONS

The paper describes a new dynamic arc furnace model that can be used to evaluate flicker concerns. The model includes the non-linear relationship between voltage and current for harmonic investigations, the arc voltage regulator controls, the electrode controls, and the random variations in the arc characteristics.

The arc furnace model was verified using field measurements of flicker levels with one furnace operating under strong source conditions. Simulations with two furnaces under a variety of source conditions showed that flicker could be a concern under certain operating conditions. An unweighted rms flicker level of 0.5% was considered to be the maximum acceptable level for this study.

Actual flicker levels should be less than predicted for most conditions since the simulations essentially modeled two furnaces operating at the initial melt stage at the same time. The flicker with two furnaces operating is also characterized by slightly higher dominant frequencies, which could result in a higher allowable flicker level. Based on these two considerations, no remedial measures were recommended for the two furnace operation but the flicker levels will be monitored to verify actual performance.

7. ACKNOWLEDGEMENTS

This investigation was funded by Entergy Services Inc., as part of the overall evaluation of supply requirements for the Bayou Steel plant in LaPlace, LA. The contributions of various engineers at both Entergy and Bayou Steel were critical to the success of the effort. These Mike Labiche and Long Nguyen at Entergy and Keith Arcuri at Bayou Steel in particular.

8. REFERENCES

[1] R.C. Seebald, J.F. Buch, and D.J. Ward, “Flicker Limitations of Electric Utilities,“ *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No. 9, September 1985.

[2] M.K. Walker, “Electric Utility Flicker Limitations”, IEEE Trans. on Industry Applications, Vol. IA-15, No. 6, Nov./Dec. 1979.

[3] UIE Disturbances Study Committee, “UIE Flickermeter, functional and design specifications”, Bulletin UIE, 1983.

[4] IEC Publication 868, “Flickermeter, functional and design specifications”, 1986.

[5] M. Sakulin, H. Renner, and R. Bergeron, “UIE/IEC Flickermeter for 120 V Incandescent Lamps,” Fourth International Conference on Power Quality Applications and Perspectives, New York, May 1995.

[6] A. Robert and M. Couvreur, “Arc Furnace Flicker Assessment and Prediction,” 12th International Conference on Electricity Distribution (CIRED), Paper 2.02, Birmingham, England, May 17-21, 1993.

[7] A. Robert and J. Marquet, “Assessing Voltage Quality with Relation to Harmonics, Flicker, and Unbalance, “CIGRE/CIRED CC02 Working Group, CIGRE Paper 36-203, 1992.

[8] EMTP Rule Book, 1982

[9] G. Manchur and C.C.Erven: ”Development of A Model for Predicting Flicker from Electric Arc Furnaces”, *IEEE Transactions on PAS*, 1992.

[10] G.C. Montanari, A. Cavallini, M. Loggini, L. Pitti, and D. Zaninelli, ”Arc-Furnace Model for The Study of Flicker Compensation in Electrical Networks”, *IEEE Transactions on Power Delivery*, Vol. 9, No. 4, October 1994.

[11] CEA Research Report: ”Analysis of Flicker from Arc Furnaces,” Report by Ontario Hydro, Contract No 042 T 178, 1983.

[12] IEEE 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.*

Le Tang is an Advisory Engineer with ABB Power T&D Company, Inc. He received his BS degree from Xian Jiaotong University in Electrical Engineering, 1982 and his ME and Ph.D. from Rensselaer Polytechnic Institute in Electric Power Engineering in 1985 and 1988 respectively. His areas of interest include power system transient and harmonic analyses, power electronics and machine simulation.

Sharma Kolluri is a Senior Staff Engineer with Entergy Services, Inc. He received his BSEE degree from Vikram University, India in 1973 and his MSEE degree from West Virginia University in 1978. Sharma is responsible for directing technical studies at Entergy and his areas of interest include power system transients, stability, and insulation coordination.

Mark McGranaghan is General Manager of Power Systems Engineering at Electrotek Concepts, Inc. He received his BSEE and MSEE degrees from the University of Toledo in 1977 and 1978, respectively. Mark is responsible for a wide range of studies, seminars, and products involving the analysis of power system transients, harmonics, and power quality concerns. He is Chairman of IEEE P519A which is developing an application guide for IEEE 519-1992.