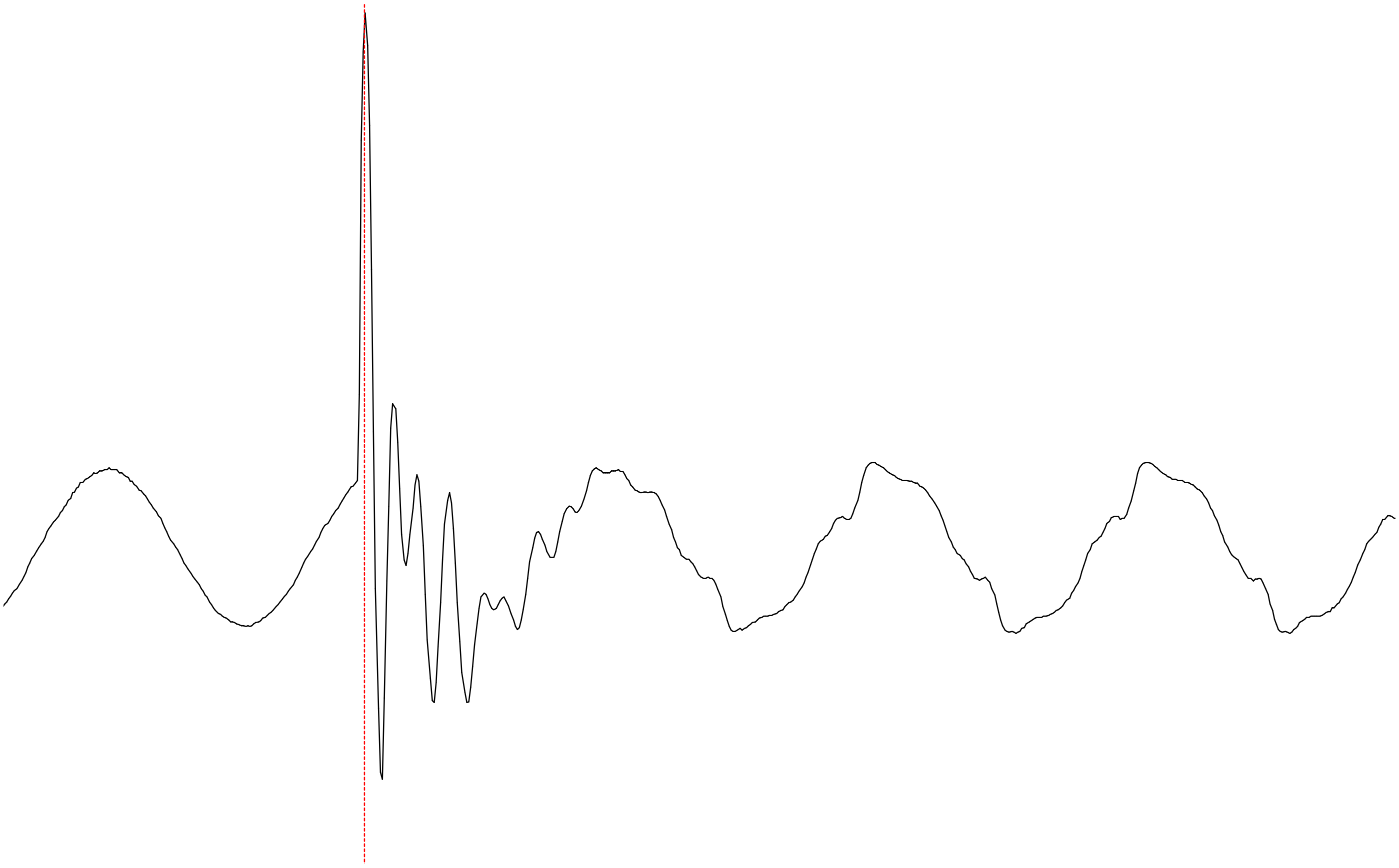
Harmonics and Transients Tech Notes



Issue # 97-2 ***July 1997*** ***Editor: Kathryn Nix***

Project Manager: Huyen Nguyen

In this issue:

Letter from the Project Manager

Dear PATH Members:

The annual PATH and Users Group Meeting is just a little over three months away, so hurry and send us your registration form to meet the October 1 registration deadline.

We are excited about this year's meeting because Professor Hermann Dommel, the developer of EMTP, will be one of our guest instructors. We will also have some our own experts at Electrotek speak on various topics.

If you have not received a registration form, please contact Kathryn Nix. We want all of you (our members) to take advantage of the opportunity to meet as a group.

Sincerely,

Huyen V Nguyen

Huyen V. Nguyen
huyen@electrotek.com

For more information concerning the newsletter or to submit a contribution please contact

Kathryn Nix
Electrotek Concepts, Inc.
408 North Cedar Bluff Road, Suite 500
Knoxville, Tennessee 37923
Phone: (423) 470-9222 x118
FAX: (423) 470-9223
e-mail: kathryn@electrotek.com

Modeling of Multiple Motors for Flicker Studies Using EMTP

S. Mark Halpin and Jeff W. Smith
Department of Electrical and Computer Engineering
Mississippi State University, MS 39762

Abstract

The methodology necessary for modeling multiple motors for the purpose of flicker evaluations using EMTP are presented in this paper. The specific points discussed include 1) the prediction vs. compensation solution techniques when multiple motors are involved, 2) automatic initialization for multiple motors, and 3) initialization of motors to be started after t=0 seconds. The information presented was developed while completing a flicker study on a 12 kV feeder serving a relatively large industrial plant. Measured data from the 12 kV system is provided to demonstrate both the "fine tuning" process often required as well as to provide general model validation.

Introduction

Flicker analysis is usually based on a comparison of measured or calculated (predicted) data to a flicker curve such as the one shown in Figure 1. For studies involving existing plants and equipment, measured data is most often used while calculated values are used if 1) new plants are proposed, 2) significant expansions are planned for existing facilities, or 3) it is necessary to predict the possible effects of mitigation equipment such as static var or switched capacitor compensators. In this paper, we consider the class of flicker analyses that depend on the use of computer simulation.

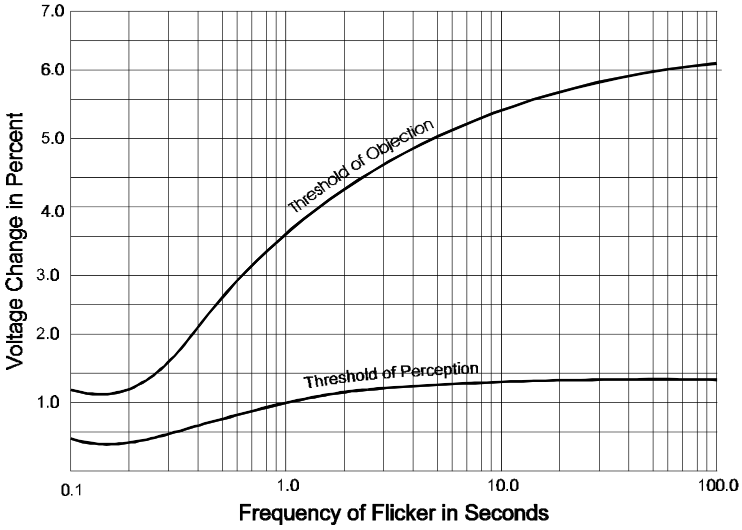


Figure 1. Typical Flicker Curve (rms voltage)

In modern electric systems, the two main causes of voltage flicker are arc furnaces and large motors (either induction or synchronous). We focus on the modeling and analysis of an existing system that is experiencing voltage flicker that is believed to be caused by large induction motors. The single-line diagram of the system studied is shown in Figure 2.

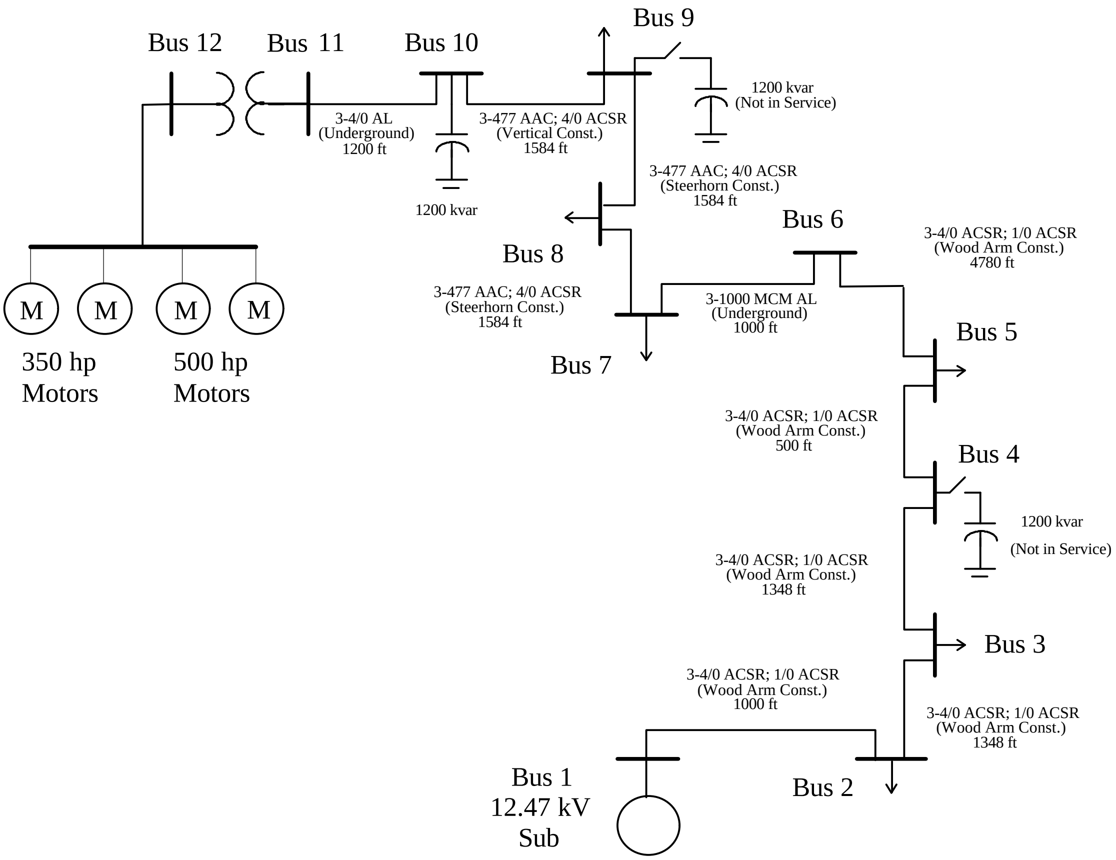


Figure 2. Single-Line Diagram for Flicker Case Study

Measurements of voltage and current were taken at the plant service entrance. Additional measurements were also made on the 12 kV feeder near bus 10 where many customer complaints were being logged. These measurements are shown in Figures 3, 4, and 5. While the relationship between the large currents drawn by the plant obviously correlated well with the voltage dips, the plant operators strongly denied that any of their equipment was being operated in a manner that could cause such objections from others in the community. As such, no measurements were allowed to be taken at the motor contactor terminals inside the plant. For this reason, it became necessary to develop a detailed EMTP model of the 12 kV system including the 4 large motors in the plant and to use this approach to verify that plant operation was in fact producing the objectionable flicker.

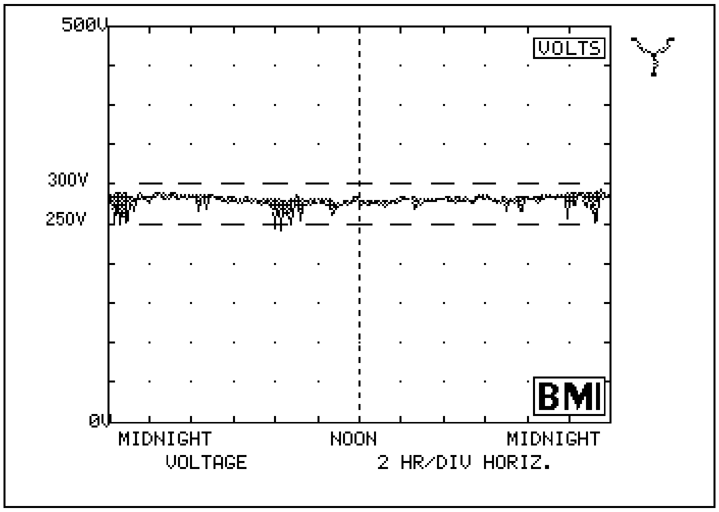


Figure 3. Line-to-Neutral rms Voltage at the 480 V Service Entrance (a phase)

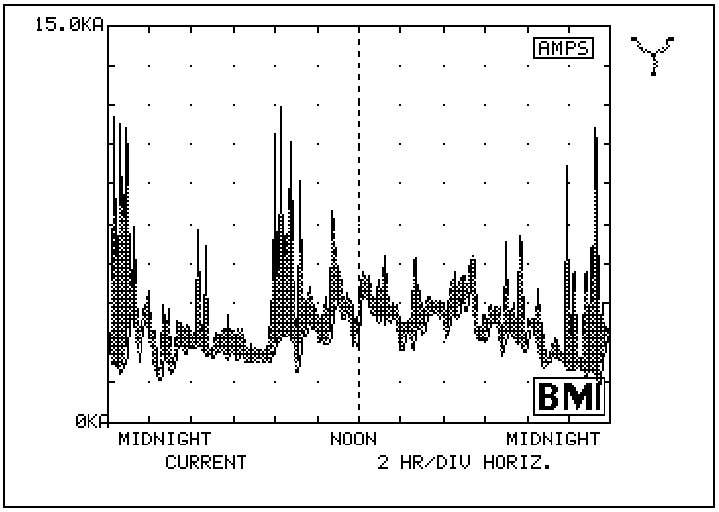


Figure 4. Line Current at the Service Entrance (a phase)

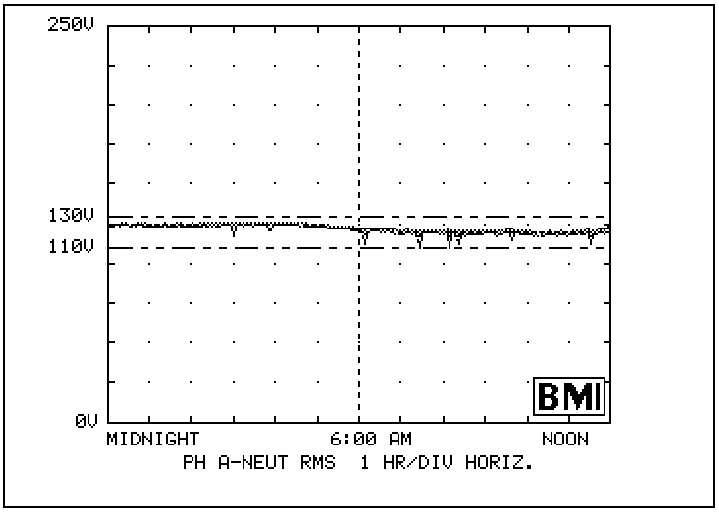


Figure 5. Line-to-Neutral rms Voltage on the 12 kV Feeder (120 V base, a phase)

EMTP Motor Modeling For Flicker Studies

Traditional motor modeling for flicker studies suggests using a constant impedance model to predict the flicker caused by motor starting and using a constant power model to predict the flicker caused by a sudden load torque change on a motor already running. These approaches, based around a power flow algorithm, have been suggested for use mainly when the detailed modeling and analysis capability offered by EMTP-type programs is either not needed or not possible. Although it is informative to consider the differences between these types of calculations and EMTP results, we focus here on the direct use of EMTP to match the measured data. Of course, this process of verifying the model is a critical step that must be taken before using the model to evaluate vendor bids for mitigation equipment.

Modeling Multiple Motors in EMTP

Analysis of systems with multiple motors must be handled carefully. There are two approaches that can be chosen using one of the first cards in the U.M. (universal machine) specifications:

1. Compensation. This approach, based on a systematic application of "reference frame theory," is supposed to be the most accurate according to the rule book. However, there can only be one motor in each part of the system that is not separated from any other part of the system by a "one time step delay device" such as a TACS element or a distributed parameter line.

2. Prediction. This approach is offered by the EMTP to avoid the separation of multiple motors by "delay" devices. Both experience and the rule book indicate this approach to be less accurate than the compensation approach.

The fact that prediction is less accurate is important, especially when the automatic steady-state initialization option is desired. Experience has shown that this initialization is tricky and it is very easy to produce a situation that will cause the EMTP to crash.

For the studies conducted on the 12 kV system (including plant load), it was necessary to consider the situation where three of the motors were running at full load and one motor was started across the line. While the motors were supposed to have been equipped with reduced-voltage starters, examination of the line current at the service entrance clearly indicates that the starters may not be present or may not be working properly. In addition, some practices in the plant called for the motors to be jogged frequently at full voltage. For these reasons, it was suspected that across the line starting was largely responsible for the flicker.

The system shown in Figure 6 represents the motors fed from the plant's 480 V bus. Except for the switches connecting I.M. #1 to the 480 V bus, all switches are closed before t=0 seconds as required for automatic steady-state initialization.

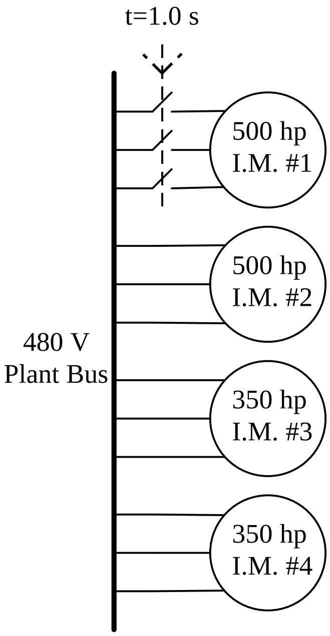


Figure 6. 480 V Plant Bus with Motors

The following section of the input file shows the switch timing. Note that I.M. #1 is connected at t=1.0 s. This is done mainly to provide a clear indication of the “pre-start” and the “post-start” voltages that will be used to compare with the measurements in Figures 3 and 5.

```
C SWITCHES CONNECTING MOTORS TO 480 V BUS (CLV12A,CLV12B,CLV12C)
/SWITCH
  CLV12ASTAT1A       1.0       99.                                      1
  CLV12BSTAT1B       1.0       99.                                      1
  CLV12CSTAT1C       1.0       99.                                      1
  CLV12ASTAT2A      -1.0       99.                                      1
  CLV12BSTAT2B      -1.0       99.                                      1
  CLV12CSTAT2C      -1.0       99.                                      1
  CLV12ASTAT3A      -1.0       99.                                      1
  CLV12BSTAT3B      -1.0       99.                                      1
  CLV12CSTAT3C      -1.0       99.                                      1
  CLV12ASTAT4A      -1.0       99.                                      1
  CLV12BSTAT4B      -1.0       99.                                      1
  CLV12CSTAT4C      -1.0       99.                                      1
```

The following section of the input file shows the current sources used by 1) the automatic steady-state initialization process (IMS1, IMS2, IMS3, and IMS4) 2) the Norton equivalent current sources for I.M. #1.

```
C SOURCES FOR U.M. MODELS INCLUDING ELECTRICAL ANALOG SOURCES
/SOURCE
C ADJUSTABLE SOURCE FOR TYPE 19 INDUCTION MOTOR MODELS
14 IMS1A-1   -2019.0    0.0001                                    6.       99.
14 IMS1A-1   -2231.0    0.0001                                    7.        9.
14  IMS1-1   -0.0001    0.0001                                   -1.       99.
14  IMS2-1   -0.0001    0.0001                                   -1.       99.
14  IMS3-1   -0.0001    0.0001                                   -1.       99.
14  IMS4-1   -0.0001    0.0001                                   -1.       99.
C DUMMY SOURCES FOR DELAYED MOTOR START (Norton equivalent)
14STAT1A-1      0.01      60.0                                   -1.       99.
14STAT1B-1      0.01      60.0                                   -1.       99.
14STAT1C-1      0.01      60.0                                   -1.       99.
```

In addition to the last three current sources in the previous data file fragment, it is also necessary to include three large resistors, each connected in parallel with one of the current sources (at nodes STAT1A, STAT1B, and STAT1C). This is easily accomplished after a /BRANCH statement and is therefore not shown here. This Norton equivalent is necessary so that the EMTP can initialize I.M. #1 with the switches in the open position. Use of a Thevenin equivalent to serve this same purpose would have resulted in a relatively fixed motor terminal voltage after the switches were closed. Although using a Thevenin equivalent would have allowed the EMTP to run, incorrect results would have been produced.

The following portion of the data file shows part of the U.M. Type 4 induction motor model. In addition to the general U.M. data, the data for the two 500 hp motors are also shown. The parameters for the two 350 hp motors are similar and are therefore not shown here. Note that the automatic steady-state initialization and prediction options are selected. The important concept is that once selected, these options apply to all motors. Slash statements can not be used to establish different options for different motors. For this reason, it was necessary to implement the Norton equivalent source for I.M. #1 so that it could be initialized with the other three motors but not actually started until t=1 second.

```
C BEGIN TYPE 19 MOTOR MODEL
19
01            1
BLANK ENDING GENERAL U.M. SPECIFICATIONS
C ********************
C 500 HP MOTOR #1 DATA
C ********************
 4    111  IMP1       2
           0.0      0.003860
           0.0      0.003860
         100.0                      IMS1
         0.013      0.000103STAT1A
         0.013      0.000103STAT1B
         0.013      0.000103STAT1C
         0.012      0.000103 ROT1A
         0.012      0.000103 ROT1B
         0.012      0.000103 ROT1C
C ********************
C 500 HP MOTOR #2 DATA
C ********************
 4    111  IMP2       2
         179.1      0.003860
           0.0      0.003860
           5.0                      IMS2
         0.013      0.000103STAT2A
         0.013      0.000103STAT2B
         0.013      0.000103STAT2C
         0.012      0.000103 ROT2A
         0.012      0.000103 ROT2B
         0.012      0.000103 ROT2C
```

Case Study Results

A complete EMTP data file was created for the system of Figure 2. Once created and verified, this system model can be expanded to include mitigation equipment. Figures 7 and 8 show the results of the EMTP analyses using the approach outlined in the sections of the data file presented previously. Of course, these results were produced after significant adjustments were made to the model to approximate the operation of the plant equipment. As shown, these simulation results match the measured data within an acceptable tolerance (less than 5%).

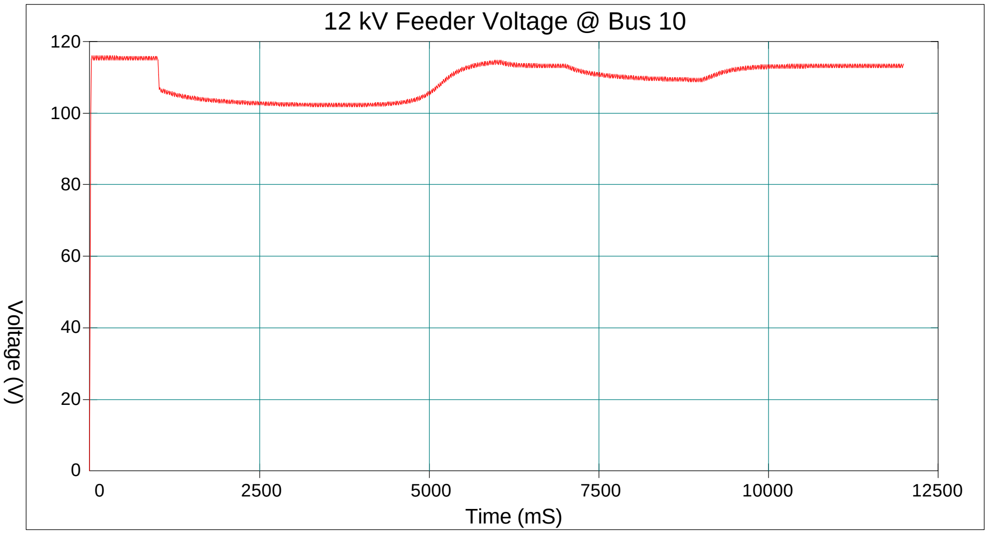


Figure 7. EMTP Prediction of Feeder Voltage Flicker

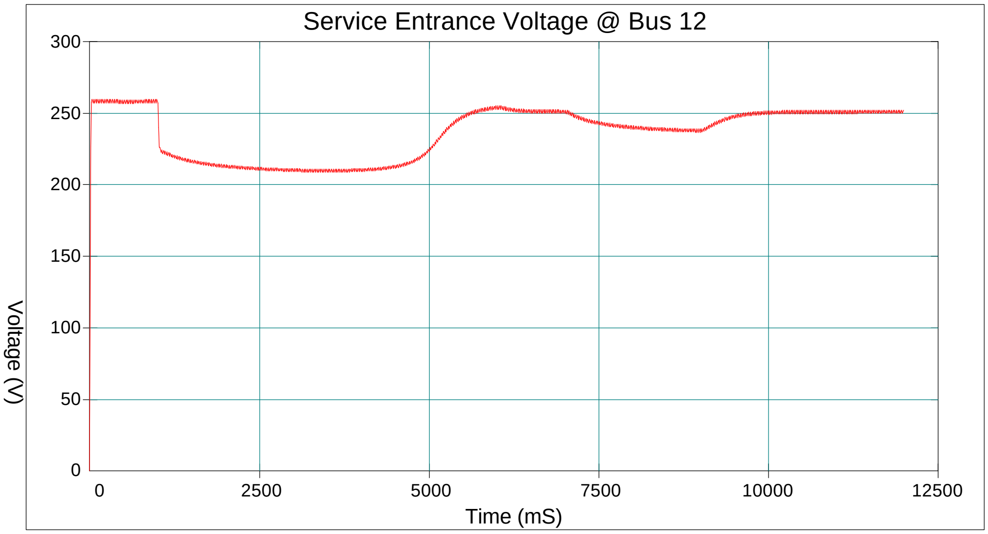


Figure 8. EMTP Prediction of Service Entrance Voltage Flicker

As previously mentioned, measurements were not allowed inside the plant. It was up to the analyst, therefore, to experiment with the model to reproduce the measured data as closely as possible. Based on discussions with the plant operators, it was determined that the 500 hp motors could experience very wide variations in load torque (in some cases the motor could approach a locked-rotor condition), and very large current draws were possible. The process controls were set to allow the motor current to exceed the rated value plus 200 A for up to 2 seconds, after which the controllers would open the process and remove the mechanical load from the motors. If this sequence of events occurred, it was possible that the motor could be repeatedly “jogged” at full voltage while under load. (Under these conditions, the reduced-voltage starter was purposefully bypassed to allow maximum torque at starting.) Therefore, the two events that seemed likely to be causing the voltage flicker were 1) starting or jogging the motor at full voltage and 2) excessive load torque being placed on the motor.

The EMTP data file was constructed to simulate both of these actions. Full-voltage starting was simulated beginning at t=1.0 second. After reaching steady-state, full load (rated) torque was applied at t=6.0 seconds. At t=7.0 seconds, the load torque was increased to near its maximum value to simulate the wide change in load torque. A steady-state analysis was conducted using a conventional induction motor analysis program to determine the maximum torque for the motor. This value served as a starting point for the trial-and-error determination of the actual value used in the EMTP studies. As expected, the maximum torque allowable in the dynamic EMTP analysis was noticeably less than that predicted by the steady-state program.

Based on the measured data, the plant operator’s indication that the motors were not started across the line appeared to be verified. The EMTP simulations predict much more severe flicker under these conditions than was shown in the measurements. (Some measurements not shown indicated more severe flicker, but not at a significant frequency.) The simulation results indicate that the flicker is most likely being produced by the load torque changes that are inherent in the process used by the plant.

Conclusions

In many cases, it is not possible to collect measurements inside a customer’s facility. However, it is often possible to obtain some knowledge of the type of equipment inside, and the method in which it is operated. From this point, it is possible to develop an approximate EMTP model that will allow the various facets of the problem to be studied in detail. In the case study considered here, measurements in the utility system were used to validate the model. Once validated, the model can be used to evaluate possible solutions.

At this time, the solutions for the system presented here are still under investigation. Static capacitors, thyristor-switched capacitors, and small static var compensators are being considered because it is not possible to change the operational practices in the plant without sacrificing overall productivity. Given vendor descriptions of their proposed mitigation equipment, it will be a straightforward process to include the appropriate power and control devices in the EMTP model developed up to this point.

Classification of Nonlinear Loads

Clemson University Electric
Power Research Asssociation
“CUEPRA”

Nonlinear loads cause harmonic distortion on the power system. They are usually characterized as sources of harmonic currents because the power system appears as a relatively stiff voltage source and these loads draw distorted current waveforms. Classification of these current waveforms for different types of nonlinear loads can be useful in evaluating the impacts associated with multiple harmonic producing loads in a facility. The waveform characteristics can be used to identify the types of nonlinear loads causing distortion in a facility and the relative impacts of the different types of loads.

This article summarizes the characteristics of the most important types of loads found in many commercial facilities. There are many different characteristics of the nonlinear loads that could be used for purposes of developing general categories:

- Fundamental frequency current phase angle (displacement power factor)
- Characteristic harmonic components
- Relative magnitudes of the harmonic components
- Phase angle characteristics of the harmonic components
- Harmonic power

The most readily available characteristics are the magnitudes and phase angles of the harmonic spectrum developed from the current waveforms. Although some loads also result in non-integer multiples of the fundamental frequency (inter-harmonics), most loads can be characterized by the spectrum of integer harmonic components.

In categorizing loads typical of commercial applications, it is useful to develop typical characteristics for the following load classes:

1? Three phase adjustable speed drives and other ac/dc converter loads.
2? Single phase electronic power supplies.
3? Arcing type devices (fluorescent lighting).

Adjustable Speed Drives

Adjustable speed drives are being applied in HVAC systems of commercial facilities to improve energy efficiency and provide better control. They can be the most important harmonic-producing loads in a facility due to the size of these loads.

Most adjustable speed drives in commercial applications (i.e. less than 500 hp) use a diode bridge rectifier to supply a capacitor. The capacitor maintains a relatively constant dc voltage, which is used by a pulse-width modulated (PWM) inverter to supply a variable frequency ac signal that is relatively free of low order harmonics to the motor. These drives will also include an isolation transformer or choke inductance to limit impacts associated with capacitor switching transients and to provide some reduction of harmonic current components.

Figure 1 gives a typical waveform associated with a PWM ASD supplied by a delta-wye isolation transformer. The associated harmonic spectrum is given in Table 1 as a range of typical harmonic component magnitudes. The characteristic harmonic components are of order np +/- 1, where n is an integer and p is the pulse number. These drives are usually six pulse, resulting in the most significant characteristic harmonics at the 5th and 7th components. The 3rd harmonic component in Table 1 results from slight unbalances in the supply voltage to the drive and will be different in each phase.

Table 1. Harmonic Current Characteristics of Load Type A

Harmonic Order	Magnitude %
1	100
3	4.4 - 4.7
5	32.1 -76.5
7	16.2 - 62.1
11	6.5 - 24.8
13	5.7 - 12.7

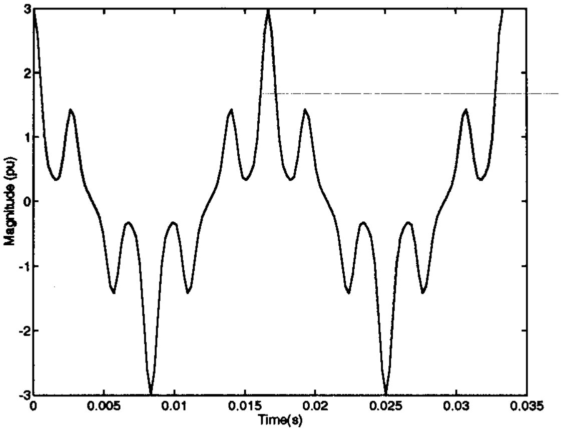


Figure 1. Typical load for type ‘A’ load

Electronic Power Supplies

PCs and other electronic loads continue to increase as a percentage of the overall load in many commercial facilities. In many 120 volt circuits, the entire circuit load can consist of electronic power supplies. These single phase loads produce significant harmonic distortion, often resulting in a need to oversize neutral conductors and derate transformers.

Most electronic loads are supplied with very simple single phase power supplies consisting of a diode bridge supplying a dc capacitor. Current is drawn in pulses by the capacitor at the peaks of the ac voltage waveform, resulting in an ac current waveform like the one in Figure 2. Table 2 gives typical harmonic component magnitudes associated with this waveform. The most important variables affecting the harmonic spectrum are the circuit impedance supplying the power supply and the size of the dc capacitor.

The high third harmonic component associated with these loads appears in the zero sequence circuit when the loads are balanced across the three phases. This means that the neutral currents in these circuits can be quite high, with rms values up to 170% of the rms phase current. This zero sequence third harmonic current becomes trapped in the delta winding of delta-wye step down transformers and is usually not a major concern for the 480 volt portion of the building electrical system.

Table 2. Harmonic Current Characteristic of Load Type B

Harmonic Order	Magnitude %
1	100
3	54.8 - 65.8
5	36.7 - 43.6
7	18.3 - 20.3
11	0.5 - 0.6
13	2.6 - 4.0

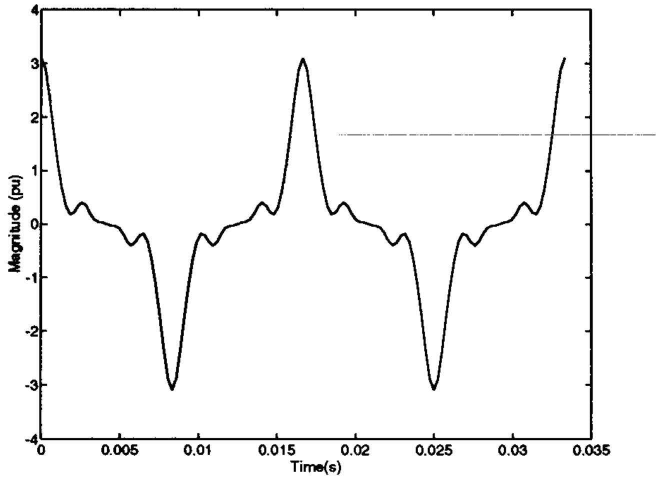


Figure 2. Typical load current for load type 'B'

Fluorescent Lighting

Fluorescent lighting can also be an important source of harmonic currents in commercial facilities. In conventional, magnetic ballast-type of fluorescent lights, the fluorescent light itself is the harmonic source. It appears as an arcing voltage behind the impedance of the magnetic ballast. Current harmonic components are limited by the ballast inductance but can still be significant. An example fluorescent lighting waveform is shown in Figure 3. Table 3 gives typical harmonic component magnitudes associated with fluorescent lights with magnetic ballasts. Since the third harmonic components of fluorescent lighting loads are usually less than 30% of the fundamental, there are no special concerns for the neutral conductors supplying fluorescent lighting load (the code already requires that the neutral conductor in these circuits be the same size as the phase conductors).

Fluorescent lights with electronic ballasts are also very popular due to their energy-saving potential. The electronic power supplies could have similar characteristics to the waveform and spectrum in Figure 2 and Table 2, respectively. Most electronic compact fluorescent lights for residential applications do have this type of characteristic. However, most electronic fluorescent lights for commercial applications have ballasts designed to reduce the harmonic production to avoid negative impacts in commercial facilities. There are many different characteristic waveforms for electronic ballast fluorescent lighting, depending on the ballast technology and filtering employed.

Table 3. Harmonic Current Characteristics of Load Type C

Harmonic Order	Magnitude %
1	100
3	6.4 - 24.3
5	6.2 - 14
7	0.9 - 5.4
11	0.2 - 6.0
13	0.3 - 2.3

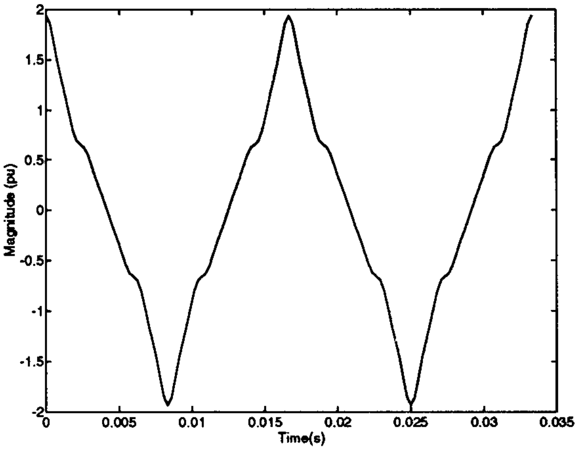


Figure 3. Typical load current for load type ‘C’

Summary

Typical characteristics of important classes of nonlinear loads commonly found in commercial facilities are presented. These typical characteristics can be used to evaluate concerns for applying new loads in commercial facilities and for evaluating the possible derating requirements associated with existing loads. The loading of a commercial facility can be divided into these major classes and the overall harmonic producing potential evaluated.