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The Potential Effects of Single-Phase Power Electronic-Based Loads on Power System Distortion and Losses

Volume 5: Considerations Related to Neutral-to-Earth Voltage

Technical Report

The Potential Effects of Single-Phase Power Electronic-Based Loads on Power System Distortion and Losses

Volume 5: Considerations Related to Neutral-to-Earth Voltage

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REPORT SUMMARY

Utilities have traditionally considered harmonics due to single large loads the main harmonics problem in power systems. However, the increase in size and proliferation of single-phase power electronics-based loads has created a need for developing analytical tools for analyzing the impact of distributed nonlinear loads on electrical equipment and on the distribution system as a whole. This report focuses on the effects of single-phase power electronic load currents on Neutral-to-Earth Voltage (NEV).

Background

The number and effect of single-phase nonlinear harmonic-producing devices connected to the power system have increased significantly over the past few years. While individual large single-phase power electronic loads do not pose a problem for electric utilities, harmonics generated by many distributed loads accumulate in the power system. The possible implications of large numbers of single-phase devices in distribution systems and in customer facilities are a growing concern for utilities and customers. This volume is the fifth part of a five-volume report that summarizes the results of an extensive research effort to analyze the impact of distributed harmonic sources on the utility system and on equipment. It focuses on the impact of third-harmonic currents from single-phase non-linear loads on NEV.

Objective

To investigate the impact of third-harmonic currents on NEV.

Approach

The project team investigated the effect of single-phase power electronic load currents on NEV by explaining the elevation of current levels in the neutral wire, by presenting a theoretical model of a grounded-wye distribution system, and by computing the NEV at a simulated distribution system substation that supplies various widely distributed single-phase power electronic loads. They computed neutral-to-earth voltages along the distribution circuit while varying the parameters that affect NEV calculations. Finally, they applied a composite harmonic current injection that accounts for diversity in phase angle and load among many single-phase power electronic loads to the distribution system and compared the resulting NEV and harmonic voltage levels.

Results

NEV has traditionally drawn attention on rural circuits. Rural circuits may be more prone to harmonic-related NEV problems because the equivalent net pole grounding impedance is higher in rural areas due to decreased load density. Otherwise, for circuits with the same net pole grounding impedance, feeder length plays no role in determining NEV at the substation. The grounding impedance of poles and transformers along the feeder, plus the grounding impedance of the substation mat, play the most important roles in determining the sensitivity of NEV to harmonic currents. Higher grounding impedances yield higher NEVs.

The report also describes conventional harmonic voltage studies on the model distribution feeder using typical single-phase power electronic loads as harmonic injectors. The results show that for short feeders, NEV can exceed 4 V at a significant number of busses before voltage distortion becomes a problem. It is apparent that existing standards for voltage distortion do not guarantee that third harmonic currents will not produce unacceptably high NEV, especially on short feeders. Elevated NEV near distribution system substations is another example of the particularly harmful effects of third harmonic currents.

EPRI Perspective

By providing utilities with analytical tools and methodologies to assess the impact of single-phase nonlinear loads, EPRI is enabling utilities to understand how these loads may impact the power system in the future. The results of this research should also help industries and utilities define meaningful and practical limits for harmonic current injection from single-phase nonlinear loads. These limits will ultimately benefit end users by improving the quality of the voltage supplied to end-use loads and minimizing the impact of harmonics voltage on equipment performance.

Keywords

Power Quality
Harmonics
Cancellation
Attenuation
Single-Phase Loads
Neutral-to-Earth Voltage

ABSTRACT

While interest in the third harmonic currents generated by single-phase power electronic loads has focused mainly on harmonic voltage problems, an additional concern on distribution systems is increased neutral-to-earth voltage (NEV). This report examines the impact of third-harmonic currents on NEV. The theoretical basis for the evaluation of the third-harmonic current effect on NEV is examined by presenting a generalized model of a power distribution system with power electronic loads. Using this model, it is shown that third harmonic currents significantly impact NEV, especially near substations. The harmonic voltage distortion for the same sample feeder caused by various widely distributed signel-phase power electronic loads is also computed. In most cases the limiting factor for harmonic currents is voltage distortion. However, for some cases, especially those involving shorter feeders, or feeders without capacitor banks, the limiting factor may be NEV.

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1

INTRODUCTION

Single-phase power electronic loads such as computers, televisions, and adjustable speed drive air-conditioners are an increasingly important source of harmonic currents in power distribution systems. Significant research efforts have described and quantified the effects of the harmonic currents such loads generate on power distribution system harmonic voltages and equipment.

However, harmonic currents in distribution systems also affect neutral-to-earth voltages (NEV), particularly near substations. Elevated neutral voltages can be the source of electric shock to humans or animals [1]. High NEV can also be a cause of electronic equipment malfunction.

Because it is common practice to connect the neutral wire to grounded objects such as water pipes, examples abound where humans and animals are brought into contact with elevated voltages as a result of high NEV. Because the human threshold of perception is as low as 1mA, neutral voltages should be held low; generally less than 4 V rms [1].

This report investigates the effect of single-phase power electronic load currents on NEV by explaining the elevation of current levels in the neutral wire, by presenting a theoretical model of a grounded-wye distribution system, and by computing the NEV at a simulated distribution system substation that supplies various widely distributed single-phase power electronic loads. The neutral-to-earth voltages along the distribution circuit are computed and the parameters which affect NEV calculations are varied. Finally, a composite harmonic current injection that accounts for diversity in phase angle and load among many single-phase power electronic loads is applied to the distribution system, and resulting NEV and harmonic voltage levels are compared.

2

NEUTRAL CURRENTS

In an ideal power distribution circuit the neutral wire carries no current. However, realities such as harmonic currents or load imbalance generally cause the neutral wire to conduct some current. Single-phase electronic loads are an increasingly significant source of third harmonic currents which for the most part return through the neutral conductor and earth.

The typical single-phase power electronic load uses a capacitor-filtered diode bridge rectifier [2]. This circuit has been shown to inject harmonic currents that have THD_I as high as 100% [2]. The third harmonic component is generally the most significant component. When many single-phase power electronic loads are present, it has been shown that there is little phase angle diversity among the third harmonic currents injected by individual loads [2]. Thus, third harmonic currents from these sources are almost completely additive.

Because balanced third harmonic currents are zero-sequence (as are all other balanced triplen harmonics), these currents, when conducted by different phases of a grounded-wye power distribution system, will tend to add in the neutral wire [3]. This is in contrast to positive or negative sequence currents which, when balanced, cancel one another and are not conducted by the neutral wire.

This effect has long been considered in the design of building wiring, and the National Electrical Code requires that neutral wires be sized in order to accommodate the increased current resulting from electronic loads [4]. However, at the distribution level, the effect of increased neutral currents resulting from electronic loads has gone largely unresearched.

3

ELEVATED NEUTRAL TO GROUND VOLTAGE

One effect of increased levels of neutral current is an increase in the voltage measured between the neutral wire and remote earth ground (NEV). To study this phenomenon, the circuit shown in Figure 3-1 is chosen to model a four-wire multi-grounded power distribution system trunk feeder for third harmonic purposes. Laterals are not explicitly included in the model, but loads served by these laterals and their grounding-impedances are lumped at the poles along the trunk feeder. Loads are modeled as fixed current injectors, and current flows through the overhead lines; return current divides between the neutral conductor segments (NCS) and the combination of the ground and the net grounding impedances Z_{gnet}. NEV at the substation is the potential between the neutral conductor and remote earth ground as denoted V_{NEV} in Figure 3-1.

Usually, it is not possible to determine precise values for the grounding impedances since they are, in reality, composite combinations of equipment, building, and pole grounds. However, there exists a reasonable range of values.

The neutral line characteristics, however, can be computed more precisely using established techniques. For the four-wire system depicted in Figure 3-1, one computes the row corresponding to the neutral conductor of the 4x4 complex impedance matrix. The values in this matrix are related to the geometry and conductors of the overhead lines.

The impedance characteristics of a segment of neutral wire is determined by first computing the row matrix shown in (1). Examining segment j of the neutral conductor,

$$\mathbf{Z}_{NCS_j} = [0,\ 0,\ 0,\ R_n] + \frac{j\omega\mu}{2\pi}\left[\ln\frac{D'_{na}}{D_{na}},\ \ln\frac{D'_{nb}}{D_{nb}},\ \ln\frac{D'_{nc}}{D_{nc}},\ \ln\frac{D'_{nn}}{r_n}\right]$$

$$= [Z_{n,a},\ Z_{n,b},\ Z_{n,c},\ Z_{n,n}], \qquad \textbf{Eq. 3-1}$$

where

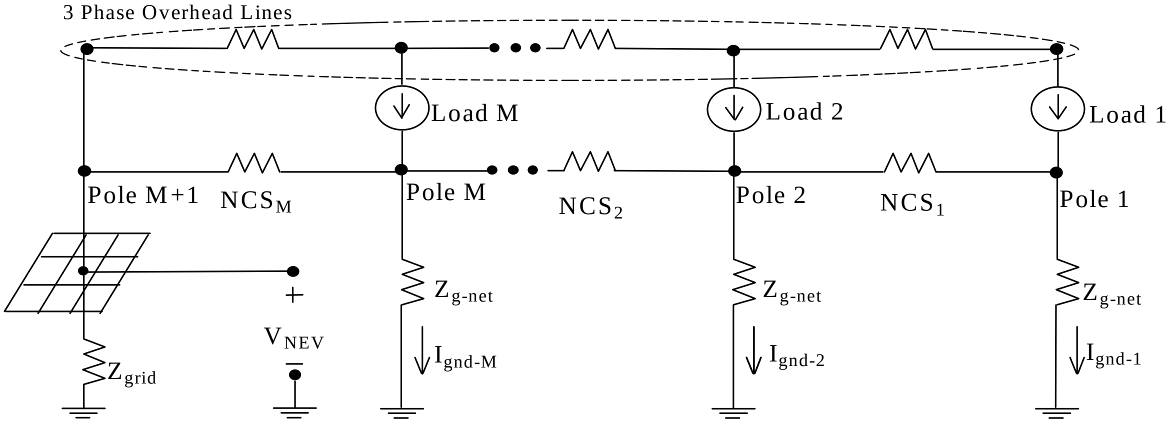


Figure 3-1
Distribution System Model for Trunk Feeder

R_n: Resistance per meter of neutral conductor.

D_{nx}: Distance from neutral conductor to phase $x \in \{a,b,c\}$ conductor.

D'_{nx}: Distance from neutral conductor to image of phase $x \in \{a,b,c\}$ conductor.

r_n: Product of the radius of neutral conductor and $e^{-1/4}$ to account for internal inductance.

The resistive skin effect will be considered when computing conductor resistance at higher-than-fundamental frequency.

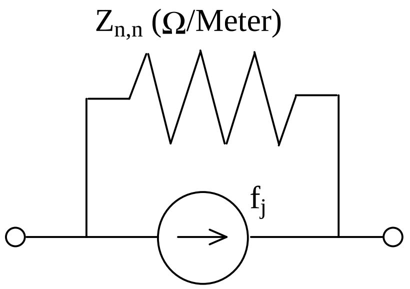
Since the triplen harmonics are zero-sequence (under the assumption of balanced currents), it is essential to consider the effect of the Earth's non-infinite conductivity. The simplest way to account for this is the method of complex depth (d_c) of return [5].

Once $\mathbf{Z}_{NCS_j}$ has been computed, the jth segment of neutral wire is modeled as follows.

Referring to the matrix computed in (1), the voltage drop along the jth neutral conductor segment is

$$\Delta V_{NCS_j} = Z_{n,a} I_a + Z_{n,b} I_b + Z_{n,c} I_c + Z_{n,n} I_n \qquad \textbf{Eq. 3-2}$$

Since load currents I_a, I_b, I_c, are modeled as fixed current injectors, then, according to (2), the segment of neutral line appears as a load-dependent current source f_j in parallel with a complex impedance as shown in Figure 3-2.



$$f_j = (Z_{n,a}I_a + Z_{n,b}I_b + Z_{n,c}I_c)/Z_{n,n}(\text{A/Meter})$$

Figure 3-2
Segment of Overhead Neutral Line Including Induced Voltage from Phase Conductors

Choosing a particular scenario consisting of line geometry, conductor sizing, grounding impedance, and circuit loading, results in a complete model for the power distribution system. Each neutral conductor segment in Figure 3-1 is replaced by the corresponding circuit shown in Figure 3-2 in order to account for the induced voltage effect of the phase conductors. Applying Kirchoff’s Current Law (KCL) at each pole labeled 1 through M+1 in the circuit of Figure 3-1, generates M+1 algebraic equations which can be solved to determine network voltages.

4

NEV EVALUATION

The third harmonic current injected by a single-phase power electronic load is generally much larger than any other triplen harmonic. Thus, evaluation is restricted to the third harmonic current impact on NEV.

For the purpose of analysis the model in Figure 4-1 is used to simulate a 12.5 kV radial trunk feeder with the following (x,y) coordinate system geometry (origin is located on the ground).

Phase A:	(-4.2, 31.0) ft.
Phase B:	(3.2, 31.0) ft.
Phase C:	(-1.1, 31.6) ft.
Neutral:	(0.0, 24.0) ft.

Poles are located every 200 feet. Load is evenly distributed at every pole along the trunk feeder. The impedance of the substation ground mat is initially set at 0.2 ohms. This model will be used to compute NEV along two different feeders one with line length 5 miles and the other with line length 10 miles.

In order to simulate lateral lines that extend from each pole, consider the net grounding impedance of each pole Z_{gnet}. The net grounding impedance at each pole is computed to be the parallel combination of the grounding impedances Z_g of the individual laterals attached to that pole.

Both the 5 and 10 mile circuits supply 5 MW total load. Assuming an average load per customer of 2.7 kW results in 1,852 total customers on the feeder. This yields an average of 14 grounding impedances at each pole. These grounding impedances are distributed along the laterals, but for modeling purposes they are consolidated into an equivalent grounding impedance at the pole on the trunk feeder. The 10 mile feeder has 7 equivalent grounding points per pole. With this in mind, Z_{gnet} for the 5 mile circuit is one-fourteenth the grounding impedance Z_g of an individual pole or service drop, and Z_{gnet} is one-seventh of Z_g for the 10 mile circuit. Individual grounding impedances, Z_g, can reasonably be expected to fall between 10 and 50 ohms. For this example, Z_g is chosen to be 25 ohms.

The results of the NEV analyses are presented in Figure 4-1. NEV is linear with total harmonic current injection, provided that the relative harmonic injection magnitudes remain constant between loads. Therefore, NEV is related in units of volts per total 3rd harmonic amps injected in the circuit. NEV can then be computed according to specific circuit loading.

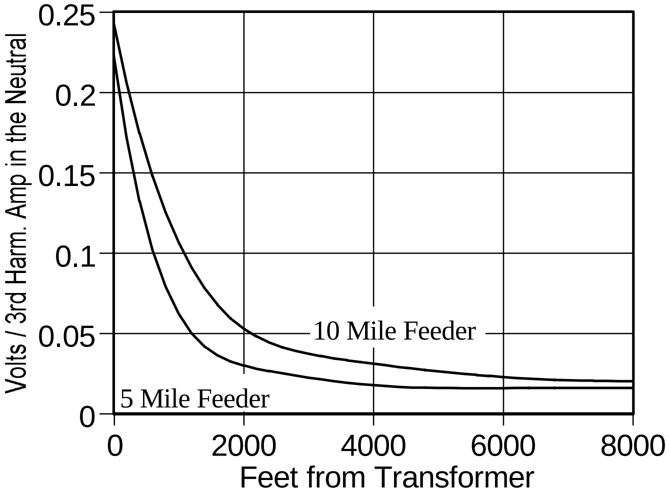


Figure 4-1
Profiles of NEV along Distribution Circuits

Figure 4-1, and subsequent studies show that, assuming constant load, NEV increases with feeder length. This is because the longer circuit has higher net grounding impedance at each pole. If both circuits have the same load density (i.e. MW per mile), NEV is inversely related to circuit length and the peak value of NEV at the substation is the same in both cases.

Whatever the assumptions regarding grounding impedances, feeder length, or circuit geometry, the NEV always follows the profile shown in Figure 4-1. NEV remains constant and low far from the substation, and rises to a peak value at the substation. The voltage rise near the substation is a phenomenon that has been observed in actual circuits with high NEV [3]. Because NEV changes so rapidly near the substation, it is reasonable to average the NEV for the one-half mile nearest the substation. For the 5 mile feeder this value is 0.0442 V per 3rd harmonic amp.

Consider the 5 mile case. The load is 5 MW, and if 20% of this load is electronic with third harmonic current 80% of the fundamental, then the expected value of NEV is 4.9 V near the substation. This voltage exceeds recommended levels [1].

NEV vs. Circuit Length

The relationship between substation NEV and circuit length is now examined. Maintaining the same distance between loads, line geometry, ground mat impedance, and the assumption of evenly distributed load, the circuit length is varied between 1 and 10 miles. The total load of 5 MW remains constant regardless of feeder length, and there is a grounding impedance for every 2.7 kW of load. Thus, the net grounding impedance at each pole increases as the circuit lengthens.

Variations in grounding impedance are considered by examining three distinct conditions where Z_g is fixed at 10, 25, and 50 ohms. Figure 4-2 shows that higher grounding impedances yield higher levels of NEV along the distribution circuit and at the substation.

The average NEV over the one-half mile nearest the substation is detailed in Figures 4-2 and 4-3. It is apparent that the NEV-to-third harmonic-ampere ratio near the substation increases with circuit length. This is a result of the higher value of net grounding impedance at each pole.

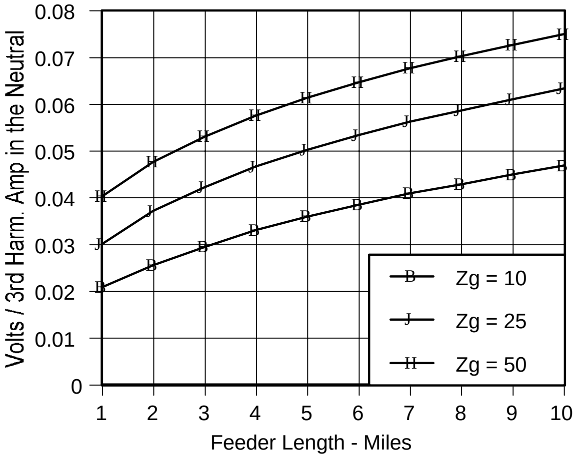


Figure 4-2
NEV near Substation vs. Circuit Length. Constant Total Load

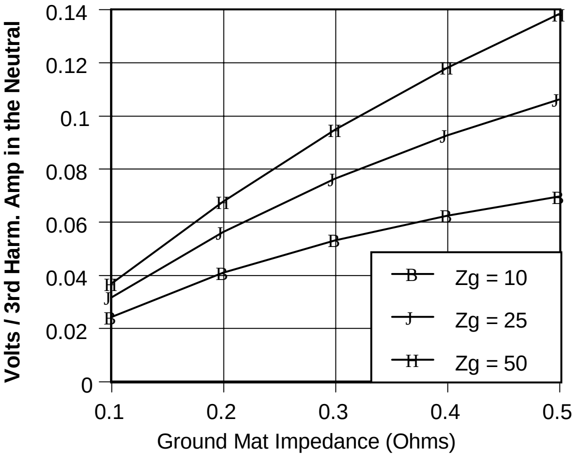


Figure 4-3
NEV near Substation vs. Ground Mat Impedance for 7 Mile Feeder

Had load density (i.e. MW/mile) remained constant instead of total load remaining constant, net grounding impedance at each pole would remain constant between feeders of varying length. The NEV at the substation would not vary with circuit length, and the asymptotic level of NEV along the feeder would be inversely related to circuit length.

NEV vs. Ground Mat Impedance

Ground mat impedance is one of the more important parameters in determining substation NEV. To observe its effect, the ground mat impedance Z_{mat} is varied between 0.1 and 0.5 ohms. The results of this analysis on a 7 mile circuit where 10 grounding impedances are lumped at each pole on the trunk feeder (i.e. the 5 MW load, 2.7 kW per grounding impedance assumption) are detailed in Figure 4-3.

NEV vs. Pole Spacing

Earlier examples assumed that load was distributed evenly between all poles. Further analysis determines that uniformly distributing unloaded poles between equally loaded poles does not affect the NEV near the substation. Pole separation has been assumed to be 200 feet. For the cases described earlier the pole spacing has been varied. Results indicate that NEV is directly related to the distance between poles but does not vary appreciably over a reasonable range of values.

5

EXCESSIVE NEV AND VOLTAGE DISTORTION

Considerable effort has already been devoted to the problem of harmonic voltages resulting from power electronic loads. Existing IEEE standards seek to maintain voltage total harmonic distortion (THD_V) levels on distribution feeders below 5% [6]. Here, the relationship between NEV and THD_V is determined.

A model is used to predict the net harmonic current injection from a large number of single-phase power electronic loads. This model accounts for both magnitude variation and phase angle cancellation between loads that operate at differing power levels and with varying designs. The resulting harmonic spectrum is shown in Table 5-1 [7]. For THD_V calculations, load with this spectrum is distributed uniformly along the distribution feeder and among the three phases until voltage distortion exceeds 5% THD at 5% of the poles along the feeder. The total rms harmonic amps per phase that are required to violate IEEE 519 standards for THD_V are recorded.

Table 5-1
Harmonic Spectrum of Power Electronic Loads

Harmonic Order	% of Fundamental
3	81
5	53
7	25
9	9
11	5
13	4
15	3

The feeder described previously is then loaded with 5 MW total load. A moderate number (1200 kVAr) of switched capacitors are added in 300 kVAr banks to correct power factor.

Relying on the techniques described earlier, the harmonic current (with the harmonic spectrum of Table 5-1) that must be injected on each phase in order to force the expected value of NEV to exceed 4 V is computed. For this analysis, in order to be consistent with the THD analysis, the NEV is averaged over the 5% of the feeder nearest the substation. Finally, only the third harmonic current is considered when computing NEV since the triplen harmonics 9 and 15 are relatively small.

The results of three different analyses are presented in Figures 5-1 thru 5-3. In all three cases, pole ground impedance is fixed at 25 ohms. Figures 5-1 and 5-2 assume constant total load among feeders of varying length. Figure 5-3 assumes a constant load density of 1 MW/Mile among feeders of varying length. The previous 2.7 kW average load per ground assumption is maintained. Regions are labeled according to whether 5% THD_v, 4 V NEV, or both are exceeded.

It is apparent that existing standards for voltage distortion do not guarantee that third harmonic currents will not produce unacceptably high NEV, especially on short feeders.

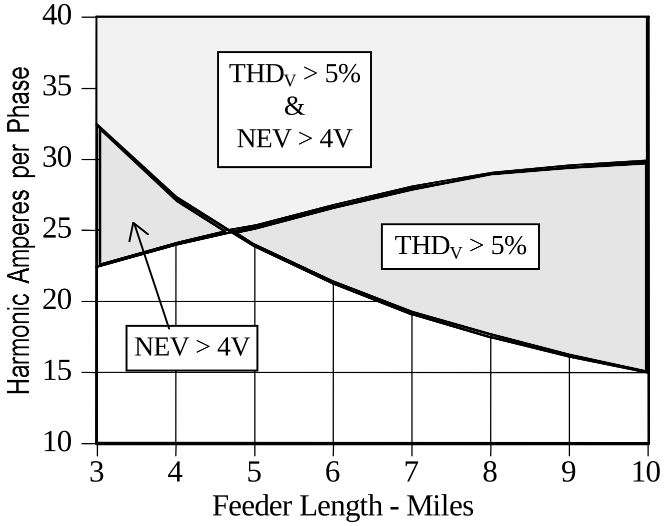


Figure 5-1
Harmonic Ampere Limits. Constant Load. Capacitors Off

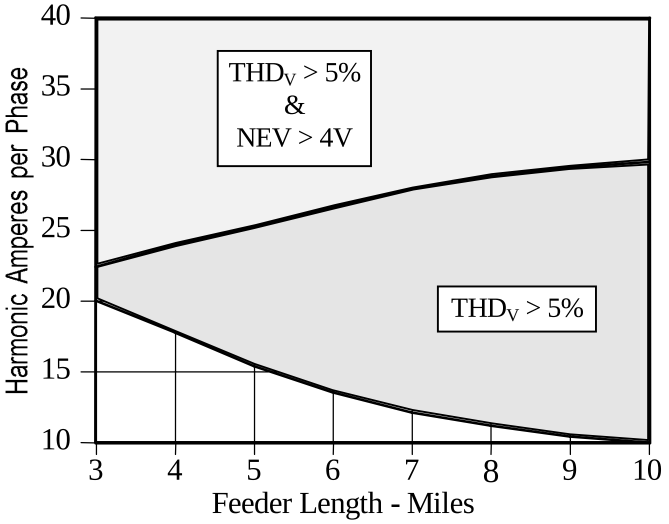


Figure 5-2
Harmonic Ampere Limits. Constant Load. Capacitors On

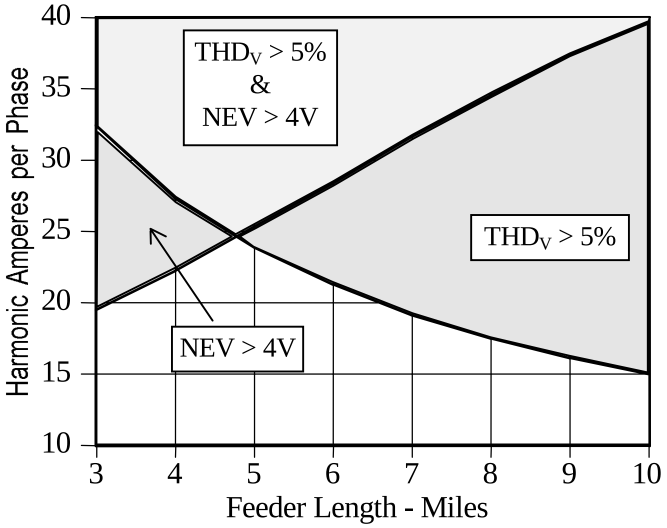


Figure 5-3
Harmonic Ampere Limits. Constant Load Density. Capacitors Off

6

CONCLUSIONS

This report presents a model which allows an examination of the impact of third harmonic currents generated by single-phase electronic loads on neutral to earth voltage (NEV) along a generalized distribution feeder. The report examines the theoretical basis for the model and presents a parametric analysis of the relation between key variables and NEV. It also presents the relation between excessive NEV and excessive voltage harmonic distortion along the generalized distribution feeder.

NEV has traditionally drawn attention on rural circuits. Rural circuits may be more prone to harmonic related NEV problems because the equivalent net pole grounding impedance is higher due to decreased load density. Otherwise, for circuits with the same net pole grounding impedance, feeder length plays no role in determining NEV at the substation.

The grounding impedance of poles and transformers along the feeder, plus the grounding impedance of the substation mat, play the most important roles in determining the sensitivity of NEV to harmonic currents. Higher grounding impedances yield higher NEVs.

Conventional harmonic voltage studies on the model distribution feeder using typical single-phase power electronic loads as harmonic injectors are also conducted. The results show that for short feeders, NEV can exceed 4 V at a significant number of busses before voltage distortion becomes a problem.

It is apparent that existing standards for voltage distortion do not guarantee that third harmonic currents will not produce unacceptably high NEV, especially on short feeders.

Elevated NEV near distribution system substations is another example of the particularly harmful effects of third harmonic currents.

7
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A

APPENDIX A – PROGRAM NEV

```
      complex y(1000,1000),a(1000),v(1000),cpa,cpb,cpc
      complex yt(1000,1000),at(1000)
      complex att(1000),fyt
      complex zn,yn,fy,f1,f2,f3,cinj,znperp
      real distf,zm,yg,zg,perft,nev(1000)
      real sum1,s2,cnt,NEVHLF,QRT,c2,fiveavg
      integer np,everyl,solve,istop,navg

      open(unit=1,file='solve.in',status='unknown')
      open(unit=2,file='solve.out',status='unknown')
      open(unit=3,file='tester.out',status='unknown')
      open(unit=4,file='profile.out',status='unknown')
      open(unit=5,file='subvolt.out',access='append',status='unknown')

      eps  = 1e-6

c     read the input parameters:
c     distf = approximate length in miles of feeder
c     perft = number of feet between poles
c     everyl= there is load every 'everyl' poles
c     Zn    = complex impedance of total neutral wire per mile
c     Zm    = impedance of ground mat
c     Zg    = ground impedance.
c     f1,f2,f3    = coupling parameters for total length of neutral wire
c     per mile
c     aperkw= amps of third harmonic per kw of electronic load in
c     rectangular form
c                 (phase is relative to fundamental)
c         solve = 1 if want to solve complete voltage profile.  = 0 otherwise
      read(1,*)distf
      write(2,*)'Total feeder distance ',distf,' miles.'
      read(1,*)perft
      write(2,*)'Poles every _ ft. -',perft
      read(1,*)everyl
      write(2,*)'Loads every ',everyl,' poles.'
      read(1,*)zn
      write(2,*)'Neutral impedance per mile ',zn
      read(1,*)zm
      write(2,*)'Ground mat impedance ',zm
      read(1,*)zg
      write(2,*)'Grounding impedance ',zg
      read(1,*)f1
      write(2,*)'Phase a induction parameter ',f1
      read(1,*)f2
      write(2,*)'Phase b induction parameter ',f1
      read(1,*)f3
      write(2,*)'Phase c induction parameter ',f1
      read(1,*)solve
      write(2,*)'Will solve for voltage profile ',solve
      np = int(distf*5280/perft)
      write(2,*)'Total number of poles: ',np
```

```
c     cinj is the injection of a single load
c     distp is the distance between poles in miles
      distp = distf / np
      cinjt = 100.0
      write(3,*)'complex injection total ',cinjt
      if (everyl.gt.200) then
       nl = 1
       cinj = cinjt
      else
       nl    = int(np / everyl)
       ndum  = mod(np,everyl)
       if (ndum.gt.eps) nl = nl + 1
       cinj  = cinjt / nl
      endif
      write(2,*)'Total number of loads ',nl
      write(2,*)'Injection at each load ',cinj, ' amps.'
      write(2,*)'Distance between poles ',distp*5280,' feet.'

      cpa = (1.0,0.0)
      cpb = (-0.5,-0.866)
      cpc = (-0.5,0.866)
c     Compute the impedances and admittances between poles
      Znperp = Zn * distp
      Yn     = 1/Znperp
      Yg     = 1/Zg

c      fy is the product of the neutral row of the impedance matrix and the current
    injection
c        given one injection (Z*I1) and the product of Yn or (Z*I1)*Yn.
      f1 = f1 * distp
      f2 = f2 * distp
      f3 = f3 * distp
c     fy = f1 * abs(cinj) * cpa + f2 * abs(cinj) * cpa +
c    1     f3 * abs(cinj) * cpa
      fy = f1 * abs(cinj) + f2 * abs(cinj) + f3 * abs(cinj)
c     fyt= fy / 3
      fy = fy * Yn / 3

      write(3,*)'f1,f2,f3',f1,f2,f3
      write(3,*)'cpa,cpb,cpc',cpa,cpb,cpc
      write(3,*)'f1*cpa',f1*cpa
      write(3,*)'f2*cpb',f2*cpb
      write(3,*)'f3*cpc',f3*cpc
c     write(3,*)'total ',f1*cpa+f2*cpb+f3*cpc
      write(3,*)'total ',f1+f2+f3
      write(3,*)'F = ',fy / yn
      write(3,*)'Zn = ',1/yn,' ohms.'
      write(3,*)'Yg = ',1/yg,' ohms.'
      write(3,*)'Complex current injection = ',cinj,' amps.'
      write(3,*)'Induced voltage per pole ',fy/yn,' volts.'

c
c     we seek to find subvolt - the magnitude of the substation neutral voltage
c
c     the dimension of the admit. matrix is one more than the number of poles
c
      n=np+1
      do 101 j=1,n
       do 102 k=1,n
        y(j,k)=(0.0,0.0)
  102  continue
       a(j)=(0.0,0.0)
  101 continue
```

```
c     build the admittance matrix a and the current matrix y
      y(1,1)   =  Yn + Yg
      y(1,2)   = -Yn
      a(1)     =  cinj + fy
      y(n,n-1) = -Yn
      y(n,n)   =  Yn + 1/Zm
      a(n)     = -cinjt - fy*nl
      icount   =  1
      icheck   =  1 + everyl
      if (n.gt.2) then
       do 10 j = 2,n-1
        y(j,icount)   = -Yn
        y(j,icount+1) =  2*Yn + Yg
        y(j,icount+2) = -Yn
        if (j.eq.icheck) then
         a(j) = cinj + fy
         icheck = icheck + everyl
        endif
        icount = icount + 1
   10  continue
      endif


      do 150 j=1,n
       do 151 k=1,n
        yt(j,k) = y(j,k)
  151  continue
       att(j)= a(j)
  150 continue

      write(3,*)'Current Matrix'
      do 152 j=1,n
       write(3,*)j,a(j)
  152 continue


c solve the system of equations using Kron reduction (Gaussian elimination)
c This has been optimized for the particular admittance matrix we are solving.  Take
c care transferring this code elswhere.

      do 50 m     = 1,n-1
        mp1       = m   + 1
        mp2       = mp1 + 1
        mp3       = mp2 + 1
        if (mp2.gt.n) mp2=n
        if (mp3.gt.n) mp3=n
        do 53 k=mp1,mp3
          y(m,k) = y(m,k) / y(m,m)
   53   continue
        a(m) = a(m) / y(m,m)
        y(m,m) = (1.0,0.0)
        j = mp1
         do 54 k = mp1,mp2
          y(j,k) = y(j,k) - y(j,m) * y(m,k)
   54    continue
         a(j) = a(j) - y(j,m) * a(m)
         y(j,m) = (0.0,0.0)
   50 continue
      a(n)   =  a(n) / y(n,n)
      y(n,n) = (1.0,0.0)

      subvolt = abs(a(n))
```

```
      v(np+1)   = a(n)
      if (solve.eq.1) then
       do 200 j=np,1,-1
        v(j) =  a(j)
        do 201 k = j+1,n
         v(j) = v(j) - v(k)*y(j,k)
  201   continue
  200  continue
      endif

      write(2,*)'Solver results'
      write(2,*)'Currents from solved voltages,    cur from user input'
      do 160 j=1,n
       at(j) = (0,0)
       do 161 k=1,n
       at(j) = at(j) + v(k) * yt(j,k)
  161  continue
       write(2,*)j,at(j),att(j)
       nev(j) = abs( v(j) / cinjt )
       write(4,*)(n-j)*perft,nev(j)
  160 continue
      if(np .lt. 11) stop

c     This computes the mean NEV for the 1/2 and 1/4 mile, and 5% of buses
c     closest to the transformer

      navg = int(np * 0.05 + 0.5)

      sum1 = 0.0
      do 501 j=np,(np-navg),-1
       rx = nev(j)-nev(j-1) / 2.0
       sum1 =sum1 + rx
  501 continue
      fiveavg = sum1 / (real(navg))

      j = 2640 / perft
      k = n - j + 1
      cnt = 0.0
      c2= 0.0
      sum1  = 0.0
      s2  = 0.0
      istop = n - j / 2 + 1
      do  103 i = n,k,-1
       rx = nev(i) - nev(i-1) / 2.0
       sum1 = sum1 + rx
       cnt = cnt + 1.0
       if (i.ge.istop) then
        s2 = s2 + rx
        c2 = c2 + 1.0
       endif
  103 continue
      QRT = s2 / c2
      NEVHLF = sum1 / cnt

      write(2,*)'Substation Voltage ',subvolt
      ei1 = abs( subvolt / cinjt )
      write(2,*)'Effective impedance at substation  -all ',ei1
      write(5,888)zg,zm,np,distf,subvolt,ei1,QRT,NEVHLF,fiveavg
  888 format(2f8.4,i5,f6.1,5f8.4)
      write(2,*)'Voltage Distribution'
      if (solve.gt.eps) then
       do 99 j=1,np+1
        write(2,*)j,abs(v(j))
```

```
        write(2,*)j,v(j)
   99  continue
      endif

100 continue
      stop

      end
```

Target:
End-Use Power Quality Mitigation Systems

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