Taming The Rogue Wave: Techniques For Reducing Harmonic Distortion

Autotransformers with low zero sequence impedance use phase shifting to mitigate harmonic currents.

A.H. (Tony) Hoevenaars, P.E.
A.H. (Tony) Hoevenaars, P.E. is Vice President with MIRUS International Ltd., North York, Ontario, Canada.

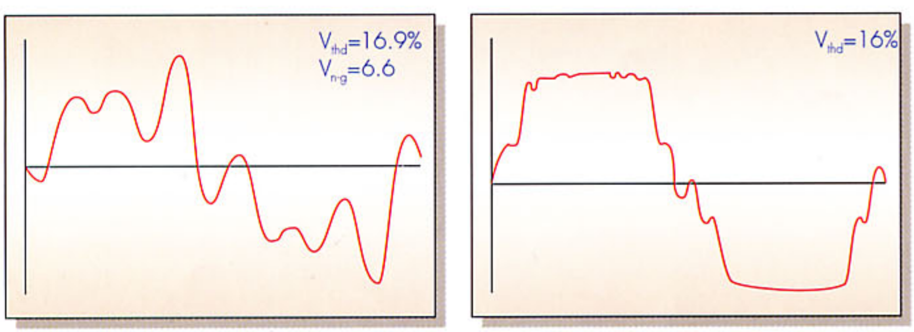
In nautical circles, the "rogue wave" is a devastating wave feared by even the most skillful of sailors. It can creep up on a ship with little warning with a force that can cause tremendous damage. In a similar manner, many of today's electrical systems are dealing with their own rogue waves: distorted voltage waveforms, as shown in **Fig 1**.

Like their nautical cousins, the electrical system rogue waves can be very devastating and rarely provide advance warning. They are the result of harmonic generating non-linear loads, which are proliferating throughout our commercial and industrial buildings. Unlike the nautical version, however, once voltage distortion has reached rogue wave status, it's not a one time occurrence but a continuous problem that can only be corrected by either elimination of the harmonic generating loads themselves (which is rarely possible) or through some form of harmonic mitigation.

Causes and symptoms

The ever increasing density of non-linear loads, such as PC's, printers, telecommunications equipment, and adjustable speed drives (ASDs) has begun to put tremendous stress on our electrical distributions in the form of harmonic distortion. Many of the subsequent problems have been well documented in recent years, especially those related to the overheating of neutral conductors, transformers, and other electrical distribution equipment, which can bring on premature failures. Some harmonic problems that have received less attention, but in many ways are even more serious, include high voltage distortion, neutral-to-ground voltage, and poor power factor (PF). In extreme cases, these phenomena are direct contributors to subsequent problems with the equipment connected to the power distribution. Examples include the following:

- Computer operational problems.
- Hardware component failures.
- Motor burnouts.
- Generator voltage regulation and frequency control problems.
- UPS and generator overheating.
- Failure of PF correction capacitors.



Problems experienced

- Computer hardware failures
- Computers locking up
- UPS refusing to go to by-pass
- Clocks running double speed

- Computer hardware failures
- Computers locking up

Fig. 1. *Examples of rogue wave voltage distortion and associated problems.*

How non-linear loads create voltage distortion

By far the majority of the voltage distortion found in today's distribution systems is produced by the loads themselves, not the supply. Much of today's electrical load is nonlinear, meaning it consumes current in a non-sinusoidal manner. Since, by definition, a non-sinusoidal waveform is composed of harmonic currents, non-linear loads are considered to be harmonic current sources. In other words, by consuming current in a non-sinusoidal manner, these non-linear loads produce harmonic currents that circulate through the power distribution system.

Most voltage distortion is the result of the interaction of these harmonic currents with the impedance of the electrical distribution system. As the harmonic currents pass through the system's impedance, they produce voltage drops at each harmonic frequency in relation to Ohm's Law: $V_h = I_h \times Z_h$. (See **Fig. 2** on page 34.) The voltage drops appear as harmonic voltages, and the accumulation of these voltages at all the harmonic frequencies produces the voltage distortion.

The relationship is:

$$V_{thd} = \sqrt{V_2^2+V_3^2+V_5^2+...+V_h^2} \div V1$$

where:

V_{thd}=Total harmonic distortion of voltage,

V_h=Voltage at harmonic number "h"

V_1=Fundamental voltage

Distortion levels can be quite high when system impedance is high. A fatal combination is high densities of non-linear loads in systems with high impedance or low fault level. This situation is common when weak sources, such as UPS systems or diesel generators, are used to service electronic equipment. The problem is magnified further when the equipment is serviced by long cable runs.

Voltage distortion demonstration setup

A simple way of demonstrating the relationship between harmonic voltage drop and voltage distortion is shown in **Fig. 3** (on page 36.) The objective is to show that the harmonic voltages, as measured across a harmonic current generating load, are primarily the result of the voltage drop developing as the harmonic current passes through the impedance of the power distribution system. In this demonstration, the non-linear loads chosen are 23W compact fluorescent lamps (CFLs). The main reasons for choosing these loads are as follows.

- Their current spectrum is quite typical of that found in today's electronic loads. (See phase current in Fig. 3)
- The low wattage of the lamps means that very little voltage drop is created as the harmonic currents pass through the impedance of the system. Voltage distortion can then be artificially increased by adding a relatively small reactor to increase system impedance. The voltage drop across this known reactance is then used to demonstrate how the voltage distortion is the result of voltage drops at each harmonic frequency.

The system impedance is artificially increased by inserting a 5% impedance, 3-phase, core-type, line reactor in series. Since the 3-phase reactor presents very low impedance to the zero sequence harmonics (those that return on the neutral), a similar size single-phase reactor is inserted in the neutral as well. By applying Ohm's Law as shown in Fig. 2, the voltage drops at each harmonic can be calculated. Since the inductance of the reactor (20 mH) is significantly greater than the remaining inductance in the system, the following assumptions can be made to simplify the voltage drop calculation.

- Cable, transformer, and source impedances are neglected since, in comparison with the reactor impedance, they are insignificant.
- Resistance in the reactor and the overall system is negligible as well.

This simplifies the demonstration setup system impedance as follows:

$Z_h = Z_S + Z_T + Z_C = Z_L$, for each harmonic frequency and since $Z = \sqrt{R_2 + X_2}$, neglecting resistance then, $Z_h = X_L = 2\pi fL$.

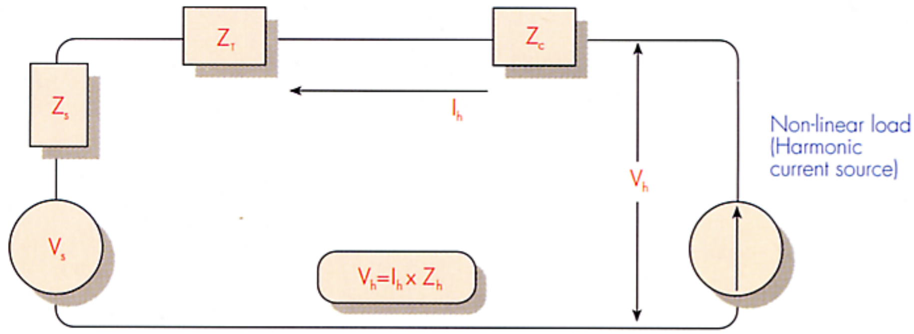
For the 5th harmonic (where h = 5, f = 300 Hz, and L = 20 mH) the system impedance becomes: $Z_5 = X_5 = 2\pi fL = 2\pi(300)(.02) = 37.7$ ohms,

Applying Ohm's Law, and using the harmonic current as measured with a harmonics analyzer, the 5th harmonic voltage drop is calculated to be:

$I_5 = 0.13A$

$V_h = I_h \times Z_h = 0.13 \times 37.7 = 4.9V$

The above calculations are applied to all odd harmonics from the 3rd to the 13th and the results tabulated in the **Table**. By comparing the calculated voltage drops with the actual measured harmonic voltage at each harmonic, you can see that they match quite closely. This confirms the harmonic voltages (which define voltage distortion) are primarily the result of the *accumulation of harmonic voltage drops*. Note that the measured voltages are slightly *higher* than the calculated voltage drops. This is due primarily to the fact that there is, in fact, some contribution to the voltage drop resulting from system impedances *other than* the line reactor (such as cable resistance).



Equivalent diagram

V_s=supply voltage (distortionless sinewave)
I_h=harmonic current
V_h=voltage drop at each harmonic
Z_s=source impedance
Z_T=transformer impedance
Z_c=cable impedance
Z_h=Z_s+Z_T+Z_c for each harmonic frequency

Fig. 2. *How harmonic-generating non-linear loads create voltage distortion.*

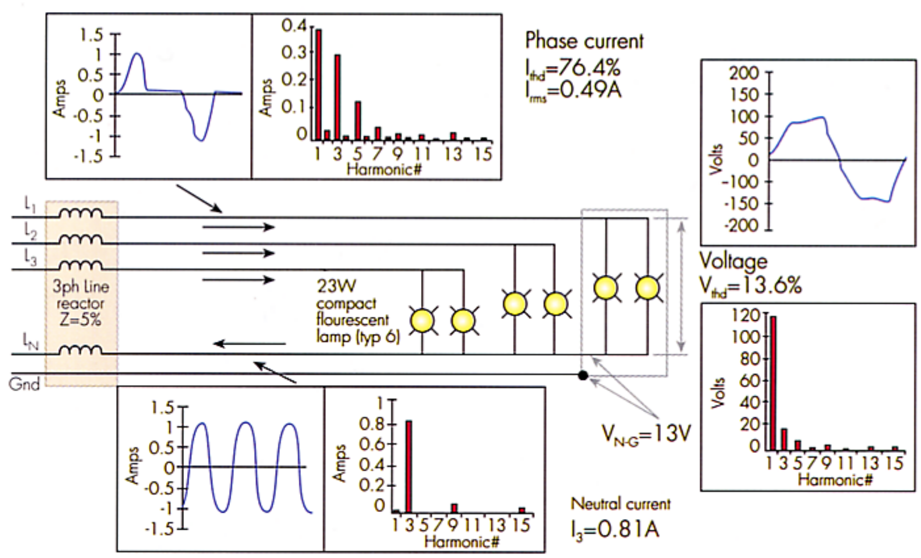


Fig. 3. *Demonstration setup to show how harmonic current distortion produces harmonic voltage distortion at the non-linear loads.*

The table also shows how the voltage drop across a neutral conductor creates a *high* neutral-to-ground voltage,which is a form of common-mode noise. The 20 mH single-phase reactor inserted in the neutral in the demonstration produces a calculated voltage drop of 18.3V at the 3rd harmonic. The measured value of neutral-to-ground voltage, at 13V (see Fig.3), approaches this calculated value. Although levels this high are not normally found in the field, it's now fairly common to find levels above 5V. An example is shown in Fig. 1 where the neutral-to-ground voltage at the first site was 6.6V.

Harmonic No.	Hz.	Current in amps (as measured)	Line reactor reactance (ohms)	Calculated voltage drop	Measured harmonic voltage
3	180	0.81	22.6	18.3	14.5
5	300	0.13	37.7	4.9	5.4
7	420	0.04	52.8	2.1	2.1
9	540	0.05	67.8	3.4	3.0
11	660	0.02	82.9	1.6	1.3
13	780	0.02	98.0	2.0	1.8

Comparison of calculated voltage drops with measured harmonic voltage on demonstration setup of Fig. 3. Total harmonic voltage distortion (V_{THD}) is 13.6%.

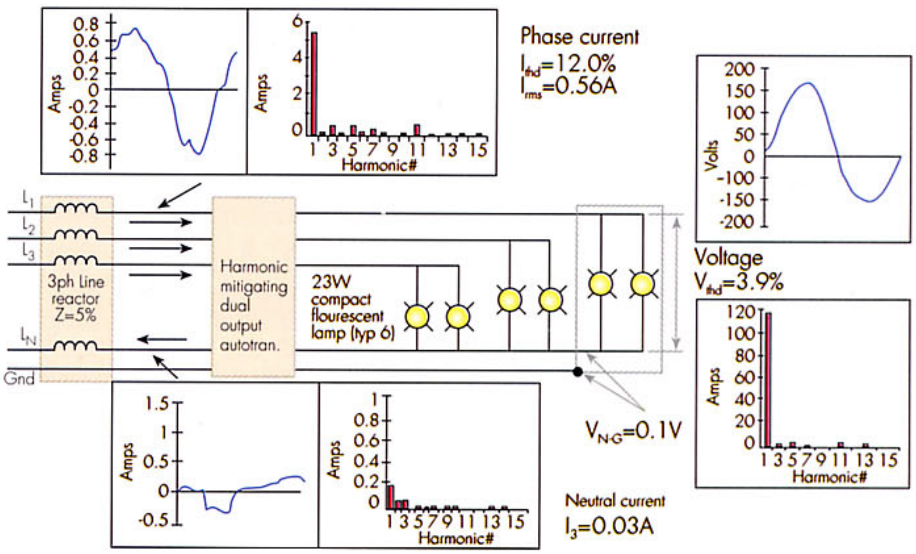


Fig. 4. *Demonstration setup with harmonic-mitigating transformer installed.*

What can be done to prevent the rogue wave from developing?

Considering Ohm's Law once again ($V_h = I_h \times Z_h$), we see that the harmonic voltage drops can be reduced by either reducing the harmonic currents or the system's impedance as seen by the harmonic generating loads, or both. Since the currents are determined by the loading and therefore, can only be changed by changing the loads themselves (or by turning them off), the only truly practical approach for reducing voltage distortion is to reduce the system impedance to the harmonic currents.

Harmonic mitigating transformers, which combine phase shifting strategies with low zero sequence impedance, are designed to reduce harmonics by providing alternate low impedance paths for the principal harmonic currents (3rd, 5th, 7th and 9th) to flow. A full explanation of how these transformers work is a technical paper in itself. In general terms, a 30° phase shift is applied to cancel 5th and 7th harmonic currents while, at the same time, flux cancellation is used to provide an alternate, low impedance path to the neutral conductor for the 3rd and 9th harmonics. By provideng alternate lower impedance paths, harmonic currents are prevented from flowing *back through* the full impedance of the system, resulting in much lower voltage drops and voltage distortion.

A dual output, phase shifting autotransformer with low zero sequence impedance is installed in the demonstration setup shown in **Fig. 4** to show how voltage distortion could be reduced. By reducing the system impedance to the harmonic currents near their source (the nonlinear loads themselves), the voltage drops across the impedance of the system (i.e. the 5% reactor) are reduced. This in turn improves the voltage waveform by reducing voltage distortion from 13.4% to 3.9%. (Compare Fig.3 with Fig. 4.)

Another significant benefit resulting from the installation of the harmonic mitigation equipment is the reduction in neutral-to-ground voltage near the loads (from 13.0V to 0.1V). Neutral-to-ground voltage develops as a result of the voltage drop created by the heavy neutral currents returning along the neutral conductor. Since the harmonic mitigating auto-transformer significantly reduces the neutral current (the 3rd harmonic component drops from 0.84A to 0.03A), the resulting voltage drop across the reactor is reduced as well.

You may have noticed that the 60 Hz component in the neutral is increased slightly with the installation of the transformer. This is the unbalanced portion of the magnetizing current of the auto-transformer. (The slight increase in phase current is also due to magnetizing current.) Since the loading in this demonstration is very small, the magnetizing current is disproportionately large. In typical field installations, the magnetizing current becomes negligible in comparison with the transformer's overall loading.

Case study: Treating harmonic distortion with a multiple output low zero sequence impedance transformer.

To further demonstrate the ability of a multiple output low zero sequence impedance transformer to reduce voltage distortion, the following case study is presented. (See **Fig. 5** on page 41). In this example, the harmonics generated by audio/visual equipment fed from a static UPS system were creating voltage distortion as high as 17.5%. Problems believed to be attributable to this high voltage distortion included some video distortion and abnormally frequent hardware failures.

Analysis of the current distortion on the system pointed to the need to treat the 3rd, 5th, 7th, and 9th harmonics. To do this, a dual output, low zero sequence impedance autotransformer (similar to that used in the demonstration setup) was installed to supply two existing power panels. As with the demonstration model, the two outputs of this transformer are phase shifted 30° apart in order to cancel 5th and 7th harmonics. The key difference between this transformer and other dual output phase shifting transformers is the way in which it handles the zero sequence, or triplen, harmonics (3rd, 9th, 15th, etc.). By canceling the zero sequence fluxes at its *secondary* windings, the triplen harmonics will not be induced to circulate in the *primary* windings. The result is a transformer with several times lower impedance to the flow of these harmonics, producing significantly less voltage drop and voltage distortion. Additional advantages include a reduction in transformer losses and temperature rise.

Note in Fig. 5 how much more linear (i.e. less harmonic content) the input current is than the output current. This is the result of the combined zero sequence filtering and phase shifting action of the harmonic mitigating transformer. By reducing the harmonic current content, voltage distortion is reduced by nearly 2.5 times, and power factor is increased (0.78 to 0.96). The UPS now benefits from the improved power factor and less heating (in the form of losses) due to harmonic currents. Oversizing of the UPS for the non-linear loads is no longer necessary.

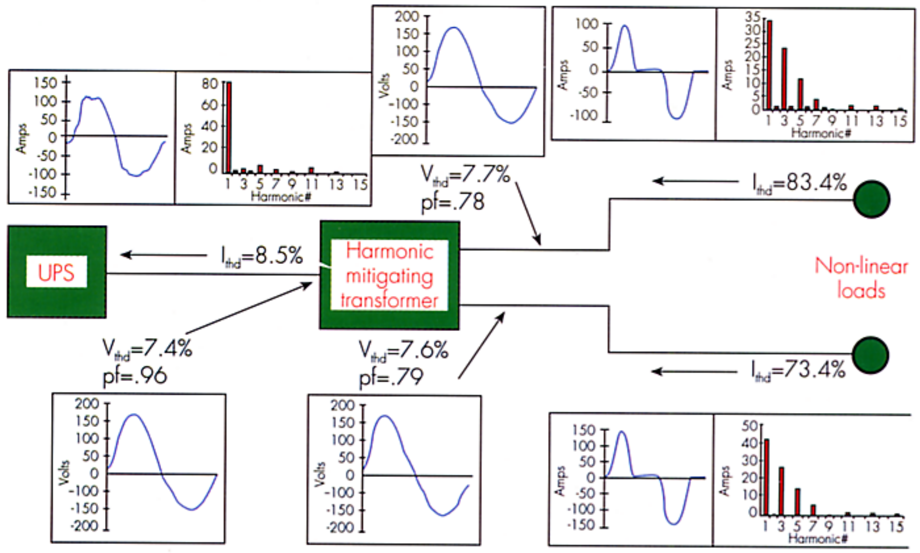


Fig. 5. *Power quality improvement downstream of a UPS through the use of a dual output harmonic mitigating transformer. Voltage distortion before treatment was 17.5%.*

You may note that although the voltage distortion has been reduced substantially, it still remains above 5%. This is due to the fact that the UPS unit is an older model that would produce close to this level of voltage distortion even if servicing a totally linear load.

What warning signs or specific conditions are likely to indicate rogue wave voltage distortion?

The roots of heavy voltage distortion are the harmonic currents generated by non-linear loads. When they circulate through an electrical systems impedance, voltage distortion develops. Therefore it follows that voltage distortion levels are highest where there are:

1. A high density of electronic loads. This includes office areas, computer rooms, telecommunications or LAN closets, broadcast equipment rooms, High Tech manufacturing production and test areas, and industrial or commercial buildings where adjustable speed drives are abundant.

2. Long cable, riser or busduct runs between the electrical supply and the harmonic current generating non-linear loads. The high conductor impedance of long service runs will produce larger voltage drops and subsequently heavier voltage distortion.

3. Small or high percent impedance transformers. Transformer impedance often has a more significant impact on voltage distortion than cable impedance, especially when the cable runs are reasonably short.

4. Electronic loads supplied by a weak source. By definition, a weak source is one with high source impedance, such as a UPS or diesel generator. Like high cable impedance, a high source impedance will result in larger voltage drops and heavier voltage distortion. Equipment which operates normally when serviced by the electrical utility supply, can experience erratic behavior when being supplied by a backup emergency generator during a power outage.

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They're critically important to every company today. But just as their numbers have multiplied, so has the problem of power system harmonic distortion. Every non-linear load introduces harmonics into the power system. Add enough of them and they will drastically distort both current and voltage waveforms. This often results in computer system failures, overloaded neutral conductors, overheated transformers, poor power factor and in the worst case, electrical fires.

The Mirus Eliminator™ or Harmony™ series products will solve all these problems by controlling the harmonics near their source. For 10 years, we've diagnosed and solved harmonic problems with over 1000 successful installations worldwide; serving small companies right up to blue-chip multinationals.

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