DESIGNING MODERN ELECTRICAL SYSTEMS WITH TRANSFORMERS THAT INHERENTLY REDUCE HARMONIC DISTORTION IN A PC-RICH ENVIRONMENT

by

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ABSTRACT

Generally, the electrical community has come to accept the fact that today's office facilities have an abundance of electronic equipment that produce harmonics. Based on the results of hundreds of electrical system surveys we have determined that the predominant harmonics are triplens; however, a high degree of 5th and 7th harmonics are also present and need to be treated for a more comprehensive solution. These harmonic rich environments are known to cause serious operational problems for users as well as building maintenance personnel. Until recently, no cost-effective methods have been proposed that can universally deal with 3rd, 5th and 7th harmonics during the design and specification stage of three phase four wire electrical distribution systems. By integrating phase shifting into an extremely low zero phase sequence impedance transformer with single or multiple outputs, substantial reduction of triplen, 5th and 7th harmonics can be achieved. The net result is that the electrical distribution system predictably becomes electromagnetically compatible with the electronic loads (e.g. personal computers) it has to supply.

1. INTRODUCTION

Traditional electrical system design had very little need to deal with harmonics because the loads typically designed for were linear in nature. Over the years, as more and more research and practical experience was gathered with linear loads, the design process became more and more predictable. With the proliferation of variable speed drives, electronic ballasts, personal computers and other electronic equipment, electrical system design strategies need to be adjusted. Because in many cases a major portion of the loads today are nonlinear in nature, the loading due to harmonics created by these loads must also be taken into consideration. While this seems to be a reasonable request , you might ask just how does one predict these new loading requirements and plan for them.

Over the years, essentially two approaches evolved and became widely used to address harmonics . Phase-shifting transformers of different configurations , used for decades in industrial and computer facilities, typically treat harmonics produced by loads that are balanced and connected phase to phase e.g. 5^{th}, 7^{th}, 11^{th}, 13^{th} harmonics. Zero sequence filters (zig-zag reactors, etc.) have been used in commercial and institutional settings to address triplen harmonics (3, 9, 15 …...) and associated problems (high neutral current, voltage distortion, etc.).

The evolution of electronic power supplies (switch-mode) has generated the need for a solution encompassing the benefits of both previous approaches. While the 5th & 7th harmonics are present and require treatment, the predominant harmonic is the 3rd, which not only causes high neutral current and neutral-to-ground voltage, but just as importantly causes a substantial increase in voltage distortion which, as a whole, is more frequently problematic for electronic equipment.

This paper describes how Symmetrical Components Theory has been used to design a completely new and innovative transformer that integrates the treatment of zero sequence harmonics (triplen etc.) as well as 5th & 7th harmonics. These transformers may be configured as single or multiple output units to accommodate various design strategies. Besides taking the guess work out of the design process, these transformers can be included at the base building design stage in a similar way that traditional transformers would be allocated. This approach, in the majority of cases, eliminates the need for remedial equipment to be added later when problems are already occurring. Case studies of actual distribution systems are presented that document the effectiveness of this approach.

2. BACKGROUND

Until the mid-1980's, there was essentially no significant harmonic-generating equipment in commercial or institutional buildings. As a result, standard practices for electrical system design were appropriate and the biggest concern was maintaining the requisite Power Factor, which could be achieved by adding a capacitor bank of the necessary kVAR. From the point of view of harmonics, these buildings were basically trouble-free: no unusually hot transformers or neutral conductors, few voltage distortion problems, and infrequent cases of resonance or capacitor bank overloading.

The decade of the eighties brought digital electronics and the personal computer age. The arrival of these radically new types of loads has meant problems of a magnitude that no one imagined. The consumption of these new (nonlinear) loads is far from the ideal sinusoidal waveform (linear) that power systems were designed to feed and the result is serious harmonic problems.

This paper will focus on the impact of the Personal Computer (PC) and similar electronic equipment on power distribution systems. The PC and PC-based workstations are moving rapidly into the workplace everywhere - from the office having traditionally little load, to computer rooms used to phase-phase and 3-phase loads. Another good example of where electronic loads dominate the load profile is broadcast facilities.

A few special notes should be made about this type of equipment. It is connected phase-neutral (120V), which means that the neutral conductors in the system are part of the current circuit. Whereas phase-phase (208V) load harmonic spectrums are rich in 5th, 7th, 11th and 13th harmonics, the 120V, phase-neutral PC draws a pulsed current with a rich harmonic spectrum dominated by the 3rd harmonic and with appreciable levels of 5th and in many cases 7th harmonics.
While it has been associated for many years with causing high neutral current and hot transformers [1,2] , the same PC that is the source of the current harmonics, is itself sensitive to voltage distortion that results. In our experience, the costs associated with downtime far exceed all other costs, yet they are the most difficult to measure. The relevant North American standard

[3] IEEE-519-1992 “Recommended Practice …” specifically singles out electronic equipment (section 6.6) and highlights its sensitivity to distortion of the supply voltage waveform listing consequences of excessive distortion such as erratic equipment malfunction and premature failure. Recommended limits are set at 5% Total Harmonic Distortion (THD) with no individual harmonic exceeding 3% of the fundamental.

It is clearly undesirable to be in a position of having to design a system knowing it feeds a PC-rich environment, acknowledging that this means a harmonic-rich environment and therefore potentially a problem-rich environment. However, you still resign yourself to waiting until the client is moved-in, operating, and experiencing problems (complains) before attempting to treat the harmonics because existing approaches require accurate information about load conditions and details of the specific harmonic spectrum at hand.

What is required is an approach that can not only tackle the harmonics successfully, but that can be applied at the design stage so that remedial action is very rarely required.

3. **WHICH HARMONICS TO DESIGN FOR**

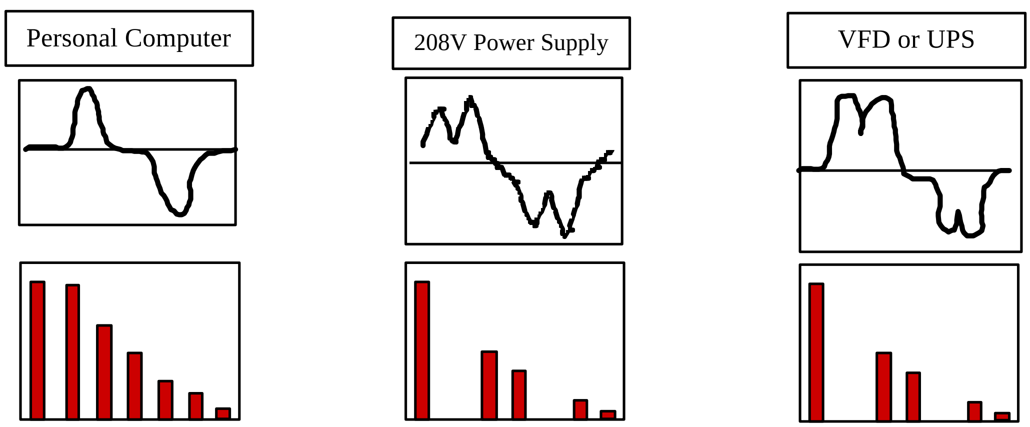
The first step towards preemptively solving a harmonic problem is to develop a typical “fingerprint” of the expected loads. It is important to note that some environments have more stable loads than others and there can also be quite a diversity of equipment connected to the same system. Also, in time the loads and their harmonic content could change. These reasons have been cited as evidence that it is not practical to quantify potential harmonic problems unless the load is well-defined and stable. While acknowledging that it is difficult to anticipate the precise magnitude of the different harmonics beforehand especially where loading varies significantly, it is possible to provide successful, off-the-shelf harmonic treatment by predicting the types of harmonics rather than trying to quantify each.

In the course of our research, we conducted and reviewed extensive field data with respect to the current spectrum of loads in commercial, institutional and industrial settings. What emerged were consistent load profiles; these findings are perhaps surprisingly simple. There are two basic load profiles - one typical of phase-neutral loads and another typical of phase-phase and 3-phase loads (see figure 1).

The results can be summarized as follows:

1. Where there are phase-neutral loads, a rich harmonic current spectrum can be expected comprising mainly of 3^{rd}, 5^{th} & 7^{th} harmonics with the 3^{rd} being predominant yet the 5^{th} and sometimes 7^{th} being troublesome.
2. As expected, where phase-neutral loads were in the majority, neutral current exceeded the phase current by a wide margin, 1.5 times on average. The data we have compiled over the past several years shows a clear tendency for the level of neutral current to increase relative to the phases. Two years ago it was common to find neutral current about equal to phase current. We have recently measured several sites at 2.2 times!
3. Phase-phase and 3-phase loads show a predominance of 5^{th} & 7^{th} harmonics with a noted absence of 3^{rd} harmonic. There is no neutral current since the neutral is not part of their circuit.
4. While there were instances of 11^{th} & 13^{th} harmonics dominating the spectrum (12-pulse UPS & drives) they were far less in overall proportion and were in very localized systems.

These are the commonly found electrical loads in our facilities today.



What we can summarize from this information is that the harmonic spectrums were consistent, predictable, and dominated by only 3 harmonics: the 3^{rd}, 5^{th} & 7^{th}. Neutral current is present and requires attention where there are phase-neutral loads.

The authors also reviewed historical data to see whether the continuing advances in switch-mode power supply technology were having an impact on the current spectrum. There is indeed a trend to higher harmonic levels. The harmonic spectrum is similar except that all harmonics tend to get higher as a percent of the fundamental. The 9^{th} harmonic in some cases is high enough to warrant treatment (the 9^{th} adds in the neutral conductor similar to the 3^{rd}).

4. THEORETICAL BASIS FOR TREATMENT OF PROBLEM HARMONICS

When trying to resolve any problem, clear identification of the goal is of prime importance since both the effectiveness and cost of the treatment are at stake. Our objectives can be listed as followed:

1. Reduce voltage harmonic levels to within limits set out in IEEE-519-1992 (5% THD voltage with no individual harmonic above 3%).
2. Ensure the transformer and cables are not overloaded.
3. Use passive approach for simplicity, highest reliability, lowest maintenance, lowest cost.
4. Avoid the use of capacitors (risk of resonance, etc.).

When dealing with harmonics it is important to understand the relationship between current harmonics and voltage harmonics. Current harmonics in themselves cause extra heating in electrical components through which they flow, namely transformers and cables. However, their effect can be more widespread. Because they flow through the system impedance, current harmonics create voltage drops at their respective harmonic frequencies, distorting the voltage waveform, which in turn affects other equipment connected to the system (see figure 3). The term used when discussing the interaction of equipment is “electromagnetic compatibility”.

Figure 3: How Harmonic Currents Create Voltage Distortion

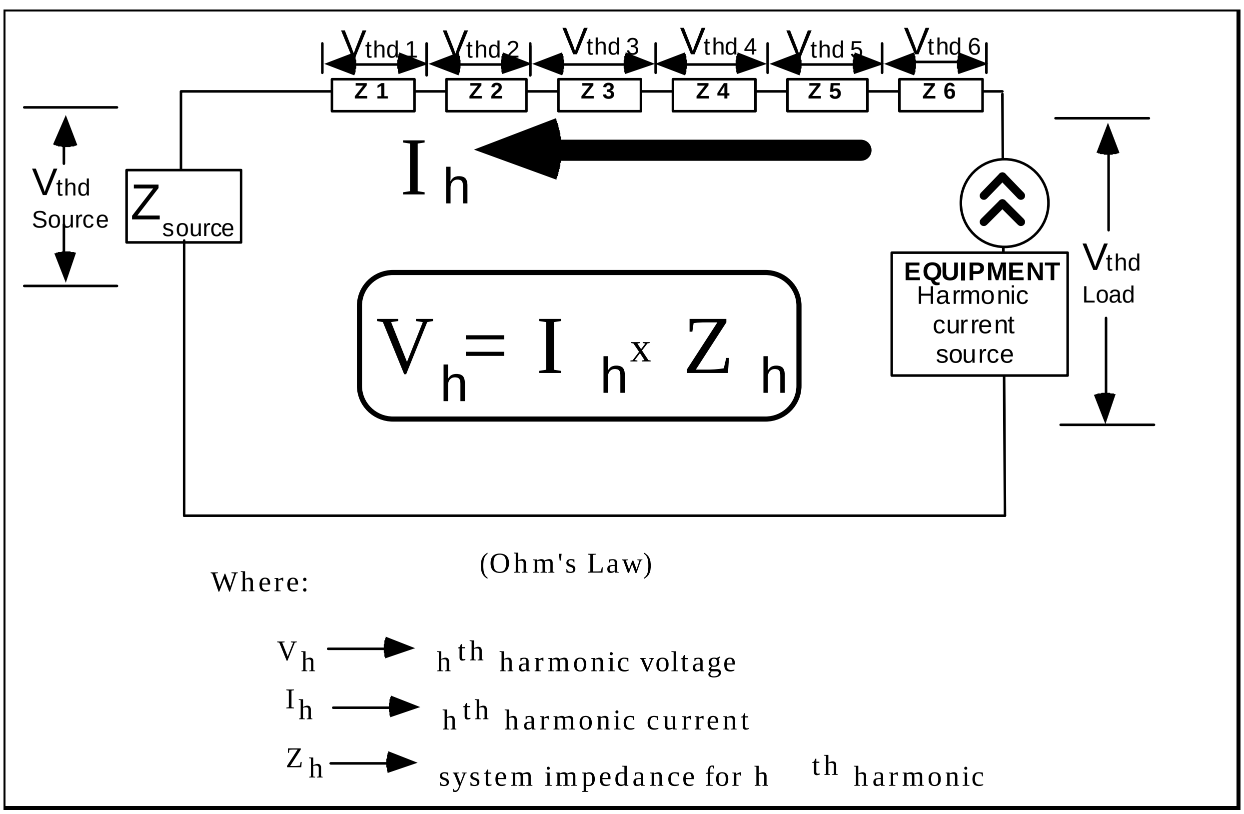


Figure 3 makes it very clear that in the treatment of voltage harmonic distortion, one can either reduce the magnitude of the harmonic current or the system impedance at the frequencies that harmonic currents are present, or both.

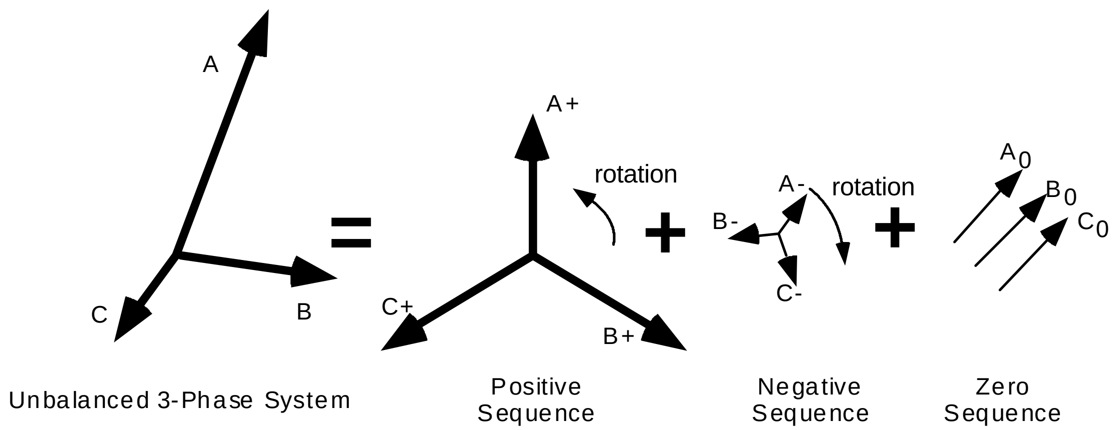
From a design point of view, there is a load requirement and provision must be made for that certain kVA of load. Although at the outset the exact profile of the load is generally not known, certain information is available. The local environment will be one of three configurations: all phase-neutral, all phase-phase or 3-phase, or a mixture of both types of loads. In terms of approach to treatment, the mixed case should be treated the same way as if the loads were all phase-neutral. The harmonic currents to be expected are as per our previous discussion, and the harmonics to be treated are either 3^{rd}, 5^{th}, 7^{th} & neutral current for phase-neutral loads, or 5^{th} & 7^{th} for phase-phase and 3-phase loads. If 12-pulse systems are used, 11^{th} & 13^{th} harmonics are predominant.

Symmetrical components & 2 families of harmonics

An in-depth treatment of Symmetrical Components Theory is beyond the scope of this paper, but it needs to be touched upon in order to understand the basis upon which harmonics can be treated.

In the early part of this century, an Engineer named Fortesque [4] developed a method by which any system of 3 unbalanced vectors can be represented by a set of 3 balanced systems of vectors which he called positive, negative and zero sequence components (see figure 4).

Figure 4: Example of Symmetrical Components



The following chart shows the harmonic sequence based on Symmetrical Components Theory.

Harmonic	1 (fund.)	2	3	4	5	6	7	etc.
Sequence	+	-	0	+	-	0	+	

Note: unbalanced portions of positive & negative sequence currents are also zero phase sequence in nature and appear in the neutral. For example the unbalanced portion of 60Hz that flows back in the neutral is zero sequence.

The conversion involves complex mathematical manipulation, but what needs to be remembered in our application is the behavior of the different symmetrical components with respect to transformers and cables. First of all, by their nature positive and negative sequence currents flow through transformers from the secondary into the primary system.

Zero Sequence Components

Zero sequence currents are important for several reasons:

- they flow only in 3-phase, 4-wire systems, and because they are in phase in all three phases, they add together in the neutral conductor
- they are trapped circulating in the transformer primary delta windings causing additional heating
- they flow through the system impedance causing voltage distortion

Zero sequence impedance is of particular importance:

- zero sequence impedance of a delta-wye transformer is equal to its positive and negative sequence impedance (the nameplate value). This is important because the overwhelming majority of distribution transformers have this type of connection, which means the delta-wye transformer is a reasonably high impedance for 3rd harmonic current thus contributing significantly to high voltage distortion at 3rd harmonic (remember Ohm's law).
- zero sequence impedance of a cable can be several times higher than its positive and negative sequence values or at least equal to them. This means that any significant cable run feeding phase-neutral loads will result in high 3rd harmonic voltage distortion at these loads.

Neutral to ground voltage, sometimes referred to as common mode noise, is a direct product of the neutral current and zero phase sequence impedance of the cables.

The notion of symmetrical components is important because all currents of the same type behave in the same way. A zig-zag reactor treats high neutral current on the basis that it is a zero sequence filter by its nature and since all currents flowing on the neutral are zero sequence, the approach works. This approach is now widely used for removing neutral current.

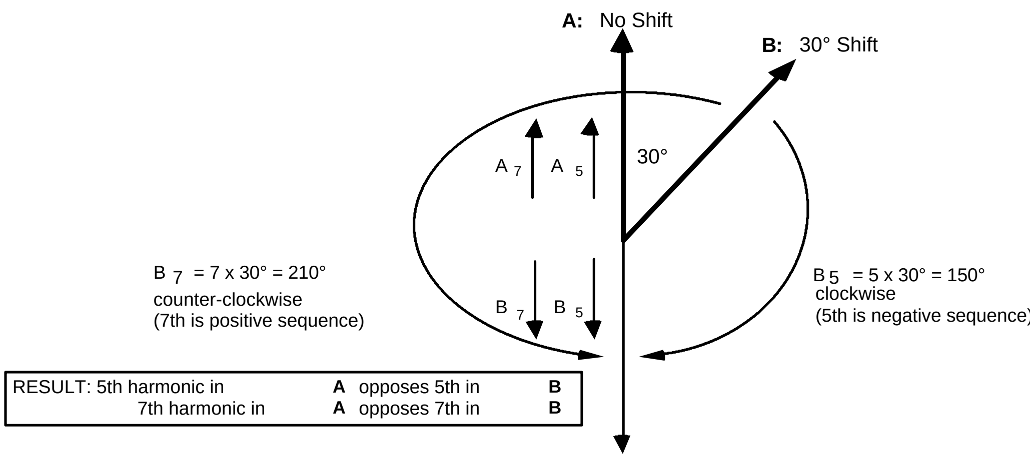
The zero sequence network and the behavior of zero sequence currents is key because the predominant harmonic in phase-neutral loads - the 3rd harmonic, is zero sequence, therefore low zero sequence impedance is vital to the overall success of any complete treatment involving phase-neutral loads.

Remember that because they are all in the same family, any modification of the zero sequence network affects **all** zero sequence currents (3,9,15… & unbalanced portions of others).

Positive & Negative Sequence Components

Understanding of positive & negative sequence currents is key to resolving the other harmonics we have identified as needing to be treated - the 5th & 7th. As noted in the above table, 5th is negative sequence and 7th is positive sequence in nature. The fact that they both flow through transformers and yet rotate in opposite direction allows us to use one phase-shift to remove pairs of positive and negative sequence harmonics from two separate sources. The case we are most interested in is the 30° phase-shift between two similar harmonic sources. As figure 5 illustrates, the phase sequence difference results in cancellation of both 5th & 7th harmonics (the result is the same for 17th & 19th etc. as well). This method has been used for decades in aluminum and electrochemical industries by using secondary phase shifted transformer windings to supply heavy non-linear rectifier loads.

Figure 5: How a 30° phase-shift between 2 sources result in cancellation of both 5th & 7th harmonic currents

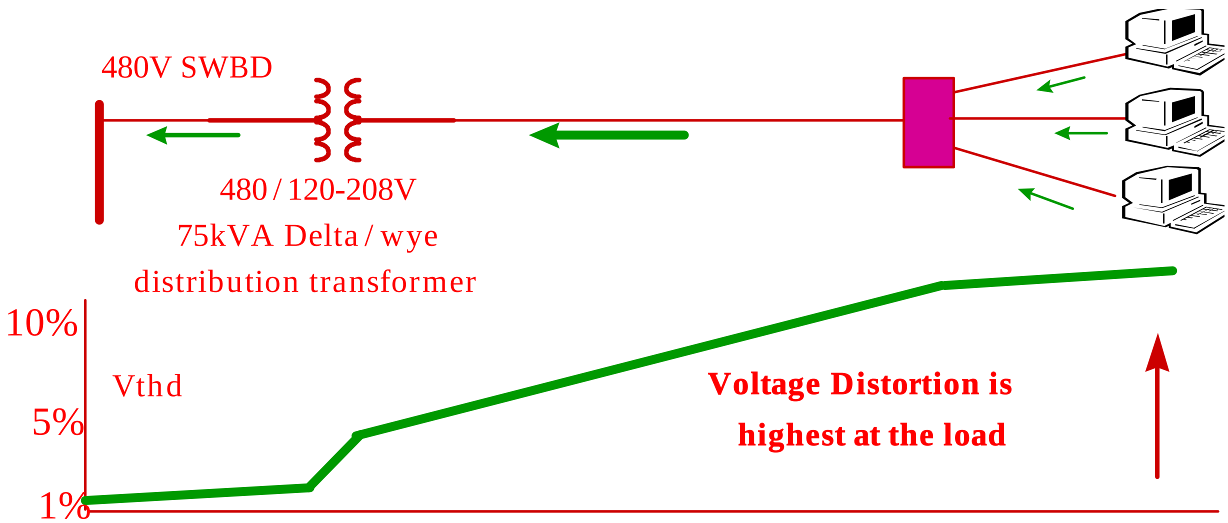


5. **Inherently Treating Problem Harmonics**

Because of the direct relationship between harmonic current and system impedance in the creation of voltage distortion, it is clear that the location of highest voltage distortion will be at the harmonic-producing loads themselves - at the deepest point of your distribution system. Figure 6 illustrates the impact of system components like transformers and cables as well as load on voltage distortion. It is the combination of high zero sequence impedance of the components and high levels of 3rd harmonic current (which is zero sequence in nature) that causes a dramatic increase in 3rd harmonic distortion at various points.

The figure also illustrates that it is true that the transformer has blocked the zero sequence currents from flowing upstream, but at the expense of a substantial increase in voltage distortion downstream at the loads due to the significant additional impedance of the transformer. The upstream electrical system may appear healthier, but a closer look at the operation of the end-use equipment like computers would show increased malfunctions and failures - too high a price to pay. A good example of this is when an isolation transformer is used to block harmonics; voltage distortion in the downstream part of the system commonly more than doubles!

Figure 6: The impact of Impedance and load on Voltage Distortion

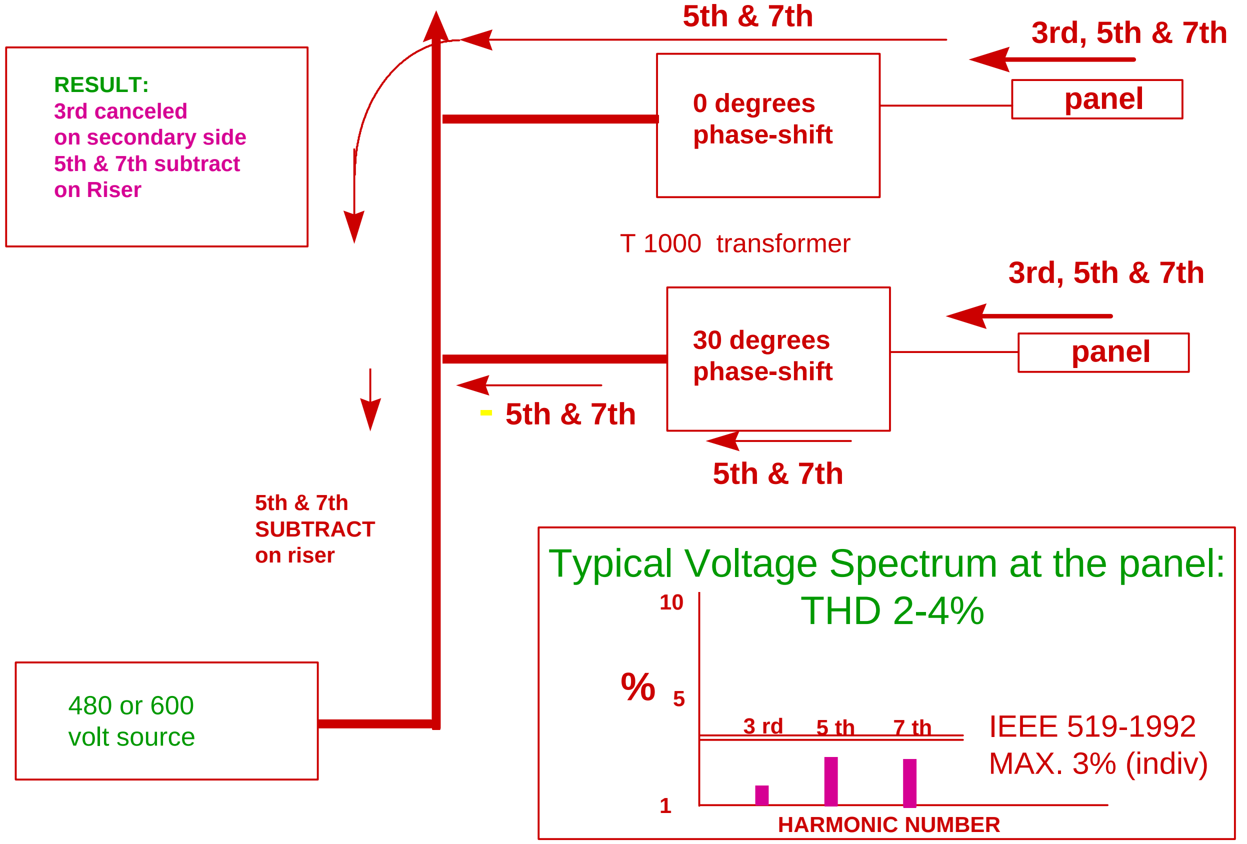


From the previous section, it is clear that symmetrical component analysis has provided us with two powerful tools in the treatment of our problem harmonics. We can now package a low zero phase sequence impedance to address 3^{rd}, 9^{th}… and neutral current, with a 30°, or any other required phase-shift between sources to cancel 5^{th} & 7^{th} harmonics. Because these capabilities can be achieved by electromagnetic manipulation (core/coil interconnections), the treatment can take the form of a transformer or autotransformer.

The following diagrams offer three design strategies for modern electrical systems.

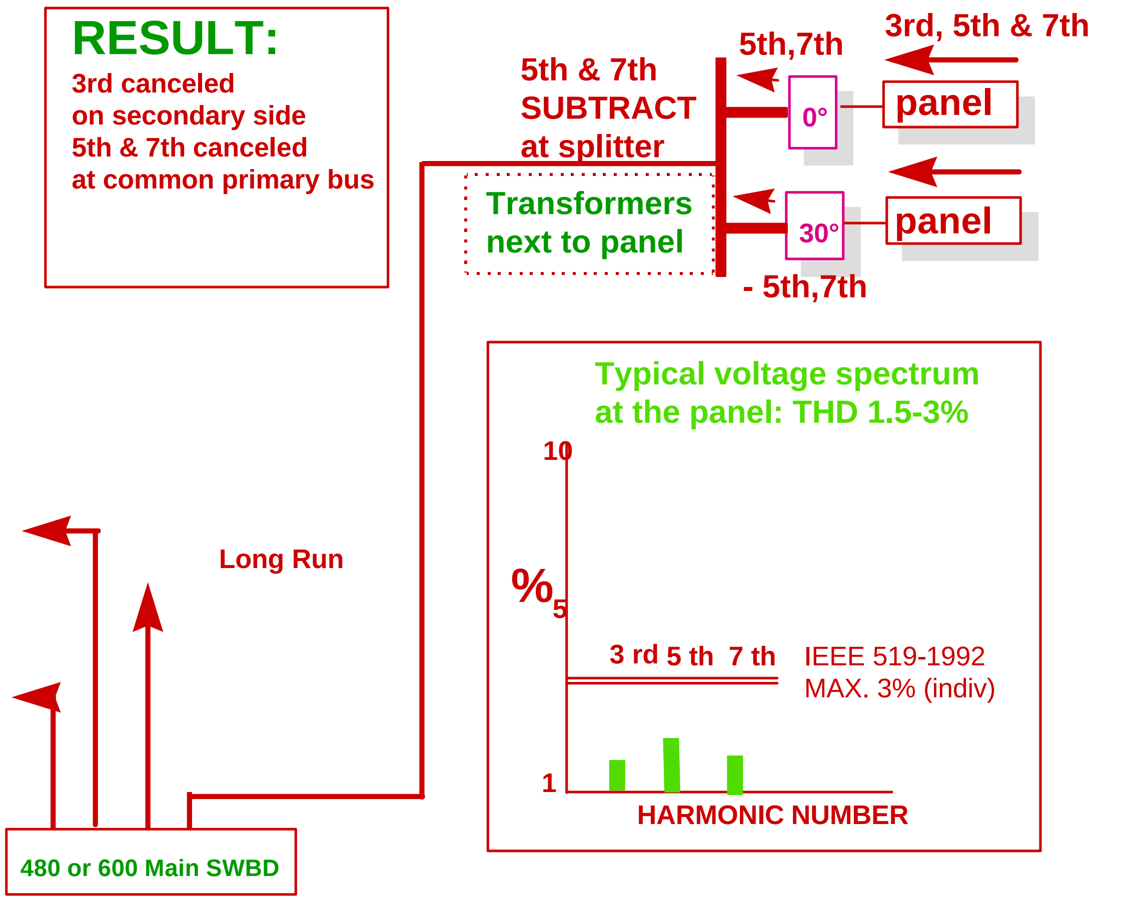
6. Practical Design Applications

A THREE PHASE FOUR WIRE DISTRIBUTION SYSTEM UTILIZING A RISER AND LOW ZERO PHASE SEQUENCE IMPEDANCE, PHASE SHIFTING TRANSFORMERS.



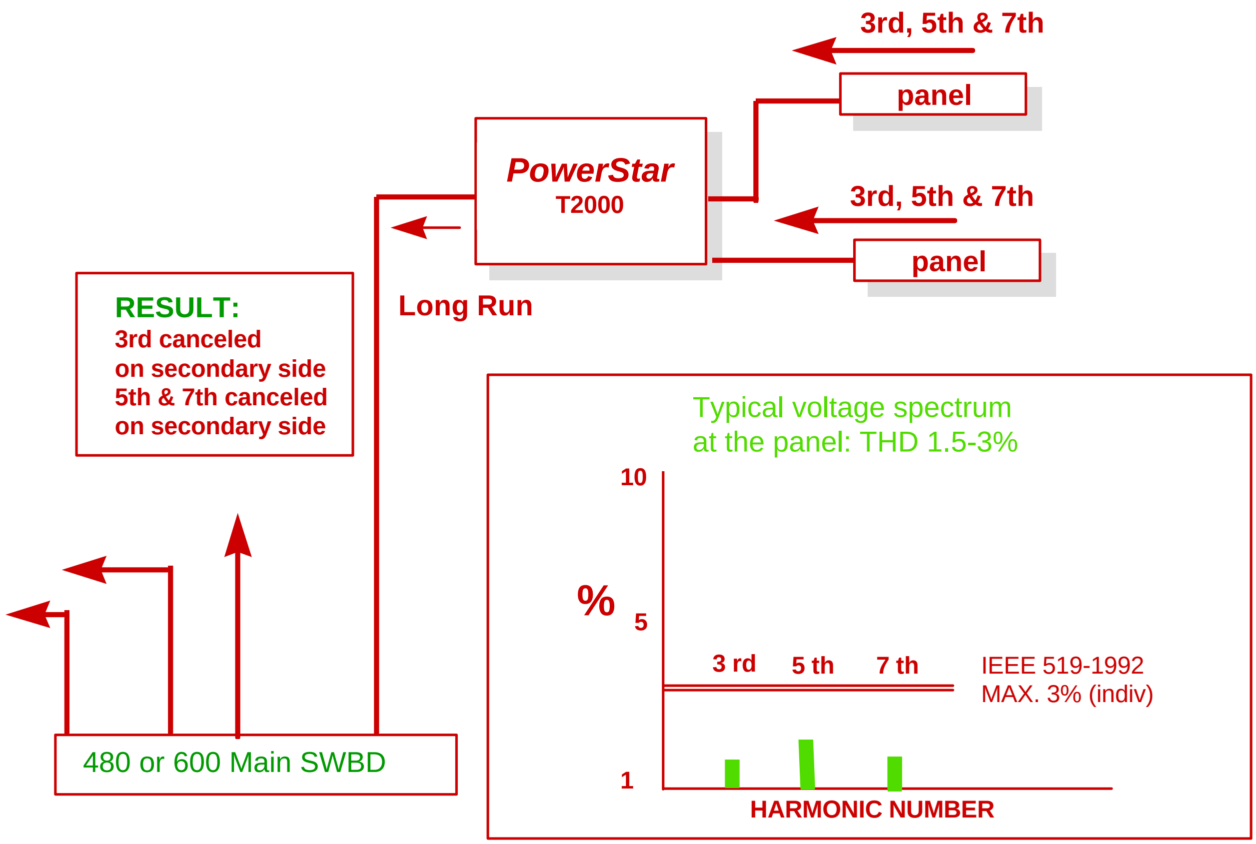
RESULT: 3RD *HARMONIC IS CANCELED ON THE SECONDARY SIDE OF EACH TRANSFORMER AND THE 5TH AND 7TH ARE CANCELED ON THE RISER.*

This example demonstrates a design for a Star configuration where long single runs can be split at the end of the run. By utilizing very low zero sequence impedance and phase shifting transformers harmonics can be eliminated.



RESULT: *3RD HARMONICS ARE CANCELED ON THE SECONDARY SIDE OF THE TRANSFORMERS AND THE 5TH AND 7TH ARE CANCELED AT THE COMMON SPLITTER PANEL ON THE PRIMARY SIDE*

This example describes a design strategy where the loads are reasonably balanced and panel loading is controllable. A single transformer with dual secondary windings cancels the harmonics in the secondary windings.



RESULT: *3RD HARMONICS ARE CANCELED ON THE SECONDARY SIDE OF EACH SECONDARY WINDING AND THE 5TH AND 7TH ARE CANCELED BETWEEN THE SECONDARY WINDINGS AS LOND AS THE HARMONIC SOURCES ARE REASONABLY BALANCED*

7. CONCLUSION

The information age has brought with it many advantages in terms of productivity and efficiency. Electronic equipment continues to reduce in size yet at the same time increase in efficiency and performance. These advances also bring with them a need to adapt the electrical infrastructure to these new types of loads. Based on studies of numerous electrical systems in different types of commercial facilities, the predominant harmonics produced by these new types of loads are 3rd with an appreciable level of 5th and 7th as well. In most cases, treating only 5th and 7th harmonics is not sufficient; the 3rd. must be treated also.

By using the appropriate transformer in the design of modern electrical systems, harmonic treatment can be inherently designed in, without quantifying individual harmonics. The integration of very low zero phase sequence impedance and phase shifting makes for a cost effective and reliable solution so that systems can be designed based simply on load and code requirements.