

Paralleling Power Sources Which Share a Common Neutral

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When paralleling power sources that share a common neutral, care must be taken to limit neutral circulating currents. In these applications, it is important that voltages produced by the generating equipment are as closely matched as possible. To properly match voltages, not only do the RMS values need to be similar but the instantaneous values, which are determined by the voltage waveshapes, should be similar as well. This is not always possible, especially when paralleling generators with dissimilar pitches or paralleling different alternative energy supplies with the Utility.

When neutral circulating current is excessive, it can cause generator overheating and/or false tripping of overcurrent protection. To limit neutral circulating current, impedance can be added in the circulating path but this must be done without restricting the fault current path. By applying a unique multiple winding reactor, neutral circulating currents can be reduced by more than 75% with minimal effect on the short circuit impedance of the system.

Generator Circulating Current

Controlling circulating currents in the common neutral of parallel generator applications can be difficult especially if the generators have dissimilar pitch configurations. Heavy neutral currents can also appear when alternative energy sources are paralleled with the Utility. This would include distributed generation (DG) equipment such as diesel or natural gas generators, wind turbines, solar panels, microturbines and fuel cells when paralleled in 4-wire systems.

Heavy neutral circulating currents can appear in the shared neutral as a result of slight differences in the voltage waveforms produced by the generating equipment. When these currents get excessive, they can cause overheating in the generator windings and false protection trips, particularly in ground fault protection schemes.

These conditions are most troublesome in permanently connected parallel applications but can also be an issue during closed transition transfers in peak shaving or back-up generation applications. When neutral circulating current is excessive, it can cause generator overheating and/or false tripping of overcurrent protection. To reduce these circulating currents, which are usually triple frequency in nature, a uniquely wound, multiple winding reactor can be used to block the flow of circulating current while introducing minimal effect on the short circuit impedance of the system.

Generator Pitches, Harmonics And Voltage Waveshape

Ideally, all generator sources would produce output voltage waveforms that were purely sinusoidal. Even with their best efforts however, generator manufacturers cannot reach this goal and therefore, generator voltages will always be somewhat distorted and contain harmonics. Which harmonic numbers are present and their level of magnitude is related to how the volt-

age is being generated. In synchronous generators for example, the harmonic voltages generated are influenced by the particular winding pitch of the generator's alternator.

A generator's winding pitch is defined as the ratio between coil pitch and pole pitch. The pole pitch of a generator is the angular distance between adjacent pole centers. In a 4-pole machine, this is 90 mechanical degrees. If the stator coil spans the same 90 degrees, the generator is considered to be full pitch. In the interest of reducing costs, stator coils are typically not wound to their full pole pitch. In a fractional pitch machine where the coil spans only 60 degrees, the winding pitch is 60/90 or 2/3.

In addition to reducing copper costs, fractional pitch machines typically produce voltage waveforms that are slightly more sinusoidal and therefore contain less harmonic distortion. Harmonic voltages will still be present though, with their specific magnitudes determined by the machine's specific winding pitch. Table 1 shows the pitch factors for synchronous generators of various pitch types [1][2]. These pitch factors are multiplied by the respective harmonic fluxes produced by the generator to predict the harmonic voltages [2]. Since differently pitched machines have different pitch factors for each harmonic number, their harmonic voltages and voltage waveshapes will be different as well.

PITCH	FUND.	3RD	5TH	7TH	9TH
2/3	0.866	0.0	0.866	0.866	0.866
4/5	0.951	0.588	0.0	0.588	0.951
5/6	0.966	0.707	0.259	0.259	0.966
6/7	0.975	0.782	0.434	0.0	0.782

Table 1: Pitch factor impact on harmonic voltage magnitudes in synchronous generators.

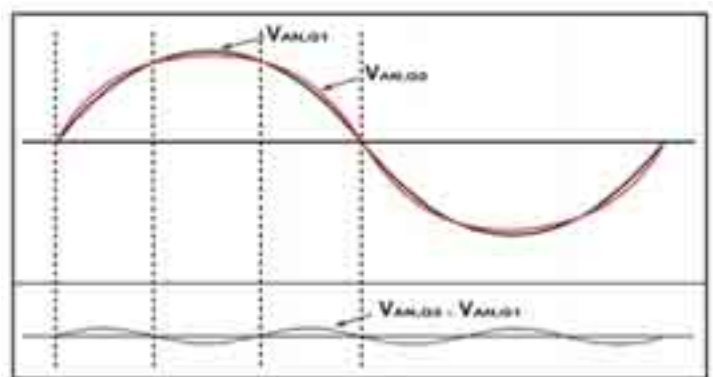


Figure 1: How differences in instantaneous voltages of paralleled equipment can produce line-to-neutral voltages that result in circulating currents.

Figure 1 provides examples of the line-to-neutral voltages of two dissimilarly pitched generators, G1 and G2. G1 generates a voltage with a slightly higher peak (typical of 5/6 pitch generators) while G2 generates a somewhat flat-topped voltage waveform (typical of a 2/3 pitch generator). When paralleled, these generators will produce a phase-to-neutral voltage that reflects the instantaneous differences in the two voltages, even when the RMS values are perfectly matched. Since this voltage passes

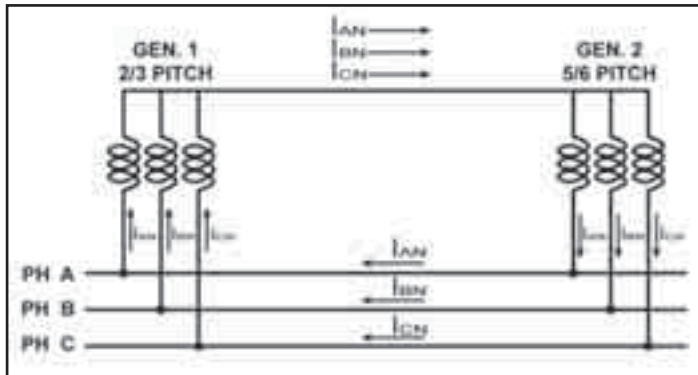


Figure 2: Flow of circulating current in a 3-wire paralleled generator application with neutrals connected and ungrounded.

three cycles in the time that the individual generator voltage passes a single cycle (the fundamental frequency), it is primarily triple frequency in nature (180 Hz on a 60 Hz system).

Circulating currents will appear as shown in Figure 2 and will also be predominantly triple frequency. The amount of circulating current introduced by each phase will be proportional to the magnitude of the differential instantaneous voltage for that phase and the zero phase sequence impedance of the system (generators and connecting cables). The total circulating current in the common neutral will be the sum of the circulating current in each phase.

Since the zero phase sequence impedance of the cables is normally quite small relative to that of the sources, it can typically be ignored. For the system shown in Figure 2 then, the circulating current can be calculated using the following equation:

$$I_N = \frac{3(V_{AN,G_1} - V_{AN,G_2})}{(Z_{0G_1} + Z_{0G_2})}$$

Equation 1

It is important to note that it is not the generator's specific pitch value that causes the circulating current but rather the difference in voltage waveshape of the two differently pitched generators. Therefore, the fact that a 2/3 pitch generator has a very low pitch factor for the 3rd harmonic does not mean that it will perform any better in paralleling operations. In fact, a 2/3 pitch generator has very low zero sequence reactance and therefore, has less impedance to reduce the flow of circulating neutral current [3]. Circulating currents can result with any generator pitch type when it is not matched with a similarly pitched unit or it is paralleled with the Utility.

Further complicating the issue is that this analysis has assumed that the generator loading is linear. Today's power electronic loads (such as variable speed drives, UPS systems, computer equipment, AC/DC rectifiers, etc.) are nonlinear in nature and as such, are current sources of harmonics. During their operation, the current harmonics they draw will increase the voltage distortion throughout the distribution system. This includes the output terminals of the generator where the generator's source impedance (particularly the subtransient reactance or Xd") will create voltage drops at each harmonic number in relation to the nonlinear load harmonic currents [4]. These voltage drops will introduce additional harmonic distortion at the generator's output terminals. Differently pitched generators will have different impedances to the various harmonics and therefore, the differential voltage may be much greater than would be expected with linear loading.



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Traditional Methods Of Treatment

The requirement to parallel generators is not new and therefore, circulating currents in the common neutral is also not a totally new phenomenon. What has changed however is the frequency that these incidences are occurring as the use of DG equipment increases.

One method of limiting circulating currents has been to ensure that all generators have the same pitch. This, of course, is not always possible or even preferred especially when expanding a site that has older, existing generators.

Another approach is to add impedance in the common neutral. Standard reactors could be used for this purpose but any impedance added to reduce the circulating neutral current would also significantly reduce the single phase fault level in the system. A slight reduction in fault level may be preferred in large systems where the fault level is initially high but normally the level of impedance required to suitably reduce the circulating current will reduce the fault current to unacceptable levels. A fault level that is too low can be a serious safety concern since it can prevent overcurrent protection from operating and lead to fire hazards, such as arcing faults.

Occasionally, an ungrounded system is employed and the generator neutrals are not connected together. In this scenario, there will be no path for the circulating current to flow. There will also be no path for single phase fault currents so ground fault monitoring and other measures used for ungrounded systems must be employed.

Application Of A Multiple Winding Reactor To Reduce Circulating Current

A multiple winding reactor can be used to reduce neutral circulating currents in parallel generator applications. It is installed in the common neutral of paralleled generators (see Figures 3 to 5) in order to add impedance to block the flow of circulating currents. It does this without significantly decreasing the 1-phase fault level by ensuring that the impedance of the fault path to ground remains low. Also there is no change to the phase-to-phase fault level.

The reactor has three sets of terminal connections – X, Y and Z. The coils are wound such that the impedance through the Y and Z terminals is several times larger than the impedance between either the Y or the Z terminal to X. The Y to Z impedance is approximately 45% at the triple frequency of the circulating neutral current. The impedance to 1-phase fault current, on the otherhand, is < 1%. This is due both to the unique winding configuration of the reactor and to the fact that the core will become saturated during a fault condition, lowering its impedance. The system's 1-phase fault level therefore, will be reduced only minimally. 3-phase and phase-to-phase faults will not pass through the reactor so fault level under these conditions will be unaffected.

The multiple winding reactor is used when two or more generators of dissimilar pitch are paralleled together or a generator is paralleled with an alternate source, such as the Utility. In applications where multiple generators of the same pitch are being paralleled with one or more generators of a different pitch, the multiple winding reactor need only be installed in the neutral connection between the two sets of similar pitched generators as shown in Figure 4.

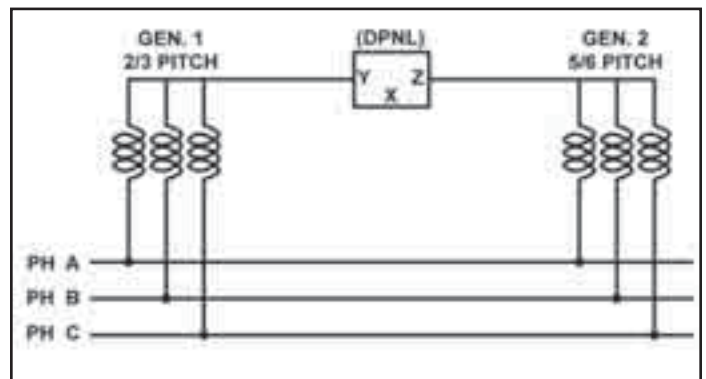


Figure 3: Installation of a multiple winding reactor to prevent the flow of circulating current in a 3-wire paralleled generator application with ungrounded neutral.

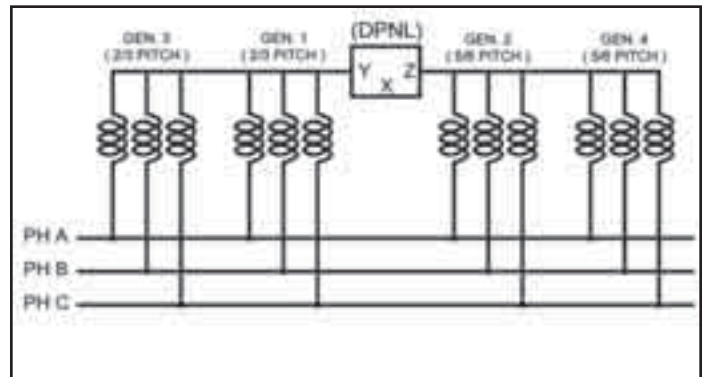


Figure 4: Installation of a multiple winding reactor where multiple generators of similar pitch are connected to one or more generators of a different pitch.

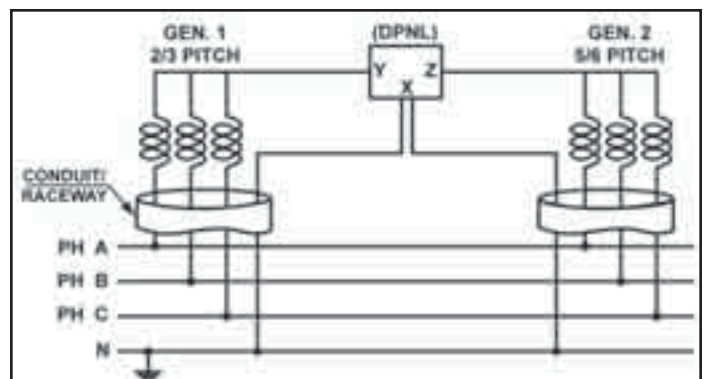


Figure 5: Installation of a multiple winding reactor to prevent the flow of circulating current in a 4-wire paralleled generator application.

In 3-wire systems, the neutral may or may not be grounded. If grounded, it should be grounded at the X terminal of the multiple winding reactor. If left ungrounded, the power system must be equipped with ground fault monitoring as per electrical code requirements.

Figure 5 shows how the multiple winding reactor should be connected in a 4-wire application where the neutral is being used as a return path for 1-phase, phase-to-neutral loads. The diagram shows the neutral being grounded at the switchboard, which is the recommended location, but it can alternatively be grounded at the X terminal of the multiple winding reactor or at the common neutral anywhere else in the distribution system.

The requirement is simply that the neutral be properly grounded and grounded at only one location. Also to reduce stray fluxes, it is recommended that the neutral conductors be run in the same conduit as the phase conductors.

Sizing The Multiple Winding Reactor

The amount of current which will circulate between dissimilarly pitched generators or other paralleled sources with somewhat different voltage waveshapes, can be relatively difficult to determine precisely. As discussed earlier, it will be proportional to the level of instantaneous phase voltage between the sources and the zero phase sequence impedance of these sources. This information is not often readily available however. Fortunately, a conservative analysis can be done to ensure that significant reduction is achieved and that the mitigation device is appropriately sized to handle the load placed upon it.

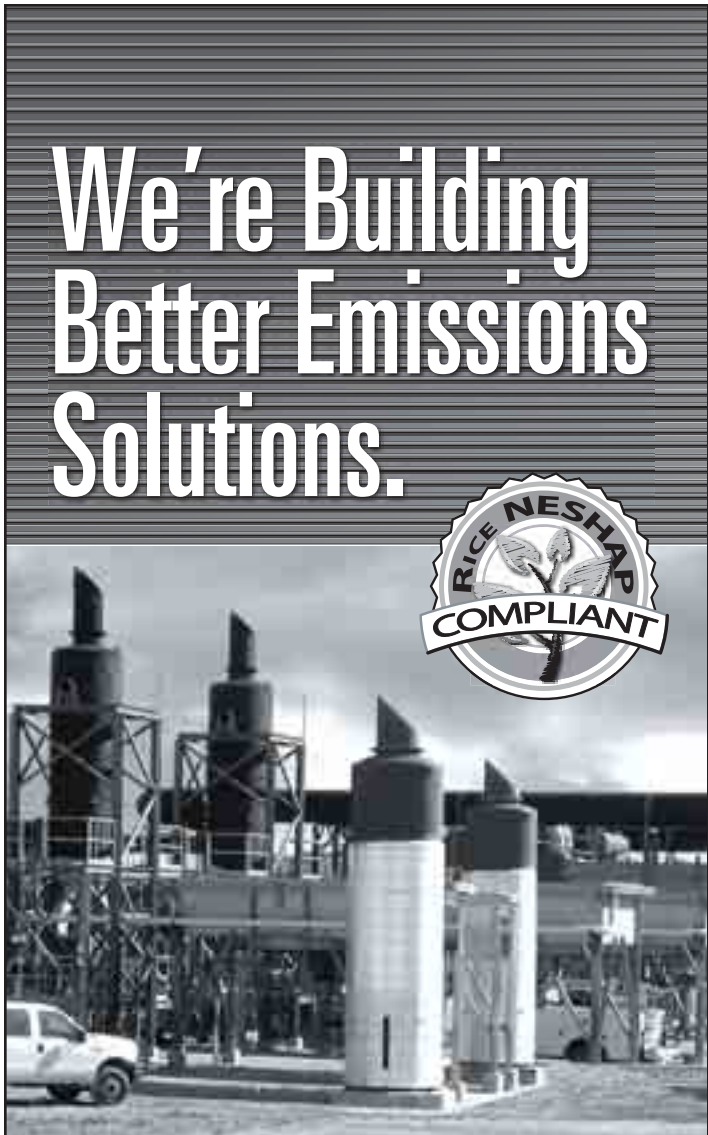
Using Equation 1, various configurations of paralleled sources can be analyzed to determine the level of neutral current that could be expected. These calculations then can be repeated but with the impedance of the multiple winding reactor included. From these calculations, a sizing table was established (see Table 2) which allows for easy selection of conservatively sized units based on the kVA or kW capacity of the paralleled power system.

For 4-wire applications, where the neutral is being used as a return path for 1-phase, phase-to-neutral loads, the reactor must be sized for the return neutral current as well as the circulating current. For this purpose, a dual current rating is applied with the highest rating being for the returned neutral current. Sizing the reactor involves first determining the total kW or kVA capacity of all generators or other paralleled sources. Then from the table, the reactor current rating that corresponds to the total capacity in the appropriate system voltage column is selected.

This will size the unit for a return neutral current rating that is at least 50% of the full phase current rating of the application. For 208-240V systems, where it is much more likely to have phase-to-neutral loads, the return neutral rating will be at least 85% of the full phase current rating of the application. If the actual return neutral current is expected to be higher than these levels, then a larger sized unit can be selected. The larger size will be just slightly less effective in reducing circulating current. For 3-wire applications or for applications where return neutral current is known to be lower, the next smaller size unit can be selected.

Reactor Rating (Amps)		Total Capacity of all Paralleled Sources - kW [kVA]			
Return Neutral	Circulating	208-240V	460-480V	575-600V	660-690V
200	100	68 [85]	250 [312]	320 [400]	360 [450]
500	250	160 [200]	640 [800]	800 [1000]	900 [1120]
1000	500	335 [420]	1280 [1600]	1600 [2000]	1800 [2250]
1500	750	500 [625]	2000 [2500]	2400 [3000]	2720 [3400]
2000	1000	675 [840]	2500 [3126]	3200 [4000]	3600 [4500]
2500	1250	840 [1050]	3200 [4000]	4000 [5000]	4500 [5625]
3000	1500	1000 [1250]	3800 [4750]	4800 [6000]	5475 [6843]

Table 2: Multiple winding reactor selection table for 60 Hz systems [5].



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Application With Dissimilarly Pitched Generators

A restaurant industry distribution facility in Conroe, Texas expanded its standby generation capacity by adding a 1000 kW generator to the existing 750 kW unit at the site. A 1-Line of the installation is shown in Figure 6. When energized, the electrical contractor noticed that there was an excessive amount of current in the common neutral of the two generators. The contractor was concerned that this extra current would cause the generators to overheat.

When the new generator was purchased, it was bought from the same manufacturer but being unaware of any issue associated with matching generator pitches, the purchaser never specified a particular pitch configuration. As it turned out, the new 1000 kW generator had a 5/6P winding while the existing 750 kW generator was 6/7P. This difference in pitch was enough to create the circulating current which was measured by the contractor to be in excess of 150A.

In order to reduce the circulating current, a multiple winding reactor was installed in the common neutral between the two generators (see Figures 7 and 9). A 1300A unit was selected based on the total 1750 kW generator capacity. (This size was available at the time but now a 1500A unit would be used.)

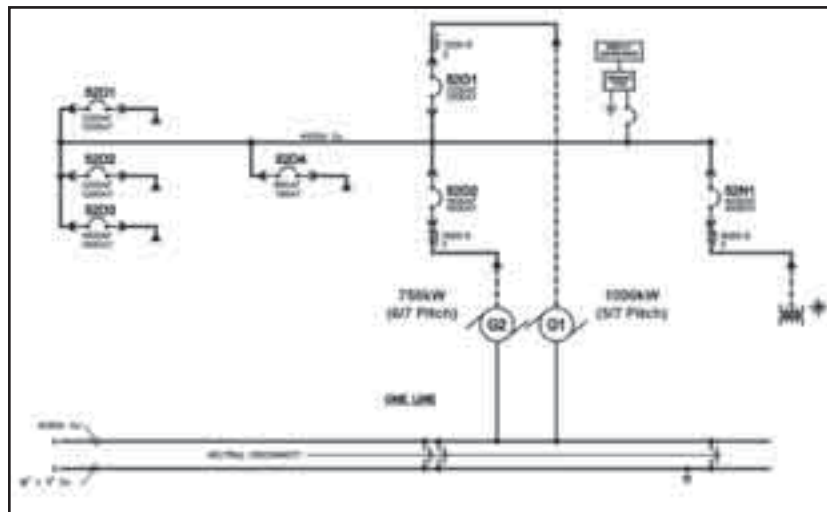


Figure 6: Installation of dissimilarly pitched parallel generators at a distribution facility.

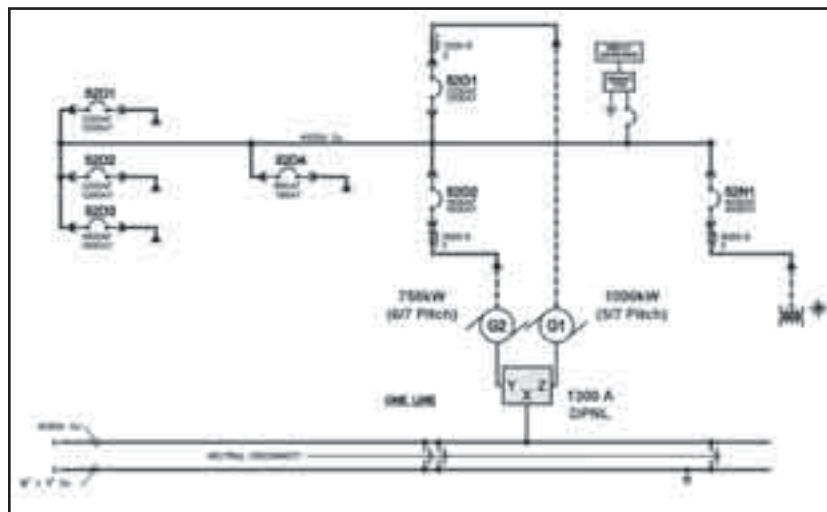


Figure 7: Installation of 1300A multiple winding reactor at a distribution facility.

Figure 8 shows the residual current in the neutral after the multiple winding reactor was installed and running under peak load condition. The total of 38A was a significant reduction from

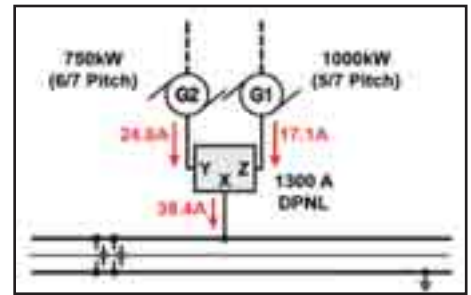


Figure 8: Flow of neutral current after installation of multiple winding reactor.

the initially measured value. It is important to note that most of this current is return neutral current from phase-to-neutral loads. Virtually all of the circulating current was eliminated.



Figure 9: Photo of multiple winding reactor installation.

Generator Paralleled With Utility Application

Use of the multiple winding reactor to control neutral circulating current is not only limited to paralleling of dissimilarly pitched generators. It can also be effective in other parallel source applications with common neutrals and dissimilar voltage waveforms. For example, when a generator is operated in parallel with a Utility source, the voltage waveforms are likely to be somewhat dissimilar and therefore result in neutral circulating current [6]. This can occur in either permanently paralleled applications or during closed transition transfers in peak shaving or backup generation applications. Also, other sources of distributed generation, such as wind turbines, solar panels, fuel cells, microturbines, etc., can have excessive circulating neutral currents when paralleled with the Utility in 4-wire systems.

After the Heating Plant at an American College was fit up with peak shaving generators, it was found that circulating current in the neutral reached over 900A even with relatively light loading on the system. Two similarly pitched 800 kW generators were paralleled with a 1500 kVA Utility transformer (see Figure 10). The excessive neutral current was causing the Utility transformer and generators to run hot even under light loading.

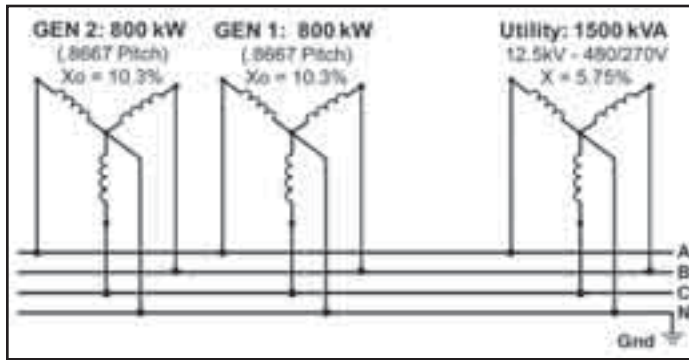


Figure 10: Simplified 3-Line Diagram at an American College Heating Plant.

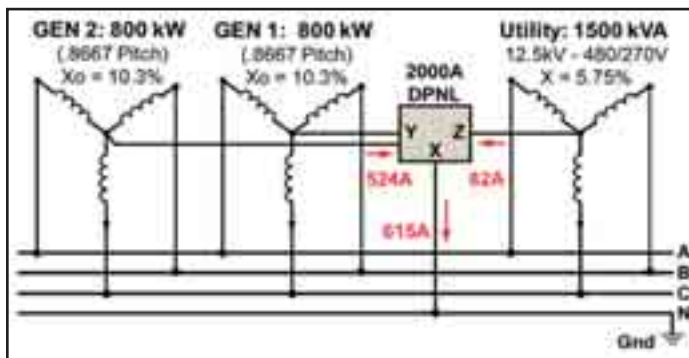


Figure 11: Simplified 3-Line Diagram at an American College Heating Plant with multiple winding reactor.

The total supply capacity of this application was 3500 kVA (1500 kVA transformer plus 1000 kVA for each generator). From the selection table, this would normally require a 2500A multiple winding reactor but based on the amount of 1 ph loads, it was decided that a 2000A unit would be sufficient.

Figure 11 shows the system 3-Line with the multiple winding reactor connected and the measured neutral current values while operating at peak load. After installation of the reactor, neutral circulating current was essentially eliminated. The remaining neutral current is the result of 1 Phase, Ph-to-N loads such as the 277V lighting. The reduction was enough to dramatically lower the load on the Utility transformer and generators allowing for their safe operation.

Summary

When paralleling multiple generators with dissimilar winding pitches or power sources with differing voltage waveshapes, heavy circulating currents can appear in the common neutral. These circulating currents can be effectively reduced by the application of a multiple winding reactor. A uniquely wound reactor introduces high impedance in the path of neutral circulating current (triple or any other frequency) but very minimal impedance in the fault current path. This significantly reduces the circulating current by more than 75% with negligible effect on the system fault level. It is very simple to install and, as a purely passive reactor, is extremely reliable.

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About the Authors

Tony Hoevenaars is President and CEO of MIRUS International Inc. a designer and developer of world class power quality improvement products. Prior to joining MIRUS in 1996, Tony was the Chief Facilities Electrical Engineer at an IBM manufacturing facility in Toronto where he gained extensive experience in solving power quality related problems, particularly in the area of harmonics. Tony is a Professional Engineer, member of IEEE and has published various papers on power quality including papers presented at various IEEE conferences.



Michael McGraw is President of NSOEM Inc. a company he founded in 1996 that specializes in transformer and filter harmonic mitigation applications for land and offshore Oil & Gas systems and MV Solid State starting for large motors. Previously Mike was the OEM Sales Manager for MV Switchgear manufactured by Powercon Corp. Mike is a member of the IEEE. ■

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