Calculating Circulating Current

While not ideal, there is often a perspective that generators of dissimilar pitch cannot be paralleled together. The reality is that this can be done but special attention must be given the amount of circulating currents which would be created in a specific scenario along with each specific generators allowable current. The CAT A&I team can support dealers with these types of efforts. Additional details on different pitch generators can also be found in a separate paper titled, "Effects of Generator Pitch and Paralleling Applications".

When paralleling generator sets that share a common neutral, care must be taken to limit the neutral circulating currents. This means matching the third harmonic voltage and zero sequence reactance of the generators as closely as possible. By matching these values as closely as possible will insure that the circulating current is balanced equally between the generator sets that are operating in parallel. When there is excessive circulating current on the neutral, it can cause excessive heating in the windings of the generator with the lowest zero sequence reactance (path of least resistance). It can also cause nuisance tripping of your protective devices. Winding pitch actually has very little to do with circulating currents. Conceptually, it really is as simple as Ohm's Law: I = V/R. Of course that is an over simplification, but it is the same concept applied to three phase AC systems. Now let's take a deeper dive into how to calculate circulating current.

Look at the Harmonic Neutral Currents: It should be noted that not all neutral currents are third harmonic currents. If a generator has an unbalanced load, a fundamental current (i.e. 60 Hz) will flow in the neutral. This current may or may not be superimposed on top of a third harmonic current. In order to determine the respective neutral current quantities, the following equations can be used:

Neutral current due to phase current imbalance:

$$I_{imb} = A^2 + B^2 + C^2 - (AB) - (BC) - (CA)$$

Neutral current due to third harmonic content

$$I_{har} = N^2 - [A^2 + B^2 + C^2 - (AB) - (BC) - (CA)]$$

Where:

A = Phase A RMS current

B = Phase B RMS current

C = Phase C RMS current

N = Neutral current

Note: Several approximations have been made in deriving these equations, and any error due to approximation yields a slightly higher calculated neutral current.

Paralleling Generators and 2/3 Pitch

3rd harmonic current will flow in a wye connected neutral. However, this is usually of little significance from a heating or de-rating standpoint because this current splits three ways in the wye connected machine. Therefore, a neutral current of 30% rated current will have a 30/3 = 10% 3rd harmonic phase coil current. The resulting additional armature losses are $0.10^2 = 0.01$ or 1%. Typically the problem is a nuisance tripping issue with the ground fault relay.

Third harmonic neutral current can be an annoyance to switchgear designers. Line to neutral voltage may not read properly except on true RMS reading instruments, and protective relays may not react properly. The amount of 3rd harmonic neutral current between paralleled generators depends on the *difference* in 3rd harmonic voltages generated and the reactance between them. Two machines with identical 3rd harmonic voltages (either high or low) will have no 3rd harmonic current in the neutral. This is shown in Figure 5.

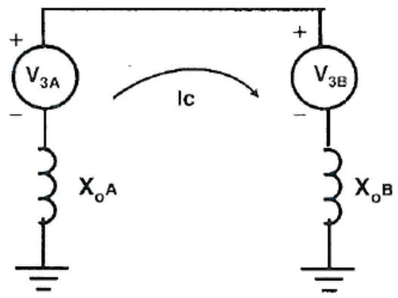

Figure 5:

$$\mathbf{I_C = (V_{3A} - V_{3B})/(3 * (X_0A+X_0B)}$$

Where:

I_C = Circulating third harmonic current

V_{3A} = Third harmonic voltage of the first generator

V_{3B} = Third harmonic voltage of the second generator

X_0A = Zero sequence reactance of first generator

X_0B = Zero sequence reactance of second generator

Note: It is the line to neutral third harmonic voltage value that is difficult to get. Most of the time you will have to get this value from the generator manufacturer. It is often not included in their published data.

If the 3rd harmonic voltages are not equal, 3rd harmonic current will circulate. The lower the zero sequence reactance, the higher the circulating current. It is inherent for a 2/3 pitch winding to have far lower zero sequence reactance than higher pitch machines.

The goal is to match the third harmonic voltages as close as possible to minimize problems. If that is not possible then a neutral grounding reactor or resistor is needed to increase the system reactance and reduce the circulating currents.

When paralleling with the utility lines, the 2/3 pitch winding maybe a disadvantage due to a low zero sequence reactance. This is assuming you are solidly grounded and there is not a wye-delta transformer used in the grid connection. This is typically not the case, as a wye-delta transformer is often used as a harmonic current trap.

Generators having any pitch can be successfully paralleled with each other and with a utility source; but if the neutrals are to be tied together, then the effects of the 3rd harmonic currents in the neutral must be considered. If necessary, reactors, resistors or switches must be installed to limit these currents. Figure 6 shows a solution where a group reactance or resistance grounding is used on the identical G1 generators. Since the three generators are identical, no current will flow between them. A neutral grounding device is required between the G1 and G2 generators. Figure 7 shows where no grounding device is used, but rather the current are allowed to flow between generators. If they are minimal, no appreciable heating will occur and the relay senses only a ground fault. In both cases, selective tripping is sacrificed, which means that more than one generator must be taken off line when the sensing device trips.

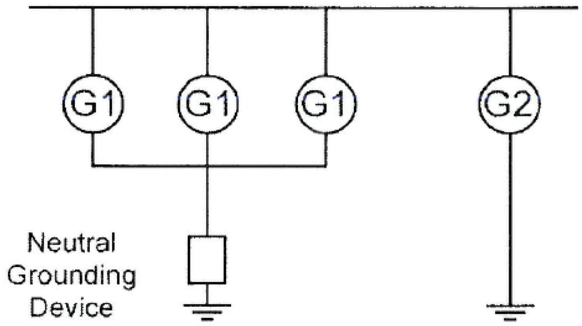

Figure 6

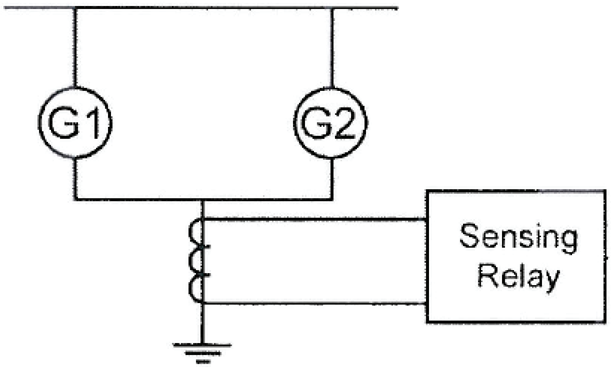

Figure 7

Phase to Neutral Currents

Phase to neutral faults account for approximately 65% of all faults in an electrical power system. Since the zero sequence reactance is lower in 2/3 pitch windings than higher pitch windings, and it is used in calculating phase to neutral fault current, the resulting fault current will be higher in magnitude. This needs to be considered when doing the coordination study.

As an example, the following table compares the phase to neutral fault current of an 826 frame SR4B generator rated 2000 ekW, with a 71.4% winding pitch to the 1825 frame SR5 generator rated 2000 ekW with a 66.7% winding pitch.

Full load current at 2000 ekW, 480 volts, 60 Hz, 0.8 power factor is 3007 amps

	SR4B	SR5
Subransient Reactance (X"d)	0.139 pu	0.112 pu
Negative Sequence Reactance (X2)	0.133 pu	0.109 pu
Zero Sequence Reactance (Xo)	0.28 pu	0.008 pu

SR4B Generator

$L\text{-}N_{sc}$ = 3 * 3007/(0.139+0.133+0.028) = 30,0700 Amps

SR5 Generator

$L\text{-}N_{sc}$ = 3 * 3007/(0.112+0.109+0.008) = 39,393 Amps

In this case, the phase to neutral fault current is 31% higher when using the 2/3 pitch design. However, this design will also produce less harmonic distortion when coupled to non-linear L-N loads.

The 2/3 Pitch Generator with Motor and Capacitive Loads

A three phase motor has no neutral connection, therefore, contains no path for 3rd harmonic current. No matter how much 3rd harmonic is present in the supply, be it generator or transformers, the motor will never see it. But motors will see line harmonics such as the 5th and 7th harmonics. These harmonics are of fairly high frequency, so skin effect is a factor. For example, the 5th harmonic is a negative sequence harmonic which means that it will induce a 6th harmonic frequency in the motor rotor (360 Hz) with attendant heating of the rotor.

A generator wound to 2/3 pitch will very likely have higher 5th and 7th harmonics, so motor temperatures will be somewhat high and motor insulation life will be shortened to some degree. IEEE Std 519 considers that motor like will not be profoundly affected by THD <5%.

When capacitors are part of the load, the 5th and 7th harmonics can cause trouble. The 2/3 pitch generator, as notes above, is likely to generate 5th and 7th harmonics of greater magnitude than more conventional machines. The higher frequencies reduce capacitive reactance which allows increased harmonic current flow. Waveform distortion can result.

It should be noted that motor and capacitive loads will also see the “harmonic pollution” of the entire system and with the increased use of non-linear loads, the harmonic pollution is typically greater than the contribution of the generator.

Single phase non-linear L-N loads usually generate high 3rd harmonic currents. When these loads are connected in a balanced manner to a three phase generator, the 3rd harmonic currents add in the neutral to produce very high neutral currents.

In this case, the inherently low zero sequence reactance of a 2/3 pitch generator will reduce the voltage waveform distortion.

This applies where the load is connected directly to the generator. If the load is supplied through a delta/wye transformer, the 3rd harmonic currents do not appear in the generator.

Questions to Ask

When there is a need to establish, expand, or refurbish a power station by adding a new generator or replace an existing one, the following questions should be asked:

- Is this a new power station?
- Will the replacement generator be identical to the existing ones?
- If not, what is the stator pitch and the third harmonic voltage of the existing ones?
- What is the grounding scheme?
- Is there a one line diagram showing the interconnections and transformers?

Note: If this is a new power station and potential expansion is planned in the future, then a 2/3 pitch generator is recommended to allow any other 2/3 pitch generator to easily parallel. Non 2/3 pitch generator of different sizes with the same pitch and manufacturer may not easily parallel since the fundamental flux wave determined by the pole shaping may not be the same.