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Alternator winding pitch and power system design

White Paper

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Winding pitch is one of many parameters in an alternator design that must be chosen to optimize the product for its intended application. As with most design decisions, the best choice depends on the application. This paper will examine the key factors influencing the selection of alternator winding pitch and advantages and disadvantages of the two most commonly used winding pitches, 2/3 pitch and 5/6 pitch. We will also discuss concerns related to paralleling alternators of different winding pitches and how these concerns are mitigated.

Winding Pitch Considerations

In this paper we will state three conclusions:

- 2/3 pitch is recommended for all 4-wire distribution systems (i.e., distribution systems which include a neutral conductor) because 2/3 pitch alternators suppress third harmonic current which will circulate in the neutral.
- 5/6 pitch alternators are acceptable in systems that do not include a neutral, including the majority of medium voltage/high voltage systems.
- Alternators of different pitches may be paralleled if measures are taken to eliminate or mitigate the risks of current circulating in the neutrals.

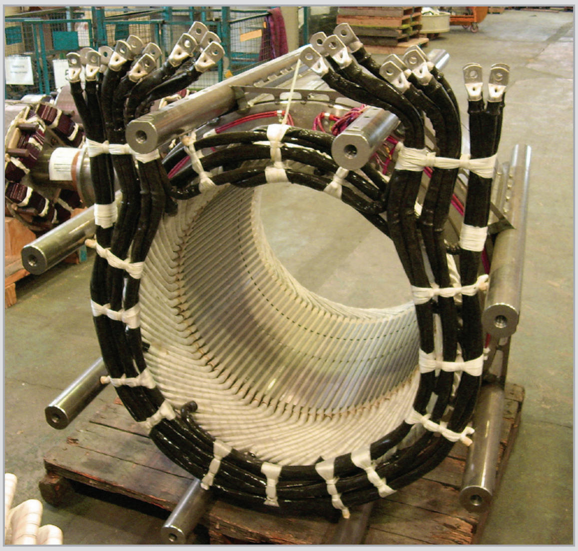

Figure 1. A wound stator with the winding inserted into the slots

What is Winding Pitch?

The term “winding pitch” refers to the ratio of the number of winding slots enclosed by each coil in the alternator stator to the number of winding slots per generator pole.

Figure 2 illustrates a full pitch winding. Here we have a 4-pole alternator with a 48 slot stator. In this alternator one pole spans twelve slots. The winding spans all twelve slots so this is referred to as a full pitch winding.

In Figure 3, the winding spans ten of the twelve slots. This winding has a pitch of 10/12, or 5/6 of the slots on the pole. This is a 5/6 pitch winding.

In Figure 4, the winding spans eight of the twelve slots, or 2/3 of the slots on the pole. This is a 2/3 pitch winding.

Winding Pitch and Harmonics

The voltage waveform shape created by an alternator when operating unloaded or driving a linear load may be described in terms of its fundamental frequency and voltage magnitude, along with the magnitude of the harmonic voltages and their frequencies. The description is necessary because all alternators exhibit some level of harmonic voltage distortion, and while these distortions are very small relative to the distortion that can be caused by non-linear loads, they may still be significant, particularly in paralleling applications.

Figure 5 shows the relationship of first-order (fundamental frequency waveform, shown in red) to third, fifth and seventh-order harmonic waveforms (shown in blue, green and tan, respectively). The harmonic voltages are effectively added to the fundamental waveform, resulting in the pure sinusoidal shape of the fundamental being somewhat distorted. At any point in time the resultant voltage (shown in black) will be the sum of the fundamental and all of the harmonics.

Winding pitch is one of several design factors that affect the harmonic content of the generated waveform. A parameter known as pitch factor (K_p) defines the reduction of harmonic content due to using a fractional pitch (i.e., less than full pitch) winding.

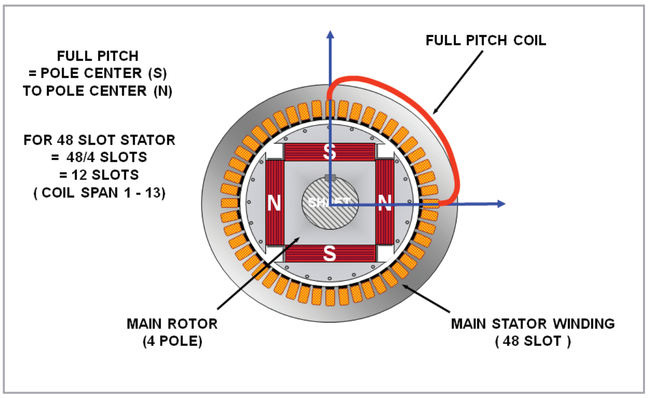

Figure 2. A full pitch winding

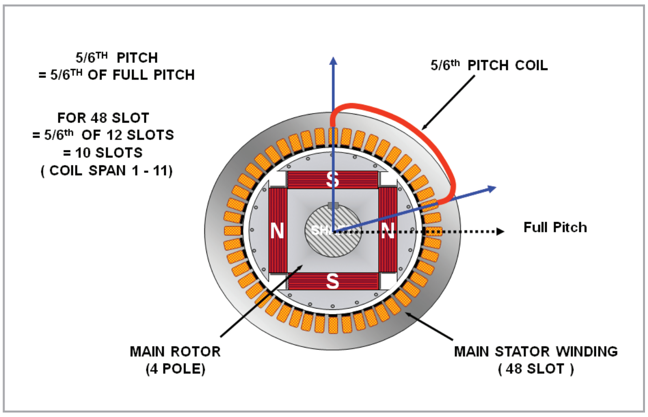

Figure 3. A 5/6 pitch winding

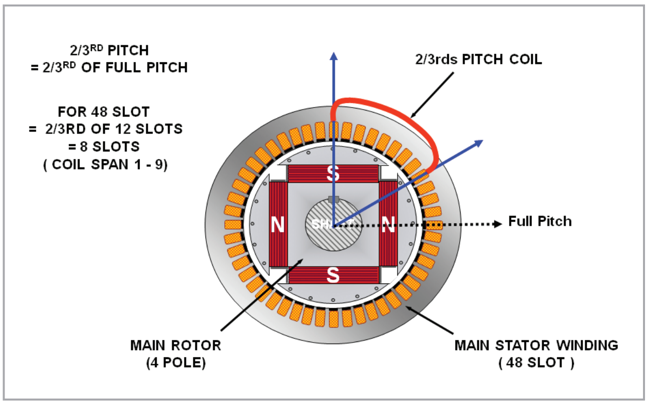

Figure 4. A 2/3 pitch winding

K_p **is defined as** $K_p = \cos(N*180(1\text{-pitch})/2)$

where:

N = the order of harmonic

Pitch is specified as a fraction (2/3, 5/6, etc.)

Note that for a full pitch winding (pitch = 1) the pitch factor is 1 for all harmonics. There is no reduction in voltage at the fundamental frequency or any of the harmonics.

Table 1 illustrates the primary advantages and disadvantages of 2/3 versus 5/6 pitch alternators. Notice that the pitch factor for the fundamental harmonic is 0.97 for the 5/6 pitch alternator and 0.87 for the 2/3 pitch alternator. This means that for a 5/6 pitch alternator the fundamental voltage is 97 percent of the fundamental voltage generated by the same alternator if it were wound with a full winding pitch, at the same level of excitation. For the 2/3 pitch alternator the fundamental voltage is 87 percent of the fundamental voltage generated by a full pitch winding. This shows that an alternator with a 5/6 pitch coil will be able to generate a higher fundamental voltage than a 2/3 pitch coil at the same level of excitation. An alternator wound with a 5/6 pitch coil is capable of greater kVA output than the same alternator would be if it were wound with a 2/3 pitch coil. This is the main advantage of a 5/6 pitch alternator as opposed to a 2/3 pitch. It allows for a more efficient use of copper and steel, as a greater kVA output can be generated using the same amount of material.

The primary advantage of a 2/3 pitch alternator is that it generates no 3rd harmonic content, as can be seen in Table 1. In fact 2/3 pitch alternators generate no triplen harmonics at all. (The term triplen harmonics refers to all odd multiples of the 3rd harmonic, so the 3rd, 9th, 15th and 21st are all triplen harmonics.)

It is important to minimize all of the harmonic voltages. The Total Harmonic Distortion (THD), a summation of all of the harmonic voltages as a percentage of the fundamental, is a commonly specified alternator parameter. With good alternator design similar values of THD can be achieved with either a 2/3 or 5/6 pitch alternator.

While it is important to minimize all harmonic voltages, the 3rd harmonic merits special consideration in low voltage, 4-wire systems. (Note that the term "low voltage" in this context refers to systems in which the line voltage is less than 1000 volts. Because there are different definitions for medium and high voltage in different regions we will use the terms "medium or high voltage" or simply "MV / HV" when referring to systems in which the line voltage exceeds 1000 volts.) The reason for this is that in 4-wire systems 3rd harmonic currents (in fact all triplen harmonic currents) from all three phases add directly in the neutral. This can result in high levels of harmonic distortion and potential overheating in the neutral conductor. Single-phase loads always have currents flowing in the neutral and in particular single-phase rectified or switching loads (such as switch mode power supplies) generate 3rd

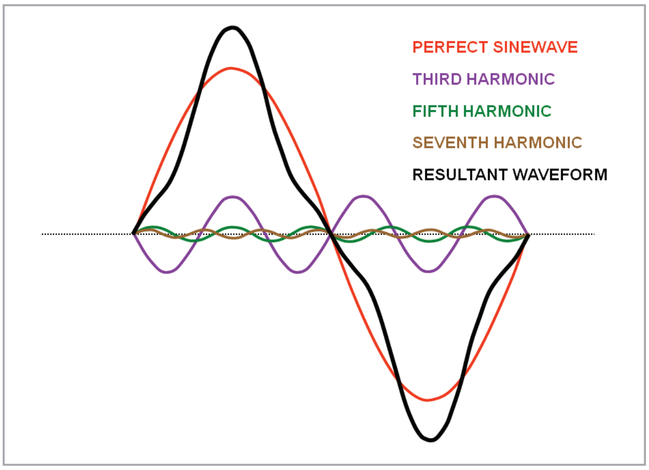

Figure 5. Waveform harmonics

Winding Pitch Factor (K_p)		
	2/3 Pitch	5/6 Pitch
Fundamental	0.87	0.97
3rd Harmonic	0.00	0.71
5th Harmonic	0.87	0.26
7th Harmonic	0.87	0.26

Table 1. Winding pitch factors for 2/3 and 5/6 pitch alternators

harmonic currents. Low voltage three phase rectified (non-linear) loads also generate 3^{rd} harmonic currents. It is for these reasons that Cummins uses 2/3 pitch alternators for all low voltage generator sets. Although 5/6 pitch windings minimize the 5^{th} and 7^{th} harmonic (as can be seen from Table 1) this advantage is outweighed by the advantage of the 2/3 pitch alternator eliminating the 3^{rd} harmonic in low voltage systems.

At medium or high voltage the effects of 3^{rd} harmonics are less of a consideration because the neutral wire isn't typically used. With MV/HV generator sets a transformer is typically used to step the voltage down to line voltage. The secondary winding of the transformer will be Y-connected, providing a neutral conductor for single-phase loads. The primary winding of the transformer will be delta connected to the generator windings. 3^{rd} harmonic currents will circulate in the delta connected primary winding and remain on the high voltage side of the transformer. While these 3^{rd} harmonic currents will generate heat (like all harmonic current), the effect is not as dramatic as the effect of 3^{rd} harmonic current adding directly in the neutral wire.

When a neutral conductor is not used, as is the case for most medium and high voltage systems, generated 3^{rd} harmonic voltage is less of a consideration. In these applications, 5/6 pitch alternators are often used successfully as long as the total harmonic distortion is kept low and care is taken to eliminate or minimize current circulating between the neutral and ground connections of the paralleled generator sets.

Paralleling Alternators of Dissimilar Pitch

When generators are paralleled, the voltages of the two machines are forced to the exact same magnitude at the point where they are connected to the paralleling bus. Differences in electromotive force (emf) generated by the alternators will result in current flow from the machine with higher instantaneous emf to the machine(s) with lower instantaneous emf. Figure 6. illustrates this phenomenon.

In this figure, two voltage waveforms (the red and blue lines) are superimposed upon each other. Note that these voltage waveforms may be exactly the same RMS voltage magnitude, but at different points in time the blue voltage is higher than the red, and vice versa. When the machines are connected together on a common bus, the differences in voltage result in current flow between the machines, which is represented by the green line. Note that in this simple example the magnitude of the current shown is exaggerated to more clearly illustrate the phenomenon. Note also that because the blue and red voltage lines cross each other three times in each half cycle, the current generated is a third-order harmonic current.

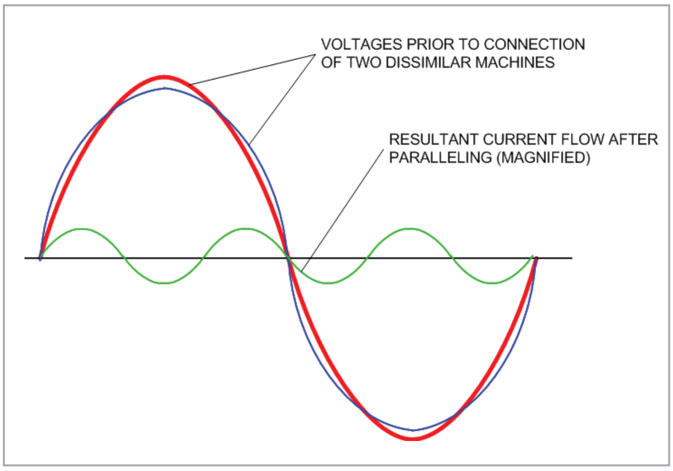

Figure 6. Current flow between paralleled alternators of dissimilar pitch

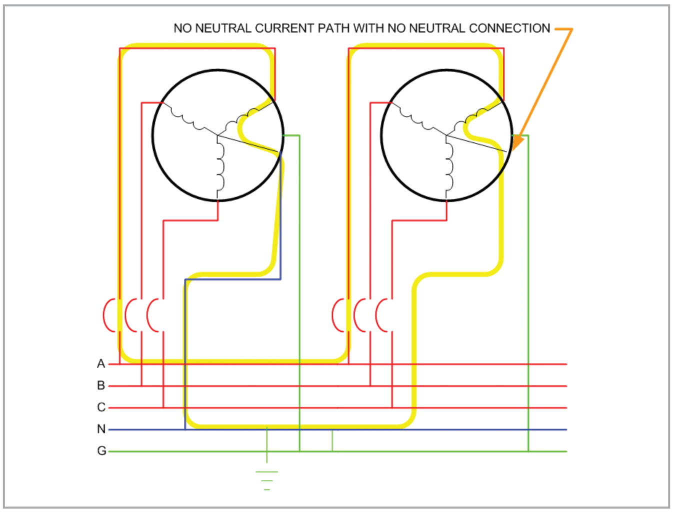

Figure 7. Neutral current in 4-wire paralleled generator sets

So, at any point in the cycle where there is a voltage difference between the machines prior to paralleling, current will flow between the machines. This is referred to as circulating neutral current and is apparent when there is a path through the neutral of the system in which the current can flow. Figure 7 illustrates circulating current flowing through the neutral conductors of paralleled generator sets.

The impact of incompatibility can be clearly seen with proper measuring devices, and is often visible with conventional AC current metering. The circulating current will be most apparent by displaying current flowing from each generator with no load on the system. There are several methods for paralleling 5/6 pitch alternators or alternators of dissimilar pitch and the most common of these methods will be described here.

Examples and Best Practices

Medium / High Voltage Examples

The most common methods for paralleling medium / high voltage generators vary across the globe. We will present different two different methods, one used commonly in North America and one used commonly outside of North America.

Figure 8 shows the most common generator paralleling configuration at medium voltage used in North America. In this system the neutral point of each generator is connected to earth through a neutral grounding resistor. The generators parallel at medium voltage and all power travels through a delta-wye transformer before it reaches the actual load. In this configuration, any harmonic distortion created by the generators remains on the high side of the power transformer and does not reach the actual load. As you can see, harmonic distortion from the power source is much less of a concern when generating at medium voltage because it does not add to the harmonic distortion that is created by the load. Plus, any 3rd harmonic voltage created by the generator will stay on the medium voltage side of the transformer and not be traveling through the neutral in the low voltage distribution system.

In this example either 2/3 pitch or 5/6 pitch medium voltage alternators are commonly used. There is one additional consideration when a 5/6 pitch alternator is used. As stated before, a 5/6 pitch alternator will produce some 3rd harmonic voltage. If there are impedance differences between the generators, there will be some amount of current that will circulate between them through the resistors and the earth ground connection. These impedance differences may be due to slight alternator differences, different cable lengths or different resistor values. In the majority of cases, impedance differences are not big enough for this circulating current flow to cause any problems. The alternator and resistor specifications should take this current into account. Many times it is easiest and most cost effective to choose an alternator and resistor that are not affected by this current flow.

When a reduction in circulating current flow is required, there are alternative grounding methods that can be used. These methods include utilizing reactors in place of resistors or using a neutral switching scheme. Reactors could be used in place of the resistors with the same configuration shown in Figure 8. The reactors need to be tuned and sized appropriately. Another reactor method is described in the following section on "Strategies for Paralleling Generators with Dissimilar Pitches". The neutral switching method is described below.

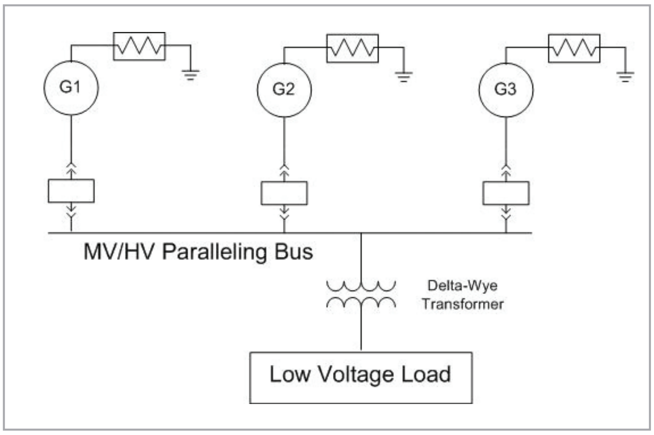

Figure 8. Paralleled medium voltage generators (typical arrangement in North America)

Figure 9 shows the most common generator paralleling configuration for medium/high voltage systems outside of North America. When the generators are stopped, all the neutral grounding switches are closed. When the generators are called to start, the first one to close its paralleling breaker will keep its neutral grounding switch closed. Then, all the other neutral grounding switches are opened. By having only one generator connected to the earthing resistor, all potential circulating currents between the generators is eliminated. If the generator system is then paralleled with the utility, the neutral grounding switch that is closed should then be opened. As with all grounding schemes, the neutral grounding resistor must be properly sized. This method has the same advantage of keeping all the harmonic current created by the generators on the high side of the transformer and not adding to the harmonic content of the load.

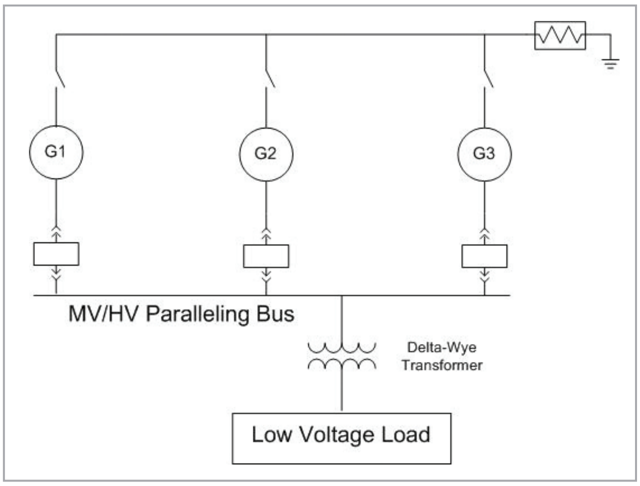

Figure 9. Paralleled MV/HV generators (typical arrangement in Europe).

Low Voltage Example

Figure 10 shows a typical low voltage paralleling system. In North America most low voltage systems operate at 480V line-to-line with some systems operating at 416V or 600V line-to-line. There are two major differences between a low voltage system and a MV/HV system that require a more careful choice of the alternator winding pitch. First, many low voltage systems include a neutral conductor that is connected between the generators and the paralleling switchgear. This neutral may also be connected to the various low voltage loads. Second, many of the low voltage loads are non-linear and generate harmonics on the power system while they are operating. Some of these loads include variable frequency drives (VFD), uninterruptible power supplies (UPS) and switched mode power supplies (SMPS). As stated before, choosing an alternator that minimizes the total harmonic distortion that it produces is important for low voltage systems. A 2/3 pitch alternator will not add any third order harmonics to the total system. Therefore a 2/3 pitch alternator is the best choice for low voltage 4-wire systems.

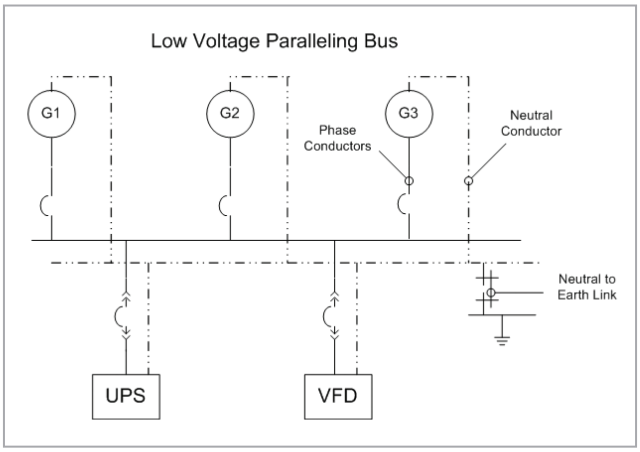

Figure 10. Paralleled low voltage generators

Strategies for Paralleling Generators with Dissimilar Pitches

Use a 3-wire distribution system when paralleling alternators of dissimilar pitch.

By avoiding a solid neutral connection between the genset bus and the loads, the most common cause of harmonic problems is minimized by removing the path on which the most disruptive current can flow. (The harmonic currents will still cause heating in the machines, but the disruptive effect of current flow in the neutral is eliminated.)

Parallel dissimilar alternators in 4-wire systems.

When paralleled generator sets are required to serve single-phase loads directly (with no delta-wye transformer in the circuit to create a neutral for the loads) there are three methods to reduce the risk of circulating neutral currents: connecting neutrals of similar pitch machines only, installing reactors between the dissimilar pitch alternators, or derating the alternator to accommodate the neutral current.

Connect neutrals of like-pitch machines only.

Low voltage systems are usually required to have a neutral-to-ground connection. In a parallel application the ideal location for this bonding point is in the system switchgear, so that there is only one neutral bond for the system. Consideration must be given to the magnitude of loads requiring the neutral connection versus loads that can operate only on the three phases. System loads will naturally balance out as long as there is sufficient line-to-neutral capacity in the system.

Care must be taken in this scenario to make sure that a generator without a neutral connection is not the first to close to the bus or the system will have no neutral to ground bond. If there is a scenario in which any generator must be allowed to be the only generator connected to the bus (in the event that all other generator sets have failed for example) use neutral contactors to make sure that only like pitch machines have their neutrals connected, similar to the system shown in Figure 9. In this design it is particularly critical for the failure modes of the neutral contactors to be considered. Alarms should be raised by failure of a neutral closure to operate correctly in either opening or closing mode. Dual neutral contactor position indicating contacts (one "a" and one "b" from different switches) should be used to be more certain of the state of the neutral contactor.

Install reactors in the neutral leg between generators of different pitches.

Reactors can be installed in the neutral leg between generators of different pitches, as shown in Figure 11, to minimize circulating neutral current. Reactors can be tuned to specific frequencies that are the biggest problems, but typically they are designed for 150/180 Hz, as this is the most problematic harmonic.

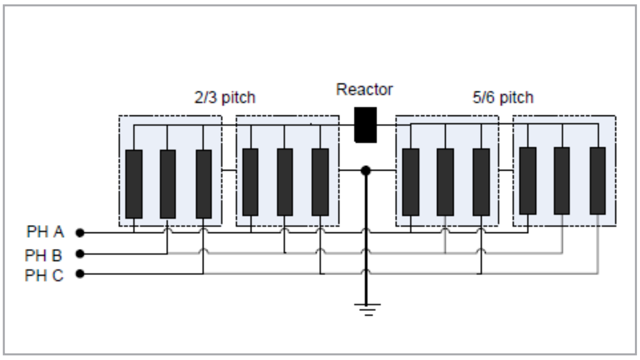

Figure 11. Reactor installed in the neutral leg between paralleled alternators of dissimilar pitches

The major issue in the use of reactors is their cost, and the custom nature of their design, making them problematic to acquire and install quickly. Also, the failure of the reactor may go undetected for a long time resulting in a change in the effecting bonding arrangement of the system and potential unexpected hazards.

Derating alternators to accommodate circulating current.

The circulating current may or may not be damaging to the alternators, depending on the magnitude of the current, the ratings of the generators in the system and the susceptibility of protective devices in the system to neutral or harmonic currents. Because the harmonic content of a generator waveform varies with the load, the negative effects of operating with dissimilar generators may be more apparent at some load levels than at others, but typically the major concern will be the magnitude of current flow at rated load, because that is the point at which the internal temperature of the alternator will typically be highest and is most susceptible to failure.

In 4-wire generator installations that use dissimilar pitch generators, generator neutral current should be measured to verify that operation of the generators in parallel will not result in system operation problems or premature generator failure. If there are no other related problems in the system, the designer may allow system operation with the neutral current and compensate by derating the alternator.

The derating factors can be calculated as follows:

Maximum allowable load on alternator

$$\text{(KVA)} = I_R / [(I_R^2 + I_N^2)^{1/2} (KVA_{gen})]$$

where:

I_R = output current of the generator set at full load and rated power factor

I_N = neutral current of the generator set at full balanced load, paralleled

KVA_{gen} = alternator rated KVA at maximum temperature rise

About the authors

Rich Scroggins is a Technical Specialist in the Application Engineering group at Cummins Power Generation. Rich has been with Cummins for 18 years in a variety of engineering and product management roles. Rich has led product development and application work with transfer switches, switchgear controls and networking and remote monitoring products and has developed and conducted seminars and sales and service training internationally on several products. Rich received his bachelors degree in electrical engineering from the University of Minnesota and an MBA from the University of St. Thomas.

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Summary

2/3 pitch alternators have long been the preference for low voltage distribution systems due to their suppression of 3rd harmonic currents. In systems that do not use a neutral conductor, 3rd harmonic currents are less of a concern and alternators of different pitches are acceptable provided that the total harmonic distortion is low.

Paralleling alternators of dissimilar pitches creates a possibility for circulating currents between the alternators. However, there are techniques that can be applied to eliminate or reduce circulating currents mitigating the risk.

Cummins Power Generation recommends 2/3 pitch alternators for all 4-wire distribution systems. 5/6 pitch (or alternators of other pitches) are acceptable for use in systems that do not use a neutral conductor. Alternators of dissimilar pitches may be paralleled if measures are taken to minimize circulating currents.

References

- "AC Generators with 2/3 and 5/6 Winding Pitch", Dr. Jawad Al-Tayie, Chris Whitworth, Dr. Andreas Biebighaeuser.
- "Paralleling Dissimilar Gensets: Part 2 – Compatible Alternators", Gary Olson, Cummins Power Generation.

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