CATERPILLAR

ENGINE DATA SHEET

EDS 70.4
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Generator Winding Pitch and Harmonics

Summary

This engine data sheet will discuss the advantages and disadvantages of various winding pitches and how it affects generator performance. It will also discuss the effects on harmonic content, waveform, paralleling, electric motors, switchgear instrumentation, and protective relaying.

Discussion

Generally, Caterpillar SR 4 Generator windings have a 3/4 to 5/6 pitch ratio. Most manufacturers wind their generators with similar winding pitch. Some manufacturers use a 2/3 pitch ratio, and we see specifications requiring 2/3 pitch ratio windings. There are very good reasons to avoid 2/3 pitch ratio generators. These reasons must be explained to generator set users. When these reasons are known, the advantage of Caterpillar Generators with high pitch ratio winding will become evident.

Harmonics

Harmonics are the multiples of the fundamental waveform frequency being produced by the generator. Because generators are magnetically symmetrical, only odd harmonics are normally of any significance. For example, a 60 Hz generated waveform will contain the 60 Hz fundamental, a 180 Hz 3rd harmonic, a 300 Hz 5th harmonic, a 420 Hz 7th harmonic, a 540 Hz 9th harmonic, a 660 Hz 1lth harmonic, 13, 17 . . . In general, the higher the harmonic order, the lower the magnitude of the harmonic. Therefore, except for telephone or radio frequency interference (RFI) noise considerations, higher harmonics are of little significance.

Generator *Coil Pitch*

To produce voltage, a synchronous generator has a direct current (DC) excited structure consisting of alternately north and south magnetic poles, usually on the rotating member of the generator or rotor. The magnetic field is thus produced which sweeps the armature (usually the stator). The magnetic field induces voltage in coils placed in slots in the armature. When the span of each of these coils is exactly equal to the span of the north to south field poles, the maximum magnetic flux is encompassed by the coil and the maximum voltage is produced. Such a positioning of coils is called *full pitch* winding. Very few machines are wound full pitch because the winding requires excessive end turn copper and provides little harmonic control. Most generators are fractional pitch windings.

Why Worry About Harmonics?

Harmonics produce undesirable effects in the generator, but motors also suffer from excessive harmonics. The remainder of this discussion will be limited to harmonics of lower orders, those with significant magnitudes, are the 3rd, 5th, and 7th.

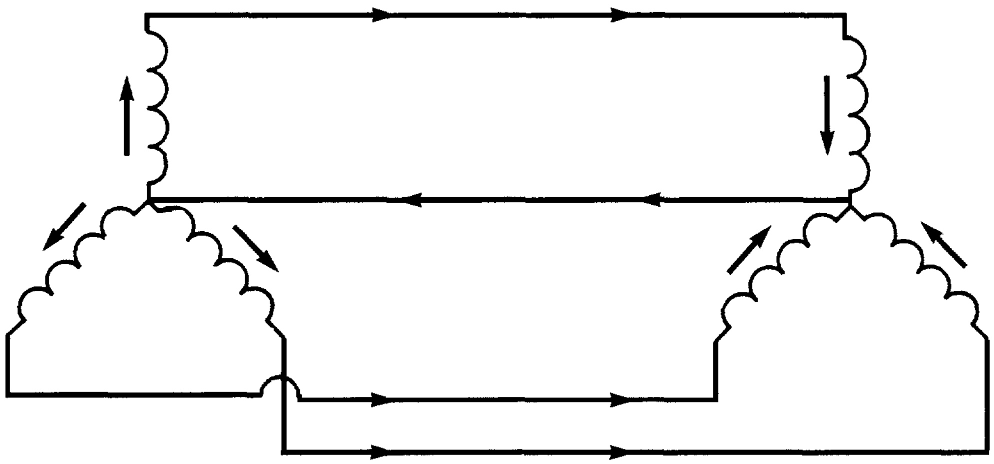
Each of these harmonic voltages generated are in the windings, but a 3rd harmonic current will not flow in a three-phase, wye-connected winding unless the neutral is connected. The 3rd harmonic current will flow in a delta-connected generator winding as shown in Figure 1. Both 5th and 7th harmonics will flow in either winding since they are line harmonics.

The major difficulty caused by harmonic currents is heat generated in the winding, core, and rotor. Since generator ratings are limited by allowable temperature rise, harmonics are, in effect, derating factors. In derating, the magnitude of the current is of obvious importance, because losses are proportional to the square of the current. Increased frequency causes increased core losses and increased copper loss from skin effect. *5th and 7th harmonics are the offenders here because they are in the 600 Hz range.*

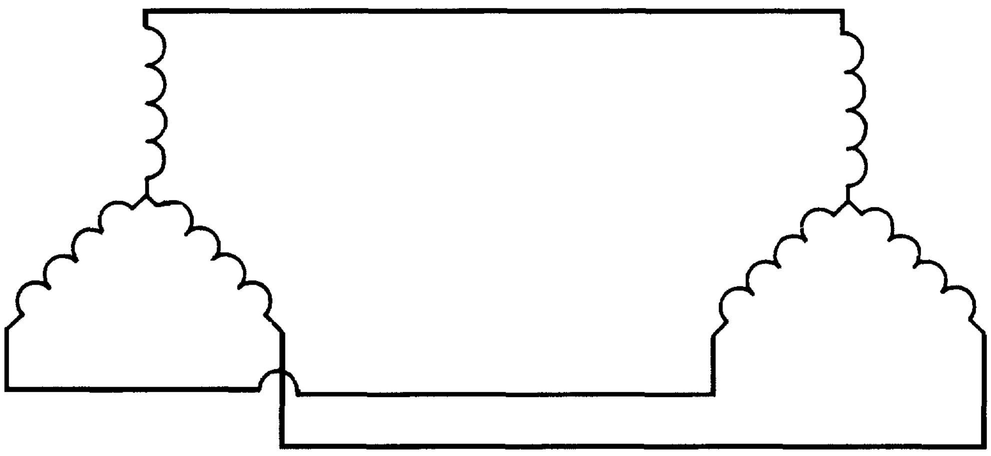
Another difficulty caused by harmonics is waveform. The more harmonic content in a generated wave, the more distortion from a sine wave occurs. If severe enough, it can cause voltage regulator sensing problems and inaccurate instrument readings.

Why 2/3 Pitch?

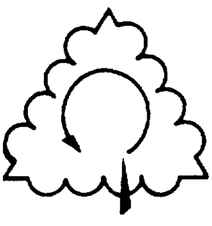
The 2/3 pitch winding became popular when manufacturers of small generators wound their machines in delta to combine three phase and three wire single



3rd Harmonic circulates through Neutral with Wye-Connected Machines



3rd Harmonic does not circulate in Wye-Connected Machines without Neutral



3rd Harmonic circulates in Delta-Connected Machine

Figure 1

phase into the same machine. For small machines, it is often more economical to combine voltages in this way rather than to use transformers to supply the three wire single phase (120-240 V).

When the generator was connected in delta, the 3rd harmonic circulates in the generator winding so derating was necessary. So, a 2/3 pitch winding was used to reduce this circulating current and achieve a higher rating.

The fact that the 5th and 7th harmonics are nearly maximum at 2/3 pitch (see Figure 2) was ignored as was the fact that most 3rd harmonics currents are generated by load equipment, such as fluorescent lighting, and that a 2/3 pitch winding will do little to impede the current flow from such sources. In fact, current flow increases because the 2/3 pitch winding has a much lower impedance (zero sequence impedance) to such current flow (zero sequence current).

A 2/3 pitch winding is used for one purpose — to prevent derating of delta-connected generators. Other harmonic problems are compromised and even the 3rd harmonic is not completely eliminated. The Caterpillar 12-lead 360- and 440-frame SR 4 Generators have a sufficiently high zero sequence reactance and the 3rd harmonic low enough that 2/3 pitch is unnecessary.

Coil Pitch and Harmonics

The choice of coil pitch has a lot to do with harmonic generation. A 2/3 pitch winding eliminates most 3rd harmonic, 4/5 pitch eliminates 5th, and 6/7 pitch eliminates 7th. Unfortunately, coil pitch cannot eliminate all harmonics simultaneously. As one is eliminated, others increase. For example, refer to Figure 2.

Pitch	Kp1	Kp3	Kp5	Kp7
⅔ (67%)	0.866	0.0	0.866	0.866
⅘ (80%)	0.951	0.588	0.0	0.588
6/7 (86%)	0.975	0.782	0.434	0.0
⅚ (83%)	0.966	0.707	0.259	0.259

NOTE: Pitch factors for the fundamental (Kp1), 3rd harmonic (Kp3), 5th harmonic (Kp5), and 7th harmonic (Kp7). These pitch factors are multiplied by the respective harmonic fluxes to predict harmonic voltages.

Harmonic Voltages:

The harmonic analysis of the line to line and line to neutral voltages both on no load and on a linear load are shown for a typical generator.

Line to Line				
	⅔ Pitch		⅚ Pitch	
Harmonic	**No Load**	**Full Load**	**No Load**	**Full Load**
3rd	0.10%	0.35%	0.10%	0.10%
5th	1.75	2.31	0.49	0.31
7th	0.76	0.35	0.15	0.19
9th	0.08	0.05	0.07	0.03
11th	0.12	0.95	0.22	0.58
13th	0.26	0.39	0.28	0.47
15th	0.02	0.02	0.09	0.04
Total	**1.93%**	**2.57%**	**0.46%**	**0.84%**
Line to Neutral				
3rd	0.20%	0.09%	2.53%	7.66%
5th	1.54	2.11	0.55	0.23
7th	0.77	0.35	0.17	0.18
9th	0.01	0.1	0.75	1.15
11th	0.18	0.94	0.11	0.63
13th	0.24	0.43	0.35	0.5
15th	0.07	0.05	0.54	0.9
Total	**1.76%**	**2.38%**	**2.78%**	**7.84%**

Figure 2

As indicated in Figure 2, the coil pitch is only one element in determining the voltage harmonic content. Reduction of 3rd harmonics in the flux wave will reduce voltage 3rd harmonics. Harmonic reduction in the flux wave is accomplished by shaping the pole head. The pole head is shaped to cause a longer air gap at the pole tips than in the center of the pole. In addition, the width of the pole head in proportion to pole center is a factor in harmonic control.

The SR 4 Generator has low 3rd harmonic voltages because pole embrace and the pole piece head shape has been proportioned to produce low 3rd harmonic flux pattern. If the 3rd does not exist or has been minimized, it does not need to be suppressed by winding 2/3 pitch. A more rational pitch can then be employed — like 5/6 to reduce 5th and 7th harmonics.

Figure 3 illustrates that pole embrace and pole piece head shape can be used to minimize 3rd harmonic voltage, This graph compares nine SR 4 generator frame sizes, none of which are 2/3 pitch, with four competitive generators of the same approximate kilowatt rating with 2/3 pitch winding. Actual test data indicates very little difference in 3rd harmonic voltage content. Considering the fact that the 2/3 pitch machine-will have lower zero sequence reactance than the SR 4 generators, any load generated 3rd harmonic would cause greater 3rd harmonic circulating current in a 2/3 pitch generator.

Most generator manufacturers around the world understand coil pitch and harmonic relationships. As stated earlier, 3rd harmonic currents have no path except in delta-connected generators or in four-wire, wye-connected neutrals. Thus, the 3rd harmonics are eliminated by a three-wire, wye connection. By judicious choice of coil pitch, say 5/6 pitch as shown in Figure 2, the 5th and 7th harmonics are quite low. Therefore, a

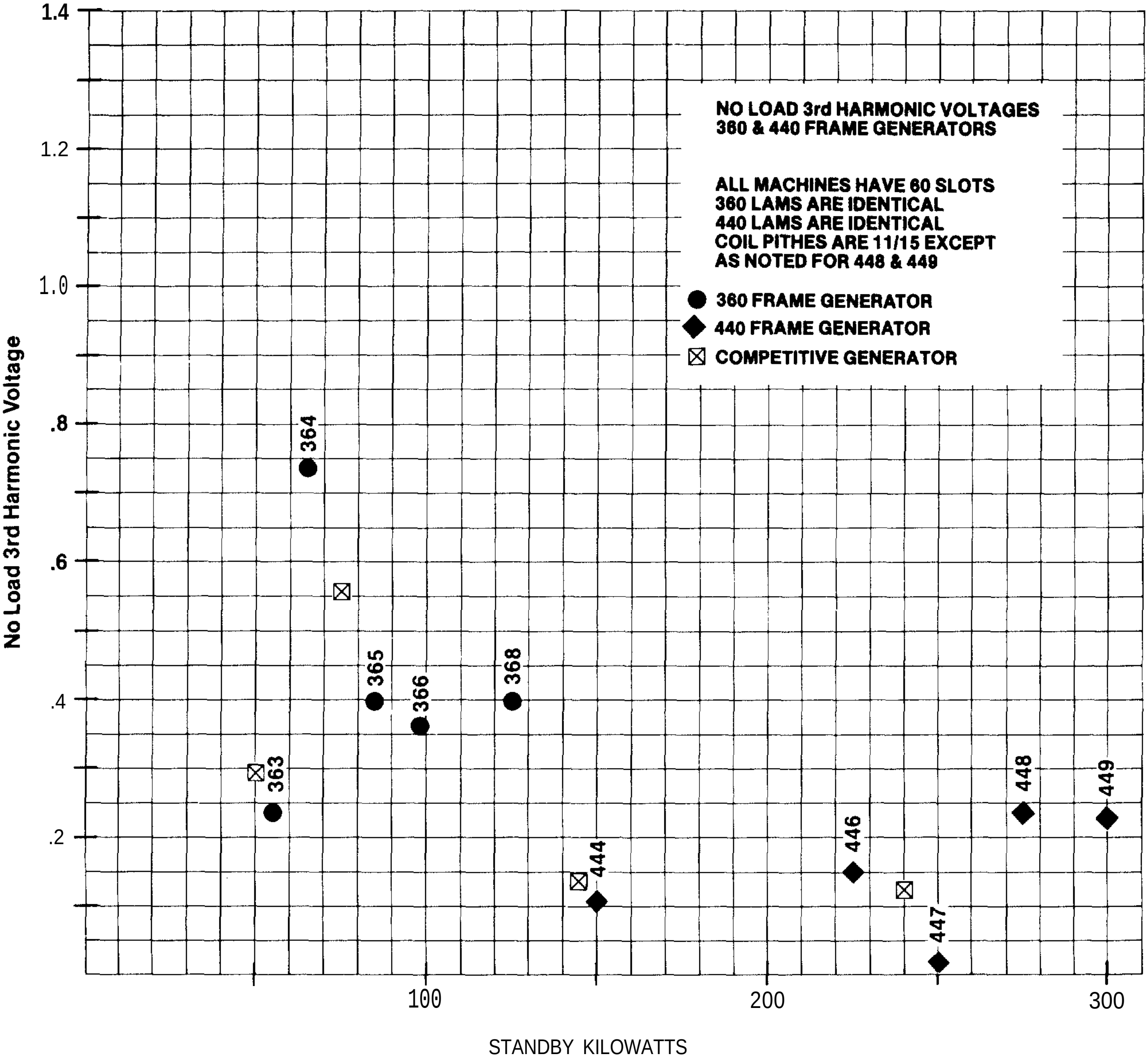

NO LOAD 3rd HARMONIC VOLTAGES
360 & 440 FRAME GENERATORS
ALL MACHINES HAVE 60 SLOTS
360 LAMS ARE IDENTICAL
440 LAMS ARE IDENTICAL
COIL PITHES ARE 11/15 EXCEPT
AS NOTED FOR 448 & 449
360 FRAME GENERATOR
440 FRAME GENERATOR
COMPETITIVE GENERATOR
No Load 3rd Harmonic Voltage
1.4
1.2
1.0
.8
.6
.4
.2
364
365
366
368
363
444
446
447
448
449
100
200
300
STANDBY KILOWATTS

Figure 3

three-wire, wye-connected, 5/6 pitch generator is about as harmonic free as a standard winding can make it. The 3rd harmonic is eliminated, while the 5th and 7th harmonics are at low values.

Paralleling Generators and 2/3 Pitch

Ignoring some of the obvious disadvantages of 2/3 pitch windings, some manufacturers looked for an advantage to 2/3 pitch winding other than in delta-connected generators. They settled on paralleling. As noted earlier, 3rd harmonic current will flow in a wye-connected neutral. However, this is usually of little significance from a heating or derating 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. Additional armature losses are $0.10^2 = 0.01$ or 1%.

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. So the advocates of 2/3 pitch winding concluded: since a 2/3 pitch generator produces very low 3rd harmonic, they must be superior for paralleling. However, 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 by the equation:

$$I_3^T = \frac{V_3' - V_3''}{(X01 + X02 + XL)}$$

I_3^T = Total third harmonic current.

V_3^1 = Third harmonic content of first generator, in volts.

V_3'' = Third harmonic content of second generator.

X01 = Zero-sequence reactance of first generator, in ohms.
X02 = Zero-sequence reactance of second generator.
XL = Inductive reactance of connecting line.

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.

What then is the cause of the neutral circulating current when two unlike generators are paralleled? It is a difference in voltage. Both generators are contributors. There is no advantage to a 2/3 pitch winding when paralleling generators. When paralleling with the utility lines, the 2/3 pitch winding maybe a disadvantage due to low zero sequence reactance.

As as example, let's compare a 4/5 pitch generator and a 2/3 pitch generator paralleled to the utility line. Consider a 480-volt, 100 kW generator paralleled to a utility bus with the neutrals tied together. Typical values for the zero sequence reactance are:

2/3 Pitch Generator	0.015 Ohms at 180 Hz
4/5 Pitch Generator	0.400 Ohms at 180 Hz
Utility Transformer	0.001 Ohms at 180 Hz

Typical third harmonic voltages:

2/3 Pitch Generator	0.1% or 0.28 Volts
4/5 Pitch Generator	2.5% or 6.9 Volts
Utility	0.2% or 0.56 Volts

Third harmonic currents will be (neutrals tied solidly):

2/3 Pitch Generator

$$\left(\frac{0.56 - 0.28}{0.015 + 0.001}\right) = 17.5 \text{ Amps}$$

4/5 Pitch Generator

$$\left(\frac{6.9 - 0.56}{0.4 + 0.001}\right) = 15.8 \text{ Amps}$$

The current per phase is 1/3 of the neutral current or 5.8 amps for the 2/3 pitch machine and 5.3 amps for the 4/5 pitch machine. This current would increase the losses in these generators less than 1%. If we look at the 2/3 pitch generator because it has the highest 3rd harmonic current, then:

150 Amps = 100% Rated Amps

$$\left(\frac{150^2 + 5.3^2}{150}\right) = 1.000627 \text{ or } 0.0627\% \text{ Additional Losses}$$

2/3 pitch generators are occasionally specified for systems where the machine is to be paralleled with the utility or other generators in the belief that this will eliminate third harmonic currents in the neutral. In fact, as the foregoing example demonstrates, due to the inherent low zero sequence reactance of the 2/3 pitch winding, any source of 3rd harmonic voltage in the system can result in high 3rd harmonic currents.

The 2/3 pitch winding is not a *cure all* for 3rd harmonic current problems. Generators having any pitch can be successful paralleled with each other and with a utility source; but if the neutrals are to be tied together, then the effects of 3rd harmonic currents in the neutral must be considered; and if necessary, reactors, resistors, or switches must be installed to limit these currents.

Phase-to-Neutral Fault Currents

Phase-to-neutral faults account for approximately 65% of all faults in an electrical power system. This fact points up another disadvantage of the 2/3 pitch winding. 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, this fault current will be considerably greater in magnitude. This means there is a greater potential for damage should a fault occur, possibly higher interrupting capacity circuit breakers will be required, and additional bus bar bracing may be in order.

As an example, let's compare the phase-to-neutral fault current of a Caterpillar 446-frame SR 4 Generator rated 200 kW with an 11/15 (0.733) winding pitch to a competitive generator rated 200 kW with a 2/3 (0.666) winding pitch. Full load current at 200 kW, 480 volts, 60 Hz is 300 amps.

	Caterpillar SR 4	Competitive Generator
Subtransient Reactance (X"d)	0.176 pu	0.110 pu
Negative Sequence Reactance (X2)	0.226 pu	0.110 pu
Zero Sequence Reactance (Xo)	0.065 pu	0.019 pu

SR 4 **Generator**

$$1\ sc = \frac{3 \times 300}{(0.176 + 0.226 + 0.065)} = 1927\ \text{Amps}$$

Competitive Generator

$$1\ sc = \frac{3 \times 300}{(0.110 + 0.110 + 0.019)} = 3766\ \text{Amps}$$

In this case, the phase-to-neutral fault current is almost doubled in the 2/3 pitch generator.

The 2/3 Pitch Generator and Motor 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 nearly double frequency in the motor rotor (almost 600 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. The effect is not pronounced and may go undetected by the user, but motor life will be affected.

Capacitive Loading

When capacitors are part of the load, the 5th and 7th harmonics can cause trouble. The 2/3 pitch generator, as noted 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.

Non-Linear Loads

Non-linear loads generate harmonic currents which cause wave-form distortion of the generator.

For balanced three phase loads, distortion is caused by voltage drop due to the harmonic currents in the subtransient reactance of the generator.

The sub-transient reactance of a generator is not a function of coil pitch. Therefore, the coil pitch does not affect wave-form distortion.

The zero sequence reactance of a generator is effective only to currents which flow in the neutral line.

Single phase non-linear 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 specific case, the inherently low zero sequence reactance of a 2/3 pitch generator will reduce the voltage wave-form distortion.

This only 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 and the 2/3 pitch winding does not help reduce distortion.

Conclusions

1. Specifications should never include 2/3 *pitch* because it is meaningless of itself. Harmonic voltages are the useful values to specify.
2. The advantages for 2/3 pitch generators are mythological and are outweighed by the disadvantages.
3. The 2/3 pitch windings are employed primarily for the manufacturer's purposes, not for the user's benefit.
4. To eliminate 3rd harmonic circulating currents between generators operating in parallel, the generators should have identical 3rd harmonic voltages.
5. Using 2/3 pitch to reduce 3rd harmonics will increase higher harmonics (5th and 7th), which will cause additional heating in motors.

6. Caterpillar SR 4 Generators are wound to optimum pitch, providing the least distortion of the waveform, producing the best quality power while providing the most economical use of copper and iron.

7. Disadvantages of 2/3 winding pitch:

   a. Using 2/3 pitch to reduce 3rd harmonics will increase higher harmonics (5th and 7th) which causes additional heating in motors. Optimum pitch performs better with delta connected loads because of the lower total harmonics that will circulate in the delta connection.

   b. A 2/3 pitch winding will generally require more copper and iron in the generator-to achieve the same ratings. This extra cost does not usually add value.

   c. Most of the world's generators are nearly 5/6 pitch. Therefore, when paralleling to unknown generators optimum pitch is best.

   d. A 2/3 pitch winding has very low impedance to 3rd harmonic currents, therefore, any load generated 3rd harmonic currents will be of greater magnitude than through higher pitched coil generators with higher impedance to the 3rd harmonic.

   e. Phase-to-neutral fault currents will be higher in a 2/3 pitch generator because of reduced zero sequence reactance.

   f. A 2/3 pitch is sometimes specified by switchgear manufacturers that use lower quality line-to-neutral sensing instruments that are not true RMS reading,

8. Applications where 2/3 pitch should be used:

   a. When paralleling, it is desirable to match the winding pitch (3rd harmonic voltage) of existing generators. This minimizes the need for neutral reactors.

   b. 2/3 pitch windings provide an advantage when single phase non-linear loads are connected in a balanced manner, with a neutral connector directly to the generator.

   c. 2/3 pitch is needed for Delta operation of higher rated generators (over 200 kW).