



Issue #WP105: Technical Information from Cummins Generator Technologies

AC Generators with 2/3rd and 5/6th winding pitch

White Paper

Dr Jawad Al-Tayie

Chris Whitworth

Dr Andreas Biebighaeuser

Abstract

Cummins Generator Technologies has a wide range of AC generator products covering many applications, from prime power to marine, oil and gas to name a few. The stator of the AC generator is manufactured with either a 2/3rd or a 5/6th winding pitch. Winding pitch of AC generators has influence on the shape of waveform (harmonic contents) and on the level of the fundamental voltage. The winding pitch will have an influence on neutral circulating current

in case of parallel operation and also will impact on the type of neutral grounding method. Paralleling generators with different winding pitch will require careful consideration if interconnecting star points of all running generators should be necessary. Both winding pitch (2/3rd and 5/6th) have some pros and cons, correct selection for any proposed application is the key for ensuring a cost effective power supply solution.

I. Introduction

The stator winding pitch of a generator is a design parameter that can be used to optimise the generator waveform shape and minimise the generator cost, because shorter pitch (lower pitch ratios) use the generator stator less effectively and require the use of more electrical steel and copper for the same kW output than higher pitch machines. For example:

- 5/6th pitch windings suppress 5th and 7th voltage harmonics but may enhance the triple harmonics (third, ninth etc.)
- 2/3rd pitch windings suppress the triple harmonics but may enhance the 5th and 7th. In addition, 2/3rd pitch wound machines generally have lower zero sequence reactances that can increase the single phase fault current.

When comparing generator specifications, the listed value for output voltage total harmonic distortion (THD%) can be similar for either a 5/6th or a 2/3rd pitch winding configuration. A well designed generator could probably achieve very similar voltage waveform THD% with either pitch.

Cummins Generator Technologies considers that 2/3rd pitch winding is best for most electrical loads that require a three phase, four wire system, because they may include a proportion of single phase loads. When a generator output voltage with triplen harmonics (e.g. from a generator that is not 2/3rd pitch) is used to power a load consisting of single phase loads with triplen harmonics, the triplen harmonics from both sources will sum together in the neutral and promote high and therefore, potentially troublesome, neutral currents in distribution system conductors.

Thyristor based and uncontrolled rectifier converters have high harmonic currents with harmonic numbers around multiples of 6 ± 1 . It is therefore technically correct to consider that an output voltage waveform with minimal 5th and 7th harmonics would be best for such non-linear loads (NLLs). (IGBT^[1] based converters and switched mode power supplies have harmonics at much higher frequency order).

On most sites, there is a mixture of NLLs and 'normal' (non-distorting) loads such as; lighting, heating, air-conditioning units, pump and fan motors, lifts, etc. What is not always appreciated is that although many of these 'normal' loads appear to be benign with respect to harmonic distortion, many now contain variable frequency drives etc., which are harmonically distorting, and can also be susceptible to a harmonically distorted supply voltage waveform, as can linear loads on the system.

In addition, in the category of 'ordinary' load it must be considered that most buildings including modern equipment will almost certainly have an IT network supporting PCs or terminals. Most such modules employ switched mode power supplies, which are notorious for generating high neutral currents which can create serious rating problems for the building distribution system if there is insufficient care with the choice of the size of neutral cables. It therefore, becomes paramount that the current waveform harmonics are considered for any generator that may be required to support such a mixed load to ensure it provides a low enough source impedance to ensure voltage THD% is kept acceptably low. For a generator this starts by identifying the generator's value of subtransient reactance (X''_d) at the site load duty point kVA, V and Hz.

The no load voltage waveform does not really tell how susceptible the generator is to NLL, it is more about stator leakage reactance, which defines this, high values are poor, therefore in marine application it is often pushed for low X''_d in former times for motor starting capability, reasons nowadays also to minimise the size of filter units.

For balanced three-phase loads, distortion is caused by voltage drop due to the harmonic currents in the subtransient reactance of the generator. The subtransient reactance of a generator is not a function of coil pitch. Therefore, the coil pitch does not affect waveform distortion. The impact of generator pitch on load generated harmonic currents is highly dependent on the system configuration.

II. STAMFORD® generators

We recommend 2/3rd pitch on all low voltage (LV) AC generators because, in general, these systems will need to use the neutral to service loads. For low voltage, both 50 and 60Hz, a 2/3rd pitch winding configuration will eliminate the triplen harmonic contribution from the generator and will not encourage an increase in the overall triplen harmonics content of the installation.

For medium voltage (MV⁽²⁾) and higher voltage (HV⁽³⁾) systems, it is acceptable to use other pitch machines, since the neutrals are rarely used to directly serve loads and there are only low levels of triplen harmonics as these are summed to zero in components such as delta-wound transformers, etc.

Originally STAMFORD products were low voltage only and these were all with 2/3rd stator winding pitch. The summing together of the triplen harmonics takes place in the distribution system the generators were powering and although high neutral currents could still occur, the generator did not contribute to these and at generator winding level there was no current summation. Due to earthing methods in the LV power plant business it was the correct pitch. This is still valid today. An additional benefit of 2/3rd pitched windings is the prevention of circulation currents through the star points of our generators when connected in parallel.

When the P80 machine was designed, it was decided to use the same pitch (2/3rd) for all LV, MV and HV machines.

III. AvK® generators

Cummins Generator Technologies has built LV, MV and HV AvK generators for many years^[4]. For AvK generators, the stator winding pitch is dependent on the application and, in some cases, the voltage level.

The pitch for AvK generators is:

- 2/3 pitch for 400 V @ 50 Hz and 480 V @ 60 Hz
- 5/6 pitch for 690 V @ 60 Hz and @ 50 Hz
- 5/6 pitch for all MV and HV
- Stationary power plants – typical voltage levels are:

400 V @ 50 Hz and 480 V @ 60 Hz => 2/3 pitch

MV and HV up to 13.8 kV => 5/6 pitch

- Marine – the electrical system neutral is unearthed/high ohmic earthed. Here earth faults are detected but because of the safety issues associated with tripping essential circuits to clear a single phase earth fault, an alarm is given allowing the fault to be repaired when convenient in the ship's progress and not causing a `Black Ship`, which would occur if the system would be `hard earthed`. This is valid for LV, MV and HV. Therefore 5/6th winding pitch is used.

Typical voltages are:

- 690 V @ 60 Hz and @ 50 Hz
- MV and HV:
 - 6.6 kV @ 60 Hz and @ 50 Hz
 - 11 kV @ 60 Hz and @ 50 Hz

- Note that neutral point earthing and equipotential bonding are often confused. Winding pitch affects neutral point bonding requirements only. Equipotential bonding, where conductive parts of the installation are electrically joined to avoid touch potential, etc., is required regardless of winding pitch choice. In addition, when generator star points are grounded it is important that neutral current is not allowed to circulate in the ground path as this may cause telecommunication systems issues as well as creating standing voltages in the ground.

- When star points of parallel running generators are connected together problems can arise with circulating current if the generators are not 2/3rd pitch. However, if all generators have the same winding pitch and rating, there is no problem for generators, but might be with 3rd harmonic currents in ships distribution system. Steps must be taken to control circulating current if generators with different winding pitches are connected to the same busbar with the star points coupled. See section 6.

IV. What is winding pitch

A coil whose sides are separated by one pole pitch (i.e., coil span is 180° electrical) is called a full-pitch coil. With a full-pitch coil, the emfs induced in the two coil sides are in phase with each other and the resultant emf is the arithmetic sum of individual emfs.

However the waveform of the resultant emf can be improved by making the coil pitch less than a pole pitch. Such a coil is called short-pitch (or fractional or partial pitched) coil. The emf induced in a short-pitch coil is less than that of a full pitch coil.

(i) Full pitch winding

Full pitch (Figure 1) = pole centre (S) to pole centre (N), for 48 slots stator (example)
 $= 48/4 = 12$ slots (coil span 1 – 13)

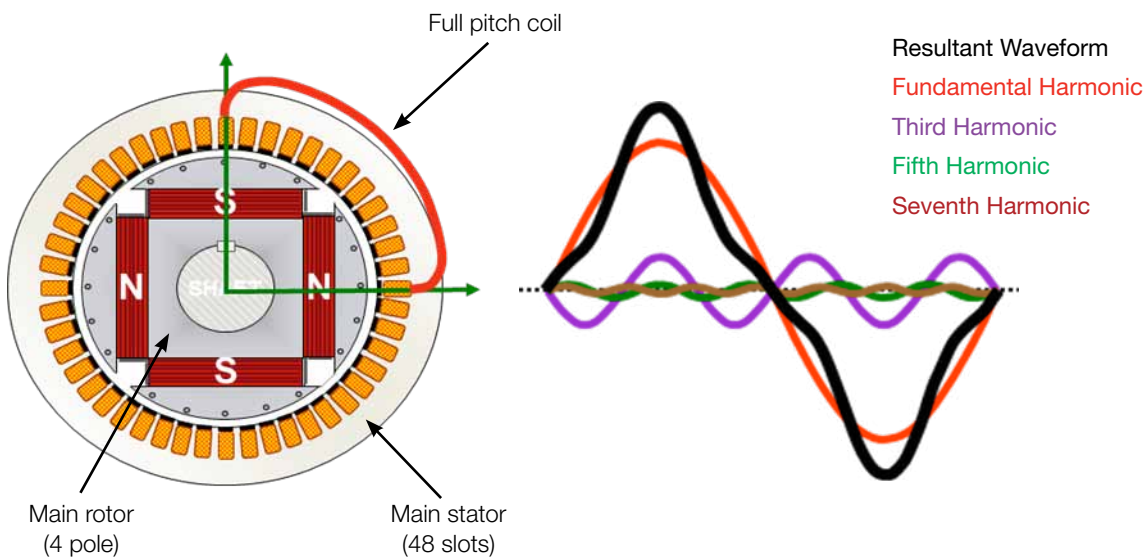


Figure 1: Full pitch winding machine with resultant waveform of the output phase voltage

(ii) Short 5/6th winding pitch

This winding pitch equals to 5/6th of full pitch, Figure 2.
 For 48 slot = $5/6$ th of 12 slots = 10 slots (coil span 1 – 11)

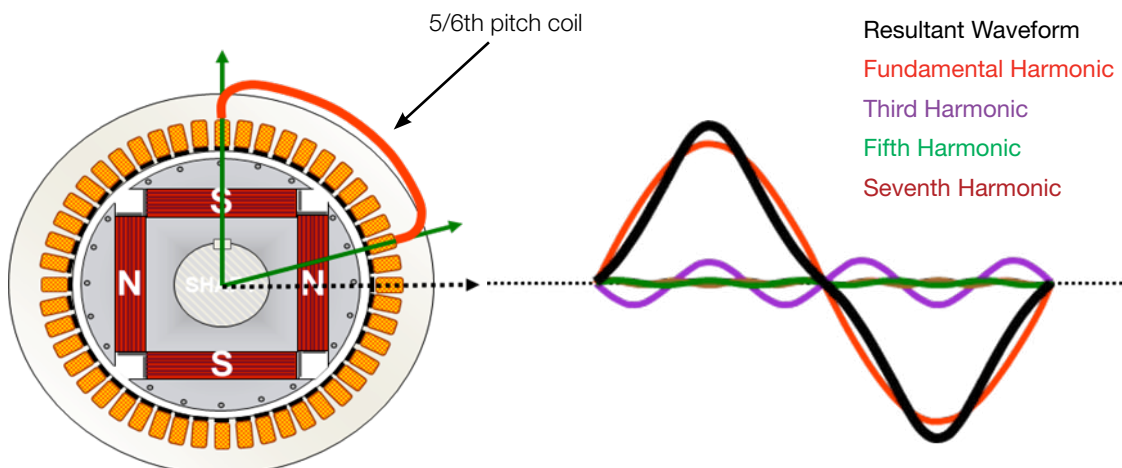


Figure 2: Short 5/6th pitch winding machine with resultant waveform of the output phase voltage

(iii) Short 2/3rd winding pitch

This winding pitch equals to 2/3rd of full pitch, Figure 3.
For 48 slot = 2/3rd of 12 slots = 8 slots (coils span 1 - 9)

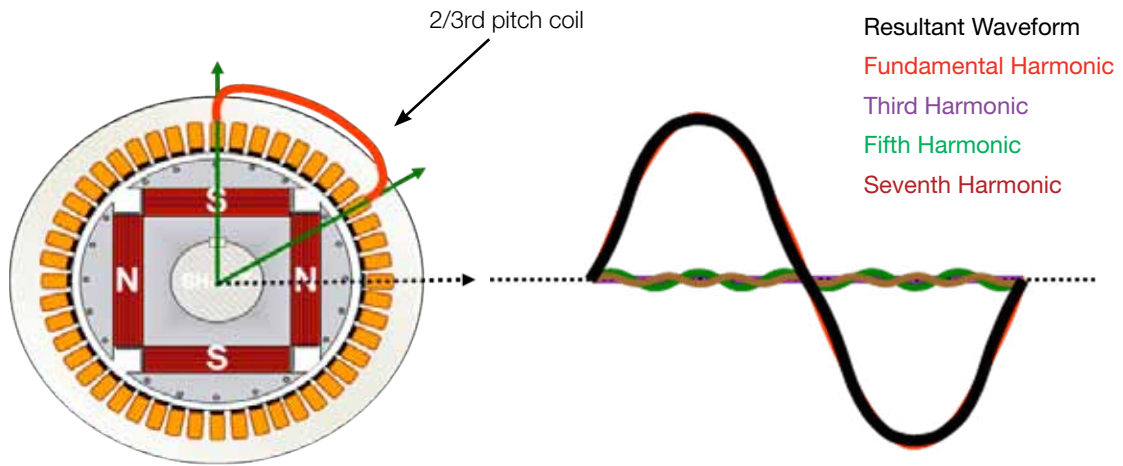


Figure 3: Short 2/3rd pitch winding machine with resultant waveform of the output phase voltage

V. High level Pros and Cons of 5/6th pitch winding

(i) Pros

- Increase of power density with lower costs and weight on the generator
- Increase of generator efficiency
- Lower iron losses for 5/6th pitch due to shorter core while same magnetic flux density
- Friction losses assumed the same
- Stator copper losses about the same – core length adder but overhang length reduction for 2/3rd pitch add up to zero, (this however depends on core length and pole number)
- Slightly lower rotor copper losses for 5/6th pitch due to shorter core while about same current density
- Additional losses about the same – neglected slightly higher losses due to damping of 5th & 7th stator winding field harmonic
- Loss reduction is between 3% to 6% of total alternator losses - depending on the load point
- In tendency a shorter and cheaper AC generator with better efficiency
- Emissions – better efficiency leads to lower fuel consumption and lower emissions
- THD:
 - Line to line voltage – THD% of 5/6th pitch has lower values as 3rd voltage harmonic adds up to 0 and 5/6th pitch keeps 5th and 7th harmonics low (IEC 60034 THD requirements are for line to line voltage only)
 - Line to neutral voltage – 2/3rd pitch has lower levels of THD% as 3rd voltage harmonic is not existing
- 5/6 winding pitch, more voltage (fundamental), better efficiency, less field current, less losses (copper and iron), Losses proportional to I^2 .

(ii) Cons

- Lower flexibility in use - cannot be used for all earthing methods. Less flexible in earthing system. Hard earthed systems required 2/3 pitch, hard earthed system is from experience an exception on MV/HV grids
- Other design aspects of 2/3rd and 5/6th winding pitches:
 - 2/3rd pitch is better regarding grid codes (due to core length increase)
 - Lower X_d value
 - Higher moment of inertia
- 2/3rd pitch is better regarding motor starting capability (lower source impedance)
- 2/3rd winding pitch, shorter coil and hence marginally less resistance, (this is true for 4 pole and short core length but this is different for long core lengths and high pole numbers)

VI. Parallel Operation of Generators

This section examines the parallel operation of generators of different winding pitch. Can a 2/3rd and a 5/6th pitch wound generator be connected together for parallel operation?

The basic requirements when operating generators in parallel are: waveform harmonic content, excitation system able to ensure kVAr sharing (droop or a static), engine able to share kW. During commissioning all generators must be set to have same voltage droop% for a given percentage kVAr load relative to each generators designed rating. If they don't have this same drooping characteristic % then they will not proportionally share the kVAr.

Section 4 showed the harmonic content of generators with 2/3rd and 5/6th winding pitch. It therefore follows that if a 2/3rd pitch is paralleled to a 5/6th pitch winding there will be differences in the harmonic 'structure' of the voltage waveform. These differences and they are electrical 'potential differences', will result in circulating currents between the two generators, in sympathy with whichever waveform - at that instant - has the highest 'electrical pressure'.

The actual level of circulating current is a complex issue, it will depend on the interconnecting/distribution system impedances and will also be very susceptible to the characteristics of the connected site load being supported by the generators.

Interconnecting generators stator winding star points will also change the characteristics of the circulating currents, both between the generators and the level of neutral current within the supplied distribution system. However, if the star points of dissimilar winding pitch generators are not interconnected, then there is no circulating current, but the generators may not exactly share reactive load proportionally and if the neutrals of some generators are not connected to the system neutral, consideration must be given to whether the site single phase loads can be supported by the generating sets with their neutrals connected, allowing for any possible maintenance conditions. Therefore, consider if the site load can be correctly supported and the site's electrical protection system will still function correctly, without the two 'dissimilar' generators having their star points interconnected.

It follows that if the site loads single phase equipment can be supported by the fully rated neutral of just one generator then don't interconnect more neutrals together if this is likely to promote unnecessary circulating currents around the neutral conductor system. However it must be remembered that if the generator that is intended to supply neutral current is off-line for any reason, no single phase loads can be supported and if these are connected, the system line-neutral voltages may become severely unbalanced. Consideration should be given to a changeover arrangement to allow other machines to become source for line-neutral current in the event of maintenance being required.

However, if the scheme's protection philosophy is such that all star points must be interconnected, then 5/6th generators need neutral reactors and then measurements have to be made as to the extent of the circulating currents to ensure that the generator stator windings are not overloaded and that the site distribution systems neutral cables are rated accordingly. Once generators have to supply real load (active and reactive) the degree of circulating current changes (reduces).

Many generators of 2/3rd, or 5/6th pitch, are used for embedded/co-generation applications with local mains/utility systems. In most cases such generators do not have their star points interconnected to the mains neutral or earth connection. In such an application the pitch factor is not an important issue. Also methods to restrict the circulating current in the common neutral may be implemented in case of dissimilar pitched generators are parallel together. Standard reactors may be used for this purpose however consideration must be given to the single phase fault level in the system.

When dealing with generators operating in parallel with a mains supply, then understand the protection philosophy of the mains network and ensure that the bonding of any generator star points to earth will not provide a parallel path for fault current outside the protections systems monitored fault-path.

VII. Star Points Connection and Equipotential Bonding

It is important to understand the differences between neutral star point reference earthing and equipotential bonding. The latter applies no matter what the winding pitch or neutral configuration and is an electrical safety consideration. The former is an electrical system design function that may have safety implications if not performed correctly. In addition, when generator neutrals are grounded it is important that neutral current is not allowed to circulate in the ground path as this may cause telecommunication systems issues as well as creating standing voltages in the ground.

There are many configurations of the neutral star point connection to earth. Figure 4 highlights some of these methods. The method of star point connection to earth depends on type of applications, voltage level and generator winding pitch.

For paralleling generators with similar winding pitch, their star neutral points can be interconnected. Depending on their winding pitch and voltage level, their star may be connected to earth directly or via current limiting impedance (reactor). Figures 5 to 7 illustrate some of the neutral and earth connection methods of parallel generators.

In some applications, an unreferenced system is employed and the generator neutral points are not connected together. In this case, there will be no path for the circulating current to flow. Also there will be no path for single phase fault currents so ground fault detection system must be utilised for such installations as stated in the requirements of the electrical code. Figure 5 shows three wire system with ungrounded neutral.

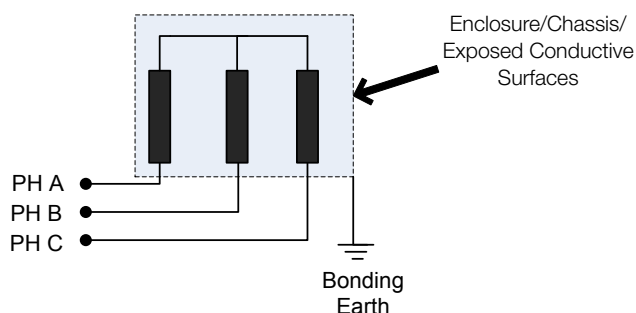


Figure 4a: No star point connection
(there is always a reference earth point connection)

There should only be minimal circulating currents between generators when their star points be connected together regardless of their applications, voltage level and winding pitch. Connecting generators with similar winding pitch will limit the circulating current. Connecting generators with similar pitch is not always possible especially when expanding a site that has existing older generators. Adding a reactor in the common neutral limits the circulating current. The neutral circulating current can be attenuated by implementing current limiting impedance (reactor) as shown in Figure 6.

Neutral current limiting reactor would also substantially reduce the single phase fault level in the system. A fault level that is too low can be a serious safety concern since it can prevent over current protection from operating and lead to serious damages and fire hazards.

Figure 7 shows that a multi winding reactor can be used to reduce the neutral circuiting current and also to provide a path for the single phase fault current.

This should not be confused with neutral earthing resistors where generator neutrals are normally connected together (with or without attenuating reactors) and the common point is grounded via a resistor with the purpose of attenuating ground fault current. Not often is each generator individually grounded through impedance to earth as this set up too many parallel paths and so difficult to get circuit breakers to trip.

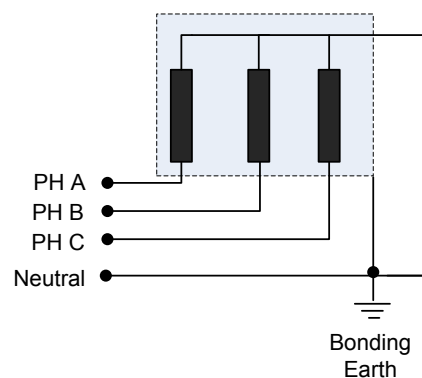


Figure 4b: Solid star point connection
(unrestricted fault current)

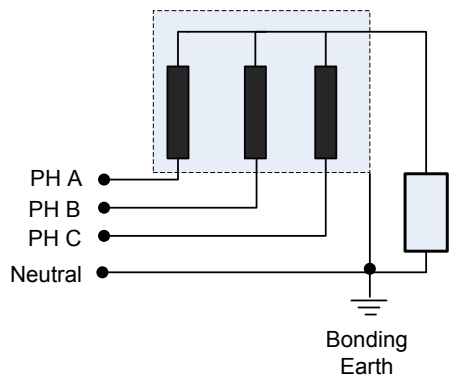


Figure 4c: Star point connection via impedance (restricted fault current)

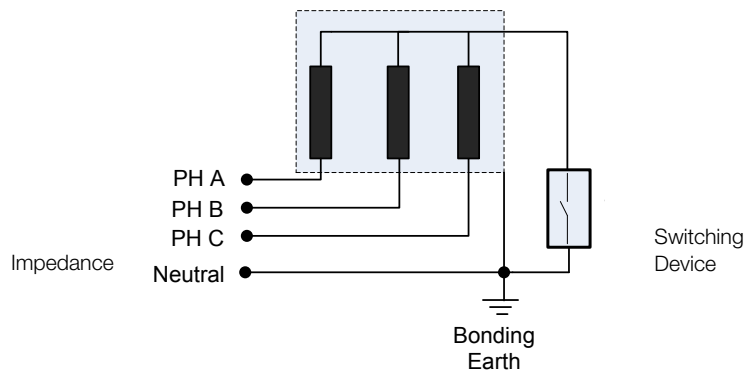


Figure 4d: Neutral star point connection via switching device

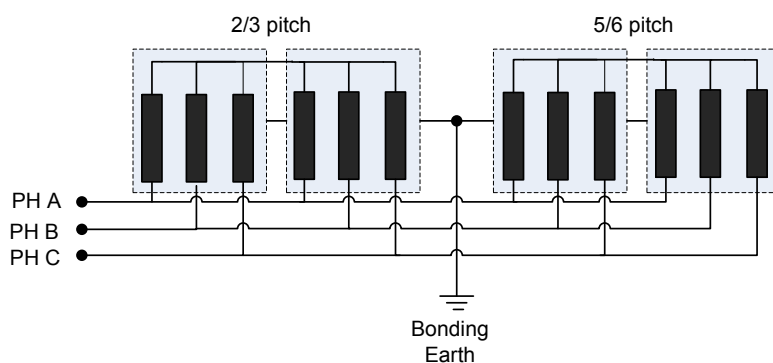


Figure 5: Neutral connection of similar and dissimilar winding pitch generators (no connection between dissimilar pitch generators, neutral not connected to earth)

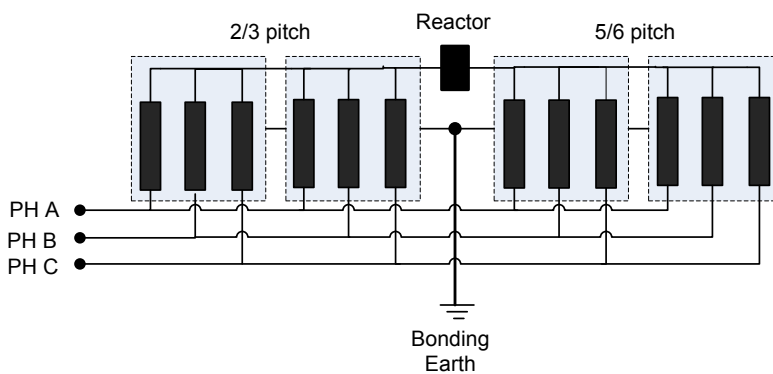


Figure 6: Neutral connection of similar and dissimilar winding pitch generators (connection via inductive reactor of dissimilar pitch generators, neutral not connected to earth)

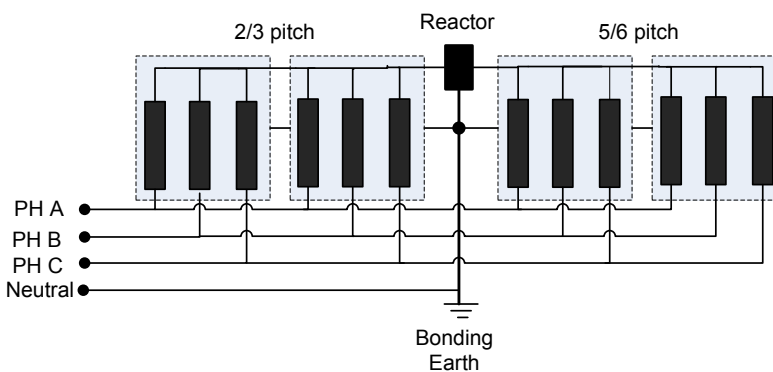


Figure 7: Neutral connection of similar and dissimilar winding pitch generators (connection via multi core reactor of dissimilar pitch generators)

Conclusion

The winding pitch of AC generators has influence on the shape of waveform (harmonic contents) and on the level of the fundamental voltage.

2/3rd winding pitch is mainly used with three-phase four wire low voltage generators due to the fact that the load is directly connected to the generator without a transformer and most likely that single phase and non-linear loads are present.

5/6th winding pitch machines are more suitable for three-phase three wire MV and HV systems as the load will not be directly connected and hence the triplen harmonics are not present as third harmonics will sum to zero in the line to line voltages. 5/6th pitch is suitable for application where the neutral point is not connected to earth solidly. Directly connected single phase loads are not present in most MV or HV systems.

5/6th winding pitch reduces the quantity of active materials and it is a smart way to increase the fundamental generated voltage within stator. Historically 5/6th pitch was preferred with NLLs to reduce the harmonics in the load currents. However recent developments in IGBT technologies have negated the need for 5/6th with NLL as harmonics occur at much higher frequencies.

The 2/3 pitch winding does have a low zero sequence reactance and while at low voltage, the advantages associated with distributed neutral outweigh the disadvantages, at MV/HV this is not the case and the low reactance causes higher than necessary ground fault currents which cause greater stress on machine windings, cables and load components.

The fact that a 2/3rd pitch generator has a low pitch factor for the triplen harmonics 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. Circulating currents can result with any winding pitch.

Usually MV and HV generators are connected to delta/star transformers and this is an important advantage of the 5/6th winding pitch for MV and HV machines as the transformer will act as barrier for the triplen harmonics.

Paralleling generators with different winding pitch will require careful consideration if interconnecting star points of all running generators should be necessary. Circulating 3rd harmonic current in the system neutral cables must be considered at project outset, and steps taken to control.

Both the 2/3rd and 5/6th winding pitch have benefits. Correct selection for the proposed application is the key for ensuring a cost effective power supply scheme.

Appendix

$$\begin{aligned} K_p (\text{winding pitch}) &= \sin (VP/2) \\ &= 0.866 \text{ for } 2/3 \\ &= 0.966 \text{ for } 5/6 \text{ for fundamental frequency.} \end{aligned}$$

Where:

V is Harmonic, 1, 3, 5, 7, ...

P is Angle, for 2/3 = 120, 5/6 = 150

Footnote

- [1] IGBT: Insulated Gate Bipolar Transistor
- [2] Cummins Generator Technologies designation for MV is 1kV up to 4.16kV
- [3] Cummins Generator Technologies designation for HV is 6kV up to 15kV
- [4] We do understand that in electrical power distribution, the term medium voltage (MV) covers the range from 1kV up to 62kV (in some areas up to 72.5kV).



Cummins Generator Technologies Ltd
Barnack Road, Stamford
Lincolnshire, PE9 2NB, UK

Tel: +44 (0) 1780 484000
Fax: +44 (0) 1780 484100
email: info@cumminsgeneratortechnologies.com

www.cumminsgeneratortechnologies.com

Copyright © 2013 Cummins Generator Technologies. All rights reserved.
Cummins and the Cummins logo are registered trade marks of Cummins Inc.
STAMFORD and AvK are registered trade marks of Cummins Generator Technologies Ltd.
WP_PIT_S_EN_GS_01