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Considerations when Paralleling Generating Sets

White Paper

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Applications where several generating sets are paralleled together are quite common today. Either to supply electrical power to a facility in island mode or paralleled together with the Utility in an infinite bus topology.

Standby generators are frequently paralleled together to protect critical applications such as hospitals or data centres in the event of a failure from the Utility. In other situations they are used for periodic emergency support to directly back-up the national electricity network. Then there is the scenario where a Utility supply is not even available and paralleled groups provide the only source of reliable energy to a specific site. The configurations are immense.

Whatever the application, paralleling is a fundamental concept in power generation and invariably introduces specific challenges that must be overcome.

Paralleling Considerations

This document looks at the various ways in which groups of similar or dissimilar generating sets can safely electrically synchronize together as a Power Plant.

There are many different forms in which these generators could be electrically connected. For the design engineer the watch-out is how will their installation stand up to the test of time?

Over the next few pages various methods of Synchronising, Paralleling and Load Sharing are discussed with a focus on equipment capabilities and how robust are the options.

The advice provided here, a technical precis of Power Topics #9015, #9016, #9017 and T-016 is based on European Norms aimed at questions raised when paralleling both Low Voltage and Medium Voltage generator sets.

If the reader's specific interest is for medium or high voltage paralleling applications, it is suggested additional advice should be solicited regarding the system earthing.

Contents

1. Generator Size Compatibility

Not all installations will have the same sized generating sets. Some dissimilar size generator considerations are:

- An emergency system with generator sets that have matching kW ratings can support a higher first priority load than a system that has generator sets with dissimilar kW ratings. For example, an emergency system with two 1000 kW generator sets will handle a first priority load as large as 1000 kW. A system with one 1500 kW generator set and one 500 kW generator set, while having the same total power rating should be limited to a 500 kW first priority load. This is because if the first generator set closing to the bus is the 500 kW machine, any load greater than 500 kW could cause it to be overloaded.
- From a load shed perspective with dissimilar-sized machines, it is desirable to drop load in large enough steps to relieve the 500 kW set in the event that the 1000 kW unit becomes the unit that is not available. In general, a manageable system is when the smallest generator set is no less than 30% of the capacity of the largest generator set in the system.
- Generator sets must have a means to determine which generator set/s will close to the bus first in a “black start” (first start) situation.
- Some manufacturers are unable to provide equipment that is certain to parallel within 10 seconds. Generally speaking older larger engines are slower to start than their smaller counterparts. So in situations where emergency load is required within 10 or 15 seconds, the system design must prevent the smaller machines from closing to the bus first, or ensure that first priority loads can always be served by the smallest machine in the system.
- Generator sets may be monitored by either a site Building Management System (BMS), or by an external monitoring system, such as for service contract facilitation or external Power Management System (PMS). Control and status information should be compatible for this duty.

2. Generator Synchronising

To parallel generators, they must first be synchronised. Synchronising means that the output voltage waveform of one generator must match the output waveform of another source in terms of voltage, frequency and phase angle. A phase angle difference between the two waveforms creates a difference in potential between the two sources. The potential difference should be as small as possible within practical limits before closing the paralleling circuit breaker.

It is imperative that at the instant of closing the paralleling Circuit Breaker, the transient current surge experienced by the in-going generator does not exceed 50% of that generators rated current. Achieving this critical requirement will limit the forced levels of synchronising alignment torques experienced throughout the generating set.

There are two forms of synchronising:

2.1 Slip Frequency Synchronising

In a slip frequency application, a synchroniser normally is used to match the voltage of the incoming generator set to that of the busbar and the frequency of the incoming generator is set to a fixed difference to that of the busbar. The different frequencies permit a moment of minimal phase angle and therefore potential difference between sources.

Figure 1 below illustrates phase angle difference between sources. Notice that when synchronised (indicated by the green OK TO CLOSE region), the phase angle difference and therefore the voltage across the synchronising circuit breaker is near zero.

When the sources are out of synchronism, the phase angle difference is large and therefore the voltage across the synchronising circuit breaker is large. If an attempt is made to close the circuit breaker in this condition, the low impedances in the circuit means that very large and potentially damaging currents would flow. In a slip frequency application there will be alternating moments of being in phase (synchronism) and being out of phase.

2.2 Phase Lock Active Synchronising

Figure 2 (page 4) illustrates the Phase Lock loop (Phase Match) method of synchronising. Notice that while there is initially a large phase angle difference between waveforms, the difference is reduced and maintained. This allows for a sustained period of synchronism.

This particular design of synchroniser by controlling voltage, frequency and phase angle, makes this mode of operation possible. The synchroniser analyses the generator output voltage and makes corrections to the engine speed (via the governor) and controls the AVR to adjust voltage amplitude and phase angle to achieve sustained synchronism.

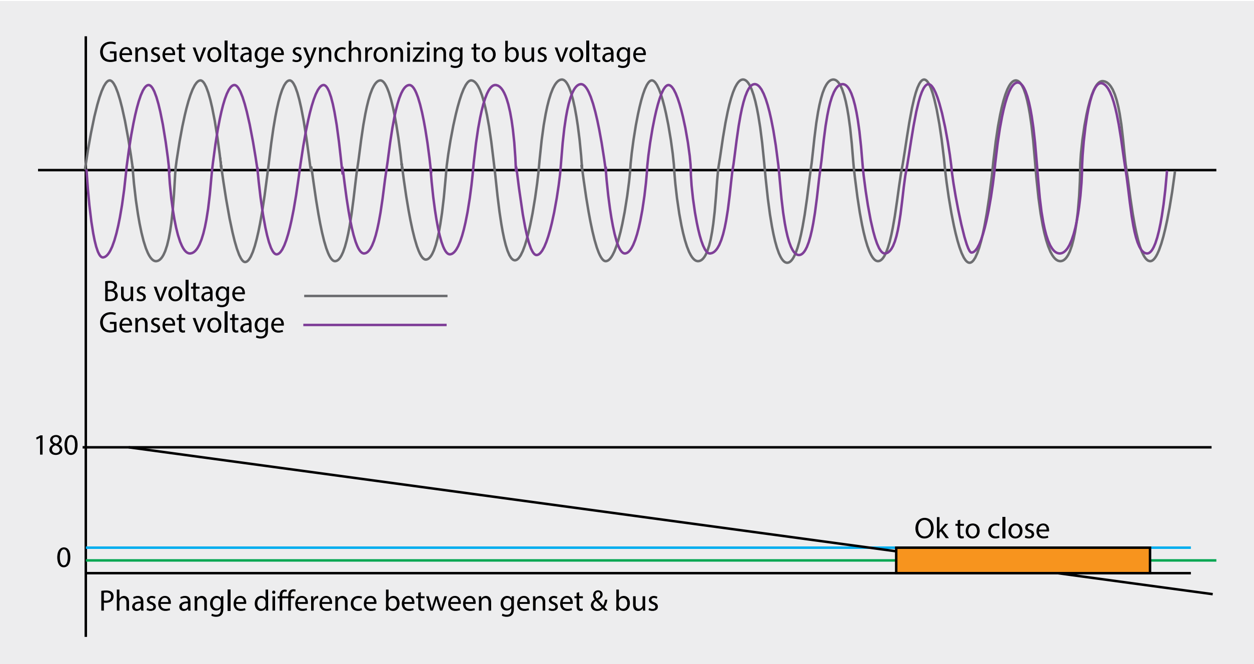

Figure 1 - Phase Angle difference when Slip Frequency synchronising.

The synchroniser becomes active when the paralleling bus is energised and the generator is running. Power Command 3.3 controllers have a synchroniser enable setting that must be true (on) as well. Most paralleling systems today will use Phase Lock (active) synchronising.

2.3 Limits to Synchronising Zone Parameters

With either system outlined above, there are limits to the 'OK to Close' zone parameters. If this window is incorrectly set then the generator set will be exposed to "Rough Synchronising" – a synchronisation event where there is excessive voltage across the synchronising circuit breaker contacts, which is damaging to both the alternator and engine. To avoid long term progressive damage to the equipment it is suggested as a worst case, transient current is limited to 50% of the alternator Full Load Current (FLC).

To achieve a transient current level of less than 50% at the moment of closure of the synchronising circuit breaker, it is necessary to reduce the level of voltage miss-match and ensure the slip frequency is below 0.1Hz/s and that the closing of the circuit breaker occurs within acceptable closing phase angle alignment limits. It is suggested that the following parameters should be ideally set...

1.	Frequency must match within	0.1 Hz.
2.	Rate of change of frequency	0.1 Hz/sec.
3.	Voltages must match within	< 1%
4.	Maximum phase angle within	< 10%

When slip synchronising, the engine speed should always be faster than the utility frequency so power will flow from the generator to Utility when paralleled together. In all cases the incoming generating set voltage should be set equal to or higher than the busbar voltage to ensure an export of kVAr (lagging power factor) from the generator. A generator voltage that is lower than busbar voltage will reduce the magnetic field strength of the field and may result in the generator becoming unstable when paralleled.

3. Picking the First Generator to Close to the Bus

There are two distinct systems for First Start generator systems.

3.1 Random Access Paralleling System

With Random Access paralleling systems, all generator sets receive a start command at the same time and independently build up their voltage and speed to rated values at which point they are

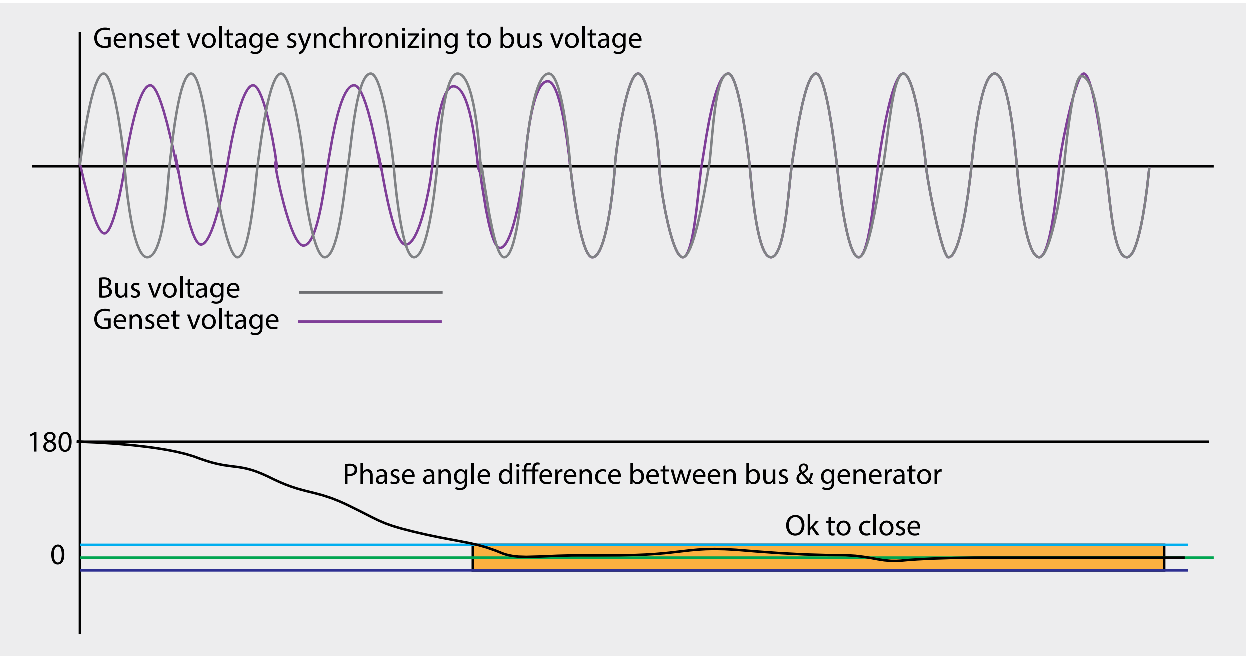

Figure 2 - Phase Angle difference with Phase Lock synchronising.

ready to close to the paralleling bus. The generator sets will not be in synchronism with each other so the generator set controls must have some kind of arbitration scheme allowing only one generator set to close to the dead bus. A dead bus sensor on the common bus prevents out-of-phase paralleling when one generator wins the arbitration.

Cummins Power Command Controls (PCC) use a scheme called First Start (Sensor) to determine whether or not to close the generator paralleling breaker on to a dead bus in paralleling applications. First start is based on the "first start arbitration". The PCC joins first start arbitration when first start conditions are met. The winner of the arbitration gets permission to close to the dead bus. All other generators in the system must then wait for the bus to become energised and then synchronise to it.

The PCC has a number of conditions that must be met before first start becomes enabled:

- The paralleling bus must be de-energised.
- The PCC must be in Automatic mode.
- The control must not have any shutdown faults present.
- The unit must be in a Ready to Load (90% voltage and frequency) state.
- There must not be Inhibit signals present.

If these conditions are met, generators will arbitrate through the first start communication lines. Each generator tries to send a series of random bursts (1 - 8ms each) through this connection for 800ms. If a generator control detects a burst from another generator during that time, the burst stops, waits for 2.5 seconds and starts over. Otherwise, after 800ms, the control turns on the first start connection (a breaker inhibit signal), to prevent other generators from getting permission to close. The control then closes the breaker to the dead bus. At this point the other generating sets recognise the bus is now live and they synchronise and close to the bus according to the type of synchronising method chosen.

3.2 Dead Bus Paralleling System

With the Dead Bus paralleling system, all generator sets start simultaneously with their paralleling breakers closed to the bus and excitation circuits disabled. This allows generator sets to be connected in parallel without being in sync because no voltage is being generated.

As engines reach a pre-set speed, the generator set controls turn on and ramp up excitation levels. This causes the voltage on the bus to build up and forces the generator sets to come into sync with each other.

There is a variation of this method known as **Dead Field** paralleling in which the generator sets start with the paralleling breakers open and then close them as the engine starter disengages. "Exciter paralleling", "run up synchronization" and "close before excitation" are other terms that describe this same basic paralleling algorithm.

However, a stationary alternator connected to the bus is effectively a short circuit potentially compromising the entire system. A means of detection is required to disconnect the alternator. This method of paralleling is not considered by Cummins to be as robust and reliable as Random Access paralleling and therefore not supported by PowerCommand controls.

The standard Cummins PowerCommand controls currently require the addition of a third party module to support this method of paralleling.

3.3 Paralleling System Comparison

There are Pros and Cons with each system.

As Dead Bus or Dead Field Paralleling have no need for arbitration or synchronising of multiple generator sets, dead bus paralleling can bring a paralleling bus to rated speed and voltage relatively quickly.

Additionally, it provides the capability of magnetising a system that has a number of transformers with big inrush currents and reduces great stresses on the alternator from large transformers during start-up.

However, this system is considered a less robust method of paralleling as each generator set represents a single point of failure. A control or excitation system fault on any generator set can compromise the entire system without sensing device to detect if a set is “lazy” in starting or has failed and remove it by declaring it “failed” and opening its breaker.

The overwhelming majority of paralleled generating sets in operation today use Random Access Paralleling to synchronise and connect to a paralleling bus. The single most important point in favour of random access being system reliability and ability to consistently provide emergency power. Even if a single generator set fails or is slow to come up to speed, the rest of the generator sets are not in any way affected and the electrical system is not compromised in anyway.

For detailed correspondence on Random Access vs Dead Bus Paralleling please refer to Cummins White Paper #GLPT-6174-EN

4. Compatible Engines

Real power (kW) provided by a generator set operating in parallel with others is a direct function of engine real power output.

- Compatible engines share load nearly equally at all load levels whilst operating at steady state load levels and during transient loading conditions.
- If incompatible engines are paralleled, load sharing problems may occur, particularly on application or rejection of large load steps.

As loads are added to a generator set, particularly in large increments, frequency will momentarily drop until the engine governor can drive more fuel into the engine to recover back to its nominal speed (frequency). The amount of speed drop and recovery time are a function of:

- Inertia in the rotating components
- How fast the governing and air intake systems can increase the fuel rate into the engine.

Active load sharing during transient conditions is dependent upon the dynamic response of the engines that are connected in parallel. Smaller engines tend to respond more quickly due to their lighter components – particularly turbochargers – and in the event of a large step load being applied to a system with unequally sized generating sets, a degree of unbalance may occur between sets. This should not be detrimental and will be rapidly equalised by the governing and load sharing system. Sets cannot be seriously overloaded, since the maximum load that can be contributed by any generating set is the fuel stop power.

Keep in mind that at lower load level changes, voltage and frequency transients are lower and recovery times will be shorter so transients may be very similar between the machines. This way dissimilar transient performance of the machines can be dealt with by adding and shedding loads in smaller steps.

In general terms, compatible engines are those with similar load sharing capabilities and similar transient performances, sufficient to meet the load demands. Care should be taken when considering paralleling generating sets with dissimilar control and governing systems as similarity assumptions may not be valid.

5. Load Sharing Factors

When a generator set is operating in a paralleled arrangement, the voltage and frequency outputs of the generator sets are forced to exactly the same values when they are connected to the same bus. Consequently, generator set control systems cannot simply monitor bus voltage and frequency as a reference for maintaining equal output levels, as they do when operated in isolation from one another.

If for example, one set operates at a higher excitation level than the other sets, the reactive load will not be shared equally – this will be demonstrated by the generators operating at different power factors and load currents. Similarly, if a generator set is regulated to a different speed settings than the others, even though its frequency will be the same as the others, it will not share kW load properly with other generator sets in the system. Each generator set in the system has two active control systems always in operation:

- Excitation control system regulating the voltage
- Fuel control system regulating the engine speed (kW).

Real power sharing (expressed as kW or unity power factor load) depends on speed setting and fuel rate control between the generator sets based on percentage of kW load. Reactive power (expressed as kVAr or zero power factor load) is primarily dependent upon voltage setting and excitation system control that is dependent on the percentage of kVAr load between the generator sets.

6. Compatible Load Sharing Control Systems

Generators can be sharing kW load and may have problems sharing their reactive power load (expressed as kVAr). With only a small increase of excitation on one set in a paralleled system, reactive load (kVAr) will increase and may not be equally shared with the other generator sets.

Reactive power is primarily dependent upon voltage matching and excitation system control between the generator sets and the means of VAr load sharing (reactive load sharing), is discussed below.

Although it is sometimes possible to integrate load share methods of different manufacturers, generator set governors and load sharing controls should ideally be of the same manufacturer to avoid conflicts in responsibility for proper system operation.

Several types of load sharing control are available:

- Droop governing and voltage regulation (reactive droop compensation)
- Isochronous kW load sharing
- Cross current compensation for VAr load sharing
- Isochronous Voltage VAr load sharing.

In general, these communication tasks are handled by commonly available communication practices such as analogue signals or by a digital communication load share line.

7. Compatible Alternators

Paralleled alternators are compatible if they can operate in parallel without having damaging or disruptive neutral currents flowing between them. The magnitude of neutral current flow related to the dissimilarity between paralleled sets depends upon the shape of their voltage waveforms.

Depending on the alternators temperature rise characteristics, age and insulating ratings, some neutral current flow between generator sets may not necessarily be damaging. However, keep in mind that a high neutral current could cause disruption in protective relay operation, particularly for ground fault sensing and may cause electromagnetic interference.

7.1 Mechanical Alternator Design Characteristics Driving Harmonics

Alternator designers can control the magnitude and orders of harmonics produced in an alternator by manipulation of several design factors, the most important of which is alternator pitch.

For paralleling applications, it is highly desirable to utilise 2/3 pitch designs because no third-order harmonics are created by the machine. Paralleling compatibility with utility (mains) sources or other 2/3 pitch machines is assured because there aren't any neutral currents related to third-order harmonics. The higher-order harmonics see relatively greater impedances due to higher frequencies and so are much less of a problem in terms of neutral current flow.

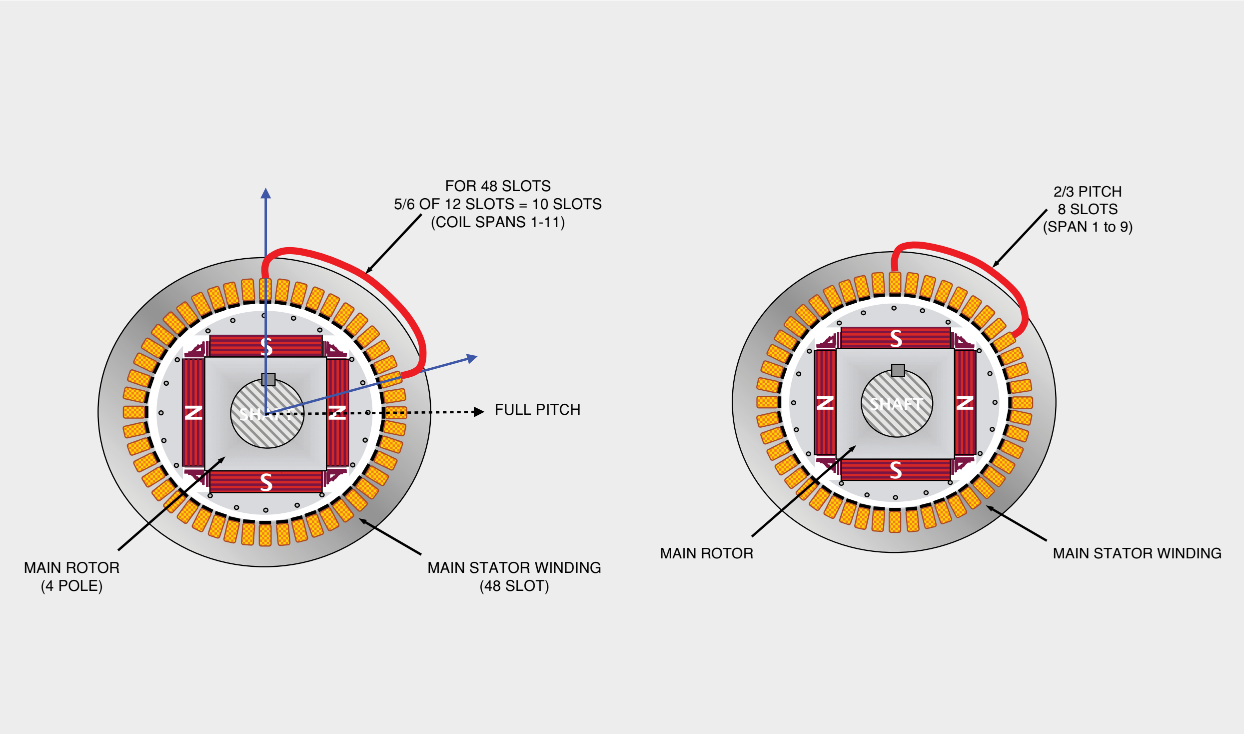

Figure 3 - Pitch in alternator design: 5/6 and 2/3.

Pitch is a term used to define a mechanical design characteristic of a generator. It is the ratio of the number of slots enclosed by each coil in the alternator stator to the number of winding slots per generator pole. In **Figure 3** (left half), which shows a 4 pole machine with 48 total slots, there will be 12 slots per pole, and since the coils span 10 slots, the alternator slot-to-coil ratio is 10/12, or “5/6 pitch”. In the right half of the illustration we see an alternator winding that spans 8 slots, so with 12 slots per pole, that machine would be 2/3 pitch. The pitch of a generator is a design parameter that can be used to optimise the generator waveform shape and minimise the generator cost. A shorter pitch (lower pitch ratio) uses the alternator stator less effectively and requires the use of more copper for the same kW output than higher pitch machines.

In general, odd-order harmonics (3rd, 5th, 7th, 9th etc.) are of greatest concern to system designers because they have the greatest impact on the operation of loads and on extraneous heating effects in the power supply and distribution system. Third-order harmonics (and their multiples) are problematical because they directly add in the neutral and can result in large neutral current flows between paralleled machines. They are also more problematic because they can migrate through the system across some transformer types. Fifth-order harmonics (and their multiples) are considered to be a concern because they are “negative sequence” currents, and will cause some level of abnormal heating in rotating load devices. However, with careful design of a 2/3 pitch machine, the fifth and seventh-order harmonics can be reduced to magnitudes of a level similar to higher pitch machines.

A good standard to achieve for machines ranging in size from roughly 100 kW to 4MW is that the machine should have not more than 5% Total Harmonic Distortion at any load between no load and full load, measured line to line and line to neutral, and not more than 3.0% in any single phase.

7.2. Circulating Neutral Currents due to Alternator Pitch Differences

Section applicable to Low Voltage, 3 phase, 4 wire, generator sets.

When generators are paralleled, the voltages of the two machines are locked to the exact same magnitude through a low impedance coupling.

Small differences in voltage, will result in relatively large current flow from the machine with higher instantaneous voltage to the machine(s) with lower instantaneous voltage. **Figure 4** illustrates this phenomenon.

In **Figure 4**, 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.

The magnitude of the current shown is exaggerated to more clearly illustrate the phenomenon. As the blue and red voltage lines cross each other three times in each half cycle, the current magnitude generated is a third-order harmonic current.

So, at any point in the cycle where there is a voltage difference between the machines prior to paralleling, current will then flow between the machines once paralleled. 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.

In general, circulating currents flowing between machines due to line voltage differences (e.g. differences in voltage setting) appear as line current only and can be reduced or eliminated by adjusting

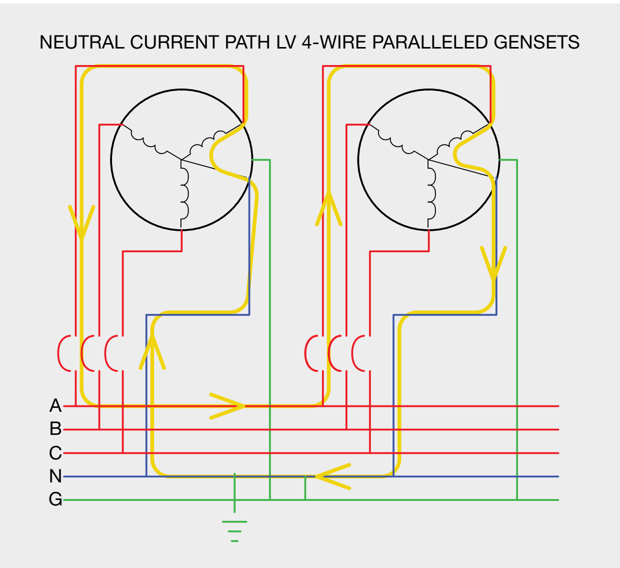

Figure 5 - Four Wire System.

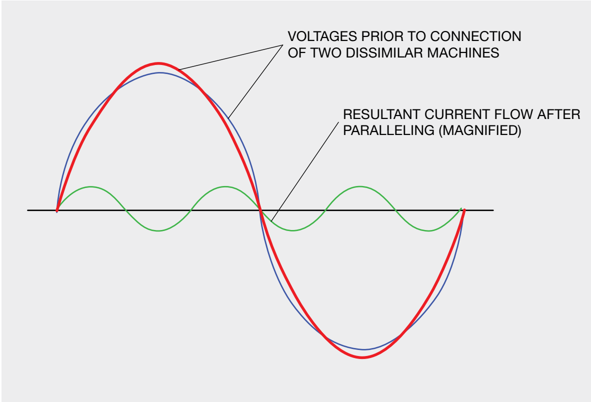

Figure 4 - Voltages before and after paralleling.

the voltage settings. Current appearing in the neutral conductor is unlikely to be due to differences in voltage settings.

In most low voltage electrical systems (below 1000 V), the neutral conductor is distributed throughout the system to allow single phase load connection and it is common practice to provide low voltage alternators with 2/3 pitched windings that will allow directly connected neutral conductors as in **figure 5** below. Higher voltage systems do not normally have distributed neutral conductors and 2/3 pitched windings are uncommon on these machines, which are often 5/6 pitched. Care must therefore be taken when considering the connection of the neutral conductors on these machines, which will vary with application – consult the machine manufacturer for advice.

If this current flow cannot be adjusted out by kVAr load sharing, a harmonic analysis test of the neutral current flow between the machines when operating with balanced linear load (or even no load) can be conducted.

This will be clearly seen with proper measuring devices but is often visible with conventional AC current metering. The system will be most apparent by displaying current flowing from each generator with no load on the system.

If the fundamental frequency of the current is the same as the system operating frequency, the current flow is a result of inaccurate kVAr load sharing or the application of single phase loads. However, if neutral current is flowing at higher than 60Hz (particularly 150Hz in a 50Hz system and 180Hz in a 60Hz system) with no load or a linear load applied to the system, then this is almost certainly due to alternator incompatibility.

7.3 In Summary - Compensating for Pitch Differences

When paralleling dissimilar generator sets, there is possibility these generator set may have incompatible alternators.

1. Should a circulating current be found in the neutral path, if this is not accompanied by circulating line current and cannot be eliminated by manipulation of voltage setting or crosscurrent compensation (droop circuit kit or other devices), then it can be assumed to be a condition caused by the differences in alternator pitch.
2. As 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. However, 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 be highest and most susceptible to failure.
3. Keep in mind this circulating current may or may not be damaging to the alternators especially if the generator is operating at low load, or if the alternator has been purposely oversized. Depending on the magnitude, this may cause:
    - Heating in the neutral conductors, or neutral earthing resistors (if fitted)
    - Nuisance tripping to other protective devices in the system
    - Disturbance to equipment that is sensitive to harmonic currents.
4. 2/3 pitch is not required for successful parallel operation of generators. Other pitches may be used (and used in conjunction with 2/3 pitch machines), but their use may limit future system expansion flexibility, or require other system measures to limit neutral current flow.

8. Load Sharing Methods

8.1 Droop Load Sharing

Droop governing and voltage regulation systems have been historically used for isolated bus paralleling for many years. This allows load sharing between any two or more compatible generators operating on an isolated bus as long as the generators can be set up to identical droop frequency and voltage at the same rate. Importantly the generators can then also be controlled to within stable frequency and voltage values.

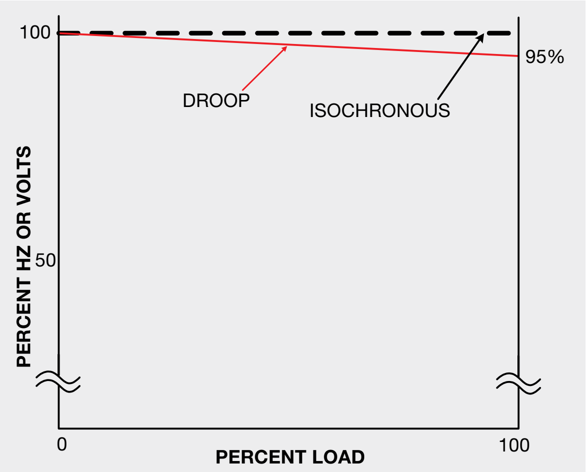

Figure 6 - Droop governing.

Droop governing or voltage regulation allows the engine speed (measured in Hz) or alternator voltage to decline by a predetermined percentage (typically 3%) as the load increases. Identical speed and voltage drops result in equal load sharing between paralleled generator sets.

The same practices can also be applied to the voltage regulation system. VAr load sharing via droop is often called VAr droop compensation.

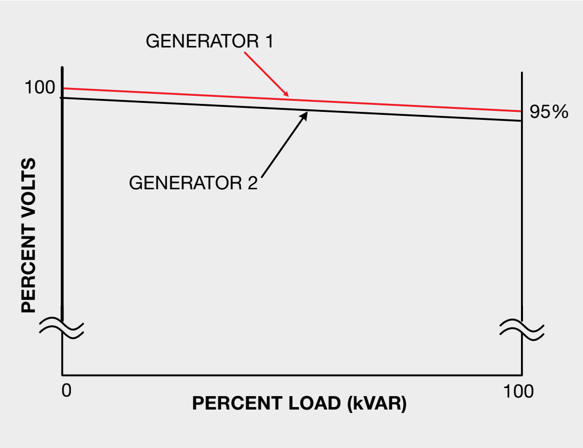

Figure 7 - Generators droop at the same rate but start at dissimilar voltages. Generator 1 always carries more load than Generator 2. At no load Generator 2 experiences reverse kVAR.

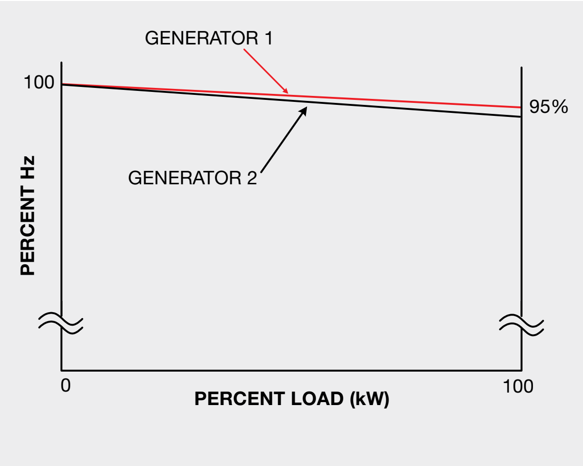

Figure 8 - Generators start at same no load frequency but have different droop rates. Generator 1 always carries more load than Generator 2.

Common droop settings for frequency and voltage can be different, typically in the range of 3% to 5% from no load to full load. The voltage variations that occur due to droop operation at this level are not significant in isolated bus systems, but because the torque curves at different load levels on dissimilar engines may vary, the frequency variations that occur with droop control can be disruptive to the operation of some loads. The major disadvantage being that this system will require attended control to maintain busbar frequency, especially where the load can vary considerably over time unless an additional supervisory system is fitted.

For a droop system to function correctly, the following conditions need to exist:

- The generators must have the same no load frequency and voltage when they are disconnected from the bus.
- Each generator must be set to drop voltage at the same rate from no load to full load.
- Each engine must be set to drop frequency at the same rate from no load to full load.

It is worth noting that frequency droop and voltage droop do not need to be the same percentage.

Droop can be calculated as follows:

Frequency (Hz) droop: $(100)[(Hz_{NL}-Hz_{FL}) / Hz_{FL}]$

Voltage (V) droop: $(100)[(V_{NL}-V_{FL}) / V_{FL}]$

NL = no load

FL = full load

Figure 7 illustrates the impact of incorrect no load voltage settings. Generator 1 always carries more load than Generator 2. Generator 2 experiences reverse kVAr at no load.

Figure 8 shows the impact of dissimilar droop settings.

Note that systems always require both kW and kVAr load sharing, but they do not both need to be the same type of system. One can be isochronous and the other can be droop. VAR load sharing via droop is often termed “reactive droop compensation”.

The major advantage in using droop paralleling is that it allowed dissimilar machines to be paralleled without concern for their load sharing interface. The voltage variations that occur due to droop operation are not significant in isolated bus systems, but the frequency variations that occur due to droop operation can be significant, especially in emergency/standby systems where the load can vary considerably over time. Common droop selections for frequency and voltage can be different and are typically in the range of 3–5% from no load to full load.

Droop governing is generally used for generator loading control in single generator set-to-utility paralleling systems, because the utility frequency is usually very constant. However, reactive droop is not effective for utility paralleling due to the greatly varying voltage level at any point in a utility distribution system as the load on the system changes.

VAr/power factor controllers should be used when generators are paralleled to a utility source (or other infinity source) as the voltage and frequency outputs of connected generator sets are then locked to the same values once connected to the utility.

8.2 Isochronous kW and kVAr Load Sharing

Today most Isochronous systems (operating without droop), are protected with a built-in pre-configured Droop Backup in case the "daisy chain" of load share lines between synchronised generators is cut. Whilst the site loses the accuracy of isochronous load sharing if there were to be damage to the load share line, the system can still continue in an emergency using the backup Droop mode.

Isochronous load sharing controls are active systems calculating the percentage of real and reactive load on a specific generator set and then compare this value to the percentage of real and reactive load on the system.

Individual generating set controllers manages both the fuel and excitation to drive the same percentage of kW and VAr load on the generator to the same value as the percentage of real and reactive load on the system. Each controller is then connected with a load sharing communication line.

Several approaches are available in the marketplace to provide this interface. As indicated previously this load share line is usually a simple twisted pair of copper wires (one pair kW and one pair kVAr) connected in a 'daisy chain' to all the other connected generator set controllers and is the only point where generator controls interact with each other when operating on an isolated bus.

Historically every supplier had different communication protocols making it difficult to add dissimilar equipment to an existing system. However, in the current build of integrated paralleling controls (those that provide all the paralleling functions on a single card), almost all use proprietary digital communication/control-based load sharing equipment which has a common load sharing interface (speed bias to governor control and voltage bias to the AVR). This now makes the controls easier to interface with nearly any generator set. In some cases load sharing interface module (gateway) are available for use with digital communication load sharing equipment. A designer will need to clearly identify the responsibility for performance of the system if the proposed gateway is not fully functional or be prepared for more dramatic system changes if the load sharing gateway performance is not acceptable.

8.3 Cross Current Compensation (Droop Circuit CT)

Cross current is the flow of current between generator sets caused by dissimilar excitation levels in those sets. Cross current compensation describes the operation of paralleled generator sets without intentional voltage droop. This is achieved by insertion of a droop current transformer (Qty1 CT), usually on "B" phase of each generator. These individual generator set CT's are then interconnected to provide an identical voltage bias to each AVR in the system.

The system works best when the voltage regulators are all of the same manufacturer and model. Not all voltage regulators work together in this mode, so best planning practice is to ensure all voltage regulators in a system using cross current compensation are all identical.

Using cross current compensation results in no intentional droop in voltage from no load to full load on the system. Therefore it is considered to be superior to a reactive droop compensation system, from a performance perspective.

8.4 Using Different Operating Modes for Load Sharing

The availability of single board paralleling controllers for upgrade of existing equipment has led to a whole range of possible variations in how generator sets can be added to existing systems, and how paralleling control upgrades can be accomplished.

When trying to interface dissimilar load sharing equipment from different suppliers, it is also possible to configure the system so that some of the generator sets in the system operate at a base load level, and others operate in a load share state.

The base load machines operate at a constant output, while the generators operating in isochronous load sharing mode will "float" with the balance of the available load. Occasionally the total load on the base-load machines will be manipulated by a Programmable Logic Controller (PLC). This system is viable when there are no sudden large load changes in a system, however great care must be taken when considering such a system, to take account of potential failure modes and to ensure that all combinations of generating sets are viable.

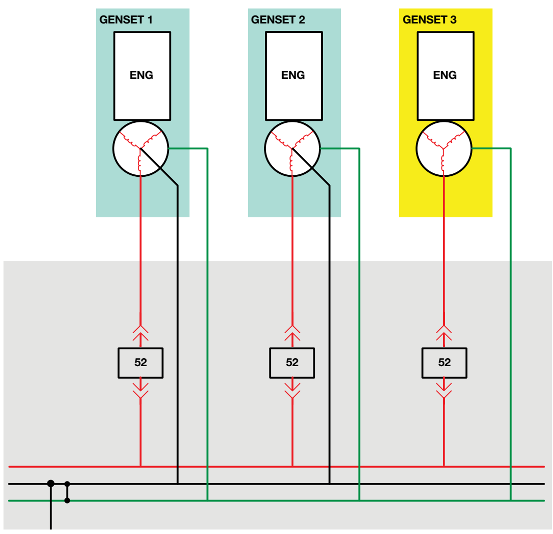

Figure 9 - System with two identical generator sets (G1 & G2), and one dissimilar due to pitch difference. The illustration shows the neutral not connected on generator G3.

Typically this arrangement could be used for example in a three generator set installation where G1 & G2 are 2/3 pitched and G3 is 5/6 pitched. This would save the cost of neutral grounding switchgear. You should also note that G3 would only provide contribution to Line-Line connected loads – it would make no contribution to single-phase loads. If there were to be significant imbalance in the system, the negative sequence limit would need to be calculated on the basis of G1 and G2, instead of all three. Note also that G3 will also make no contribution to earth faults – this can be useful in limiting earth fault levels.

Figure 9 illustrates a situation where for example, three 1000 kW generators sets are connected together in a system, with one machine dissimilar to the other two.

Points regarding this illustration:

1. It should be noted that in Europe and some other regions, disconnected Neutrals are not always permitted on publically distributed generator networks. Checks should be made first for local Code compliance. It is likely that this proposed illustration would only apply to an isolated power plant or some Grid Capacity support generator set.
2. Generator G3 must never operate on its own as there would not be a defined earth (Ground) path.
3. If generator G3 is ever operating in parallel with only one other generator set, in the event of a shutdown fault occurred on the only grounded generator, both sets must immediately disconnect and shut down.
4. Likewise if Neutral Earth Contactors were to be used in this scenario (on LV generators), the contactors have to be treated with back-up protection. Failure of the designated contactor to close could cause dangerous system voltages should an earth fault occurs and provision should be made to detect this anomaly in the control and protection scheme.

In this example the system is an isolated bus arrangement, it's assumed the three 1000 kW generators share reactive load via droop. The kW load sharing could be accomplished as follows:

1. Generator G3 is set up so that it cannot be the first to start
2. It is not used unless at least one of the other generators is on the bus
3. It operates in droop for kW load sharing
4. With the other two machines operating at rated frequency, generator G3 is set to operate at a slightly lower speed that is sufficient to cause it to operate with say a 500 kW base load output when in parallel with either or both of the other machines.

Therefore as illustrated in **Figure 10**, with G1 and G2 already running and carrying system load, G3 is then synchronised and closed to the bus.

Generator G3 then assumes its pre-set load level and then operates at a fixed 500 kW base load output until it is disconnected from the bus.

In a similar fashion, load govern (grid-parallel) loading controls can sometimes be used to cause some of the machines in a system to operate at a fixed kW and/or kVAr load level, while the balance of the system operates isochronously and shares load proportionally. In cases where this is used and the load level on the system varies significantly, a PLC or other device may be used to vary the load level on the machine(s) in load govern state to prevent over- or under-loading of the machines operating in load share mode.

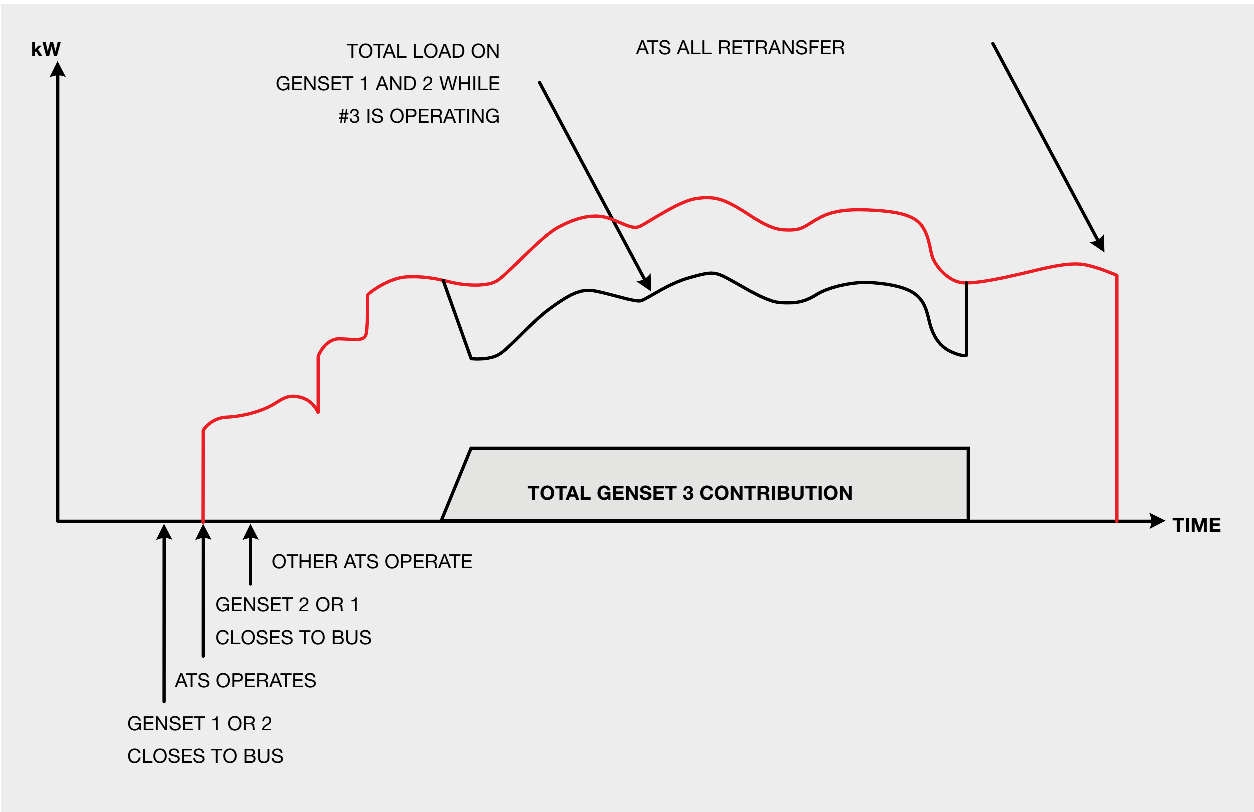

Figure 10 - G1 & G2 Load Share with G3 Pre-Set Base Load of 500 kW.

9. General Recommendations

9.1 Key Considerations

When paralleling dissimilar generator sets, a designer should take into account some key considerations as discussed in this paper:

- Transient current whilst synchronising should be limited to less than 50% of alternator full load current at the moment of coupling to avoid long term issues.
- Generators operating in parallel must have a means to share active and reactive applied system loads without being either overloaded or under loaded.
- Review the transient performance of all the generator sets in the system and verify that the load steps (particularly load rejection) of all the generator sets will not result in nuisance reverse power tripping.
- Verify if the pitch of all alternators is the same. Specify either 2/3 pitch or 5/6 pitch on all machines to avoid problems. Take mitigating steps if dissimilar alternators cannot be avoided. Unless 2/3 pitched alternators are used, ensure that if neutrals are intended to be interconnected, controls are used to prevent 3rd harmonic circulating currents.
- For emergency/standby applications, load sharing controls (both kW and kVAr) should all be of the same type and preferably of the same manufacturer and model.
- Droop control may be suitable for some prime power applications, utility paralleling and isolated bus kVAr load sharing. If droop control is used for utility paralleling applications, a system of voltage matching must be employed to ensure that the on-load generator set busbar voltage can be automatically elevated to the off-load utility voltage as otherwise, no-break transfer may be impossible.
- Load can also affect generator system voltage waveform quality. It is not uncommon to have very high levels of current distortion in an industrial load. The only way to compensate for this distortion is to provide relatively large alternators so overall total harmonic distortion of the voltage waveform with loads running on the generator set is not more than 10–15%.

9.2 Additional Reference Reading on this Subject

Cummins White Papers and Technical Manuals:

- White Paper #9015 – Paralleling Dissimilar Generators Part 1 – Gary Olson
- White Paper #9016 – Paralleling Dissimilar Generators Part 2 – Gary Olson
- White Paper #9017 – Paralleling Dissimilar Generators Part 3 – Gary Olson
- White Paper #5590 – Reliability considerations in simple Paralleling applications – Rich Scroggins
- White Paper #GLPT-6174-EN – Random Access vs Dead Bus Paralleling – Rich Scroggins
- White Paper #NAPT-5675-EN – NFPA110 Type 10 starting requirements – LaLiberte & Kaderbhai
- White Paper #6001 – Impact of leading power factor on synchronous alternators – Gary Olson
- White Paper #WP105 – AC Generators with 2/3 and 5/6 Winding Pitch – Chris Whitworth
- Technical Manual #T-016 – Paralleling Applications

About the author

Robert (Bob) Patrick is a Lead Project & Systems Application Engineer in the Sales Application Engineering Team that supports Distributors across Europe and Russia. Throughout the whole of his career Bob has gained extensive experience in both LV and MV Systems, Diesel Gensets, Synchronising Switchgear.

Prior to joining Cummins in 2001, he spent the previous 17 years in the Middle East and Africa working with both switchgear and generators. During this period Bob's role was project management, primarily installing new power plant and was directly responsible for the installation and handover of several large medium voltage turn-key projects, specifically in Saudi Arabia and Nigeria.

His first contact with the Power Generator industry was during his Electrical Technician apprenticeship. This also included a period working in the development laboratory plus on-site test and commissioning work of generators.

Bob is a certified 6 Sigma Green Belt and today this lifetime experience of the product is channelled into providing training and technical support to his colleagues across Europe.

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