Paralleling Dissimilar Generators: Part 1 – An Overview

■ **White Paper**

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As a general rule, "you can parallel anything with anything," as long as the voltage and frequency are the same at the point of interconnection. Of course, there are practical limits to this statement, and a design requiring reliability and performance may compel a system designer to replace existing generator sets when they can't be verified to be compatible with newer equipment, or if the costs of driving compatibility into the older equipment are not justified. This paper provides guidance on the issues that should be considered and how typical problems can be addressed.

Generator compatibility

Simply speaking, generator sets in a paralleling system are compatible when they have:

■ Compatible engines

■ Compatible alternators

■ Compatible load sharing control systems

■ Compatible interfaces to other monitoring and control systems, including local and remote monitoring, "first start" controls, manual controls, and load demand controls

To a limited degree, systems can operate successfully with less than completely compatible equipment, but these incompatibilities may result in the need for added equipment in the system or limitations in the flexibility or operation of the system. Before any modifications to any existing system are made, it is critical that the equipment to be modified is fully tested to verify that it can operate at full rated load with proper voltage and frequency control. If a machine can't perform properly with a dedicated load from a load bank, there is no way that it will operate successfully in parallel with other machines.

System-level issues

Before looking at generator set compatibility, it's worthwhile to consider several system-level problems that come about due to use of dissimilar generator sets.

If generator sets are of dissimilar sizes, there can be impacts on the system design. 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 500 kW generator sets will handle a first priority load as large as 500 kW. A system with one 750 kW generator set and one 250 kW generator set, while having the same total power rating, should be limited to a 250 kW first priority load, because if the first generator set closing to the bus is the 250 kW machine, any load greater than 250 kW could cause it to be overloaded.

When faced with the use of dissimilar-sized generator sets, some designers will insert bus isolation ties between generator sets in order to prevent overloading on startup. This, however, sets up another series of issues because of the added complexity in the sequence of operation and usually the need for more synchronizers in the system. Manual operation and failure mode effects are also more difficult to deal with as tiebreakers are inserted into a system.

Changes in sequence of operation may be necessary due to use of dissimiliar-sized machines. It is not advisable to design a system sequence of operation contingent on synchronizing generator sets within 10 seconds. Many manufacturers cannot provide equipment that is certain to be paralleled in 10 seconds, so in situations where local codes require service to emergency loads within 10 or 15 seconds, the system designer must choose between preventing smaller machines from closing to the bus first (minimizing the advantage of redundancy offered by many systems), or making sure that first priority loads can always be served by the smallest machine in the system.

From a load shed perspective, the problem is less difficult, but still needs a bit of thought. If there is an under-frequency condition on the bus, the system will need to drop load. With dissimilar-sized machines, it is desirable to drop load in large enough steps to relieve the 250 kW set in the event that the 500 kW unit becomes the unit that is not available. Cascading type load shedding systems continue to drop load until the system recovers, so they automatically deal with the problem via that mechanism. A system design that "knows" the kW capacity of the generator sets available on line can automatically compensate for the difference in sizes by using different sequencing when different combinations of equipment are available.

How much difference in size is "practical"? That is a matter of considerable discussion in the industry. We know that it's technically possible to parallel anything with anything, but where it's practical is less clear. In general, you probably will have a manageable system when the smallest generator set is no less than 30% of the capacity of the largest generator set in the system. If there is a larger disparity in equipment sizes, it might be easier to make the larger machine bigger, and forget about paralleling altogether.

It's useful to note that there are often large kW size differences in prime power applications, such as are used in remote, isolated cities and towns. In those applications, loads during the daylight hours are often much higher than in the evenings. A pair of 350 kW generator sets may be running during the day, and only a 50 kW set running at night. This is less of an issue in prime power applications because the load profile does not quickly change, and the systems generally have no automatic load management systems.

As a technical matter, the smallest power circuit breaker that we can provide is an 800 amp frame. So it can be costly to parallel smaller generator sets. In those cases it's possible to source 5-cycle operating molded case breakers for use in paralleling the generator. These breakers are smaller, available in fixed frame configurations so less space is needed for the equipment, and less expensive, but they are available only from a limited number of suppliers. In some cases motor starting contactors might be used for paralleling applications where smaller generator sets are used, but the contactors must generally be protected by current limiting fuses for a safe design.

Compatible engines

The real power (kW) provided by a generator set operating in parallel with others is a direct function of engine real power output. Compatible engines can share load nearly equally, at all load levels, while operating at steady state load levels and during transient loading conditions. Conversely, if incompatible engines are paralleled, load sharing problems can occur, particularly on application or rejection of large load steps.

As loads are added to a generator set, particularly in large increments, the generator set frequency will momentarily drop until the engine governor can drive more fuel into the engine to recover to its nominal speed (frequency). The amount of speed drop and the recovery time are a function of the inertia in the rotating components of the system and how fast the governing and air intake systems can increase the fuel rate in the engine. The generator set's recovery rate is determined by the type of governing system, the engine's fuel and air intake system designs, and the engine's combustion cycle (two-stroke or four-stroke).

Load sharing during transient conditions is a concern because differently sized machines often accept and reject load with different levels of ability. For example, consider a paralleled 250 kW and a 500 kW generator set. Application of a 250 kW load on a 250 kW generator set will result in a voltage dip of approximately 25%, and a recovery time of 3 seconds. For the 500 kW generator set, a 500 kW load results in a voltage dip of 30%, and a recovery time of 5 seconds. So if a 750 kW load (a full load step) is applied on the two machines, or drops 750 kW in one step from the two machines, they will not share loads equally during the transient period. It is possible to have the system exposed to potential overcurrent conditions on the faster machine or nuisance reverse power faults on load rejection.

At lower load levels, voltage and frequency transients are lower, and recovery times are shorter, so as load step size drops, it eventually gets to the point that transients of a specific level are very similar between machines. This means that dissimilar transient performance of the machines can be dealt with by adding and shedding loads in smaller steps than might be used in a system that has all the machines of the same size. A system designer can compare the single step load pickup and load rejection performance of the various machines in the system to determine if there is a potential problem with engine compatibility. When that is done, actual assembled generator set test data should be used in the evaluation, not just alternator voltage dip or engine (alone) transient performance. As a general rule, there will be no negative impacts due to difference in engine performance if the transient load steps are less than 25% of the rating of the smallest generator set in the system.

Nuisance reverse power trips on load rejection can often be addressed by increasing the time delay on reverse power to outside the recovery time for the slowest machine in the system. Do not address the issue by increasing the "Reverse Power" limit on the generator set. This could desensitize the system to the point that reverse power protection is lost.

Compatible alternators

Alternators are compatible if they can operate in parallel without damaging or disruptive neutral currents flowing between them. Depending on the generator set's temperature rise characteristics, age and insulating ratings, neutral current flow between generator sets is not necessarily damaging, but neutral currents can cause disruption in protective relay operation, particularly for ground fault sensing.

Neutral current flow between generators occurs when the voltage between the two machines is different. The voltage difference can occur because of inaccuracies in the kVAR load sharing adjustments, or because of differences in the voltage waveform shapes due to differences in alternator voltage harmonics as is illustrated in Figure 1.
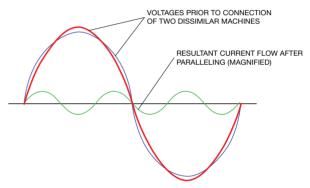

VOLTAGES PRIOR TO CONNECTION OF TWO DISSIMILAR MACHINES

RESULTANT CURRENT FLOW AFTER PARALLELING (MAGNIFIED)

Figure 1 - Whenever there is even an instant where the voltage between the two sources is different, current will flow between the machines.

If an operating system exhibits symptoms of incompatibility between alternators (such as current flow that can't 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. 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. If the fundamental frequency is 150 hertz or greater, the current flow is almost certainly due to alternator

incompatibility, and a decision is needed as to how to deal with it. Harmonic neutral current flow is caused by differences in the voltage waveform shape between two (or more) paralleled machines.

Alternator designers can control the harmonics produced in an alternator by manipulating several design factors, the most important of which is alternator pitch. The pitch of a generator set is a design parameter that can be used to optimize the generator set waveform shape and minimize costs. The pitch refers to the mechanical design characteristic of a generator set. It is the ratio of the number of slots enclosed by each coil to the number of winding slots per generator set pole. Alternators that are identical are obviously compatible. Similarly, alternators that have 2/3 pitch will have waveforms that are compatible for paralleling with each other and/or with the utility.

Compensating for pitch differences

When faced with a requirement to parallel dissimilar generator sets, a system designer has several options to avoid harmonic problems associated with generator set incompatibility:

- If possible, require that new equipment be identical to existing equipment. This may require replacement of one or more alternators in the system. Considering that the effective life of an alternator is approximately 25 years in a standby application, and that engines often be fully functional at that age, this is not an uncommon choice. Requiring a 2/3 pitch on all alternators, even if they are not paralleled, makes them compatible for future paralleling. Replacing alternators is more practical at line voltage level than at medium and high voltages, due to significantly higher cost for higher voltage machines.

- Use a 3-wire primary distribution system. By avoiding a solid neutral connection, there is no path for the neutral current flow, so the most disruptive problem of the incompatibility is removed. Note that the neutral of the dissimilar machine must not be bonded to ground when other machines are connected. Harmonic currents will still flow in the phases between the generators, but will be less apparent, and the system will not be hampered with problems associated with high neutral current flow. Transformers may be used to develop necessary neutral connections for single-phase loads.

- Connect neutrals of like machines only, and prevent the dissimilar machines from being the first to close to the bus.

- Add neutral contactors to the switchgear to connect the neutral only on the first unit to close to the bus. This, however, introduces several other potential problems and is not normally recommended.

- Install reactors in the neutral leg of each generator set to limit current flow at third and higher order frequencies. Reactors can be tuned to specific frequencies that are the biggest problems.

- Compensate for the incompatibility by over-sizing the neutral conductor, and derating the alternators.

- The designer may allow system operation with the neutral current and compensate by derating the generator set.

More information on alternator compatibility can be found in our white paper: PT-9016 Paralleling Dissimilar Generators: Part 2 — Compatible Alternators.

Compatible load sharing control systems

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 speed as a reference for maintaining equal output levels. If, for example, one set operates at a higher excitation level than the other sets, the reactive load will not be shared equally.

Similarly, if a generator set is regulated to a different speed than 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: the excitation control system regulating voltage and the fuel control system regulating engine speed. Generators can be sharing kW load and have problems sharing kVAR load, and vice versa.

So real power sharing (expressed as kW) depends on speed matching between the generator sets and fuel rate control; reactive power (expressed as kVAR) is primarily dependent upon voltage matching and excitation system control between the generator sets.

Although it is sometimes possible to integrate systems of different manufacturers, generator set governors and load sharing controls should 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 kVAR load sharing
- Isochronous Voltage kVAR load sharing

Droop load sharing

Droop governing and voltage regulation systems have been historically used for isolated bus paralleling, because they allow proper load sharing between any two or more generators operating on an isolated bus, as long as the generators can be set up to droop frequency and voltage at the same rate, and can be controlled to stable frequency and voltage values.
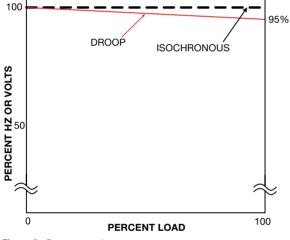

Figure 2 - Droop governing.

As illustrated in Figure 2, droop governing or voltage regulation allows the engine speed (measured in Hz) or alternator voltage to decline by a predetermined percentage (typically 3%) of the output range as load increases. Identical speed and voltage drops result in equal load sharing between paralleled generator sets.

The same practices as described here can be applied to the voltage regulation system of the generator sets in a system. Var load sharing via droop is often termed "reactive droop compensation."

Common droop settings for frequency and voltage can be different and are typically in the range of 3–5% 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 the frequency variations that occur can be disruptive to operation of some loads, especially in emergency/standby systems where the load can vary considerably over time. Droop load sharing is common on attended prime power applications.

Droop governing can generally be 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.
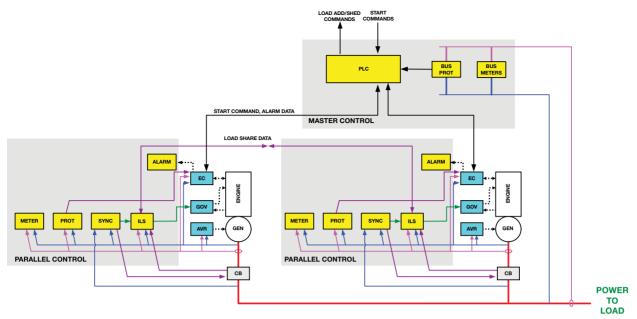
Figure 3 - A block diagram of a simple isolated bus paralleling system showing interface of generator sets, paralleling functions and master control system. Note that the only interface between the generator sets is the load sharing signals.

Isochronous kW and kVAR load sharing

Isochronous load sharing control systems are active control systems that calculate the percentage of real and reactive load on a specific generator set, compare those values to the percentage of real and reactive load on the system, and then provide control to the fuel and excitation system of the generator to drive the percentage of load on the generator to the same value as the percentage of load on the system. Load sharing is critical to paralleling compatibility because the load sharing communication is the only point where generator controls interact with each other when operating on an isolated bus.

To provide load sharing functions, each generator set in the system must have controls that will calculate the total percent of kW and kVAR load on the machine, and then have a means to compare that value to that of the system as a whole. Several approaches are available in the marketplace to provide this interface. In general, they can be broken into two large groups:

■ Systems that use analog signals for load sharing

■ Systems that use digital communication signals for load sharing (such as CAN, RS485 or Ethernet)

Analog control systems are often faster responding than digital communication/control systems and can often be made to be compatible between different manufacturers. Cummins manufactures an analog load sharing interface module (ILSI) that can be used for interface of Cummins PowerCommand® systems with other load sharing controls that use analog signals. Digital communication/control systems generally have less susceptibility to external interference than analog signals, but every supplier has a different communication algorithm that makes it difficult to add dissimilar equipment to an existing system.

Cross current compensation

Cross current is a flow of electrical current between generator sets that is caused by dissimilar excitation levels in those sets. Cross current compensation is a term describing operation of paralleled generator sets without intentional voltage droop. This is achieved by insertion of a droop current transformer (CT), usually on "B" phase of each generator, and interconnecting the CTs 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 the best planning practice is to make sure that all the voltage regulators in a system that uses cross current compensation are all identical.

If system operation in isochronous condition is desired, the best practice is to arrange the equipment so that all generators in the system use the same load sharing control system. Other alternatives for paralleling with dissimilar load sharing control systems are discussed in our document PT-9017, Paralleling Dissimilar Generators: Part 3 – Load Sharing Compatibility.

Compatibility with other control systems

Individual generator sets in a paralleling system may interface to each other and the balance of the facility in a number of ways, including:

- Generator sets must have a means to determine which generator set will close to the bus first in a "black start" (first start) situation.
- Generator sets often provide status information to a system master control, for the purpose of displaying data, allowing the master control to control system power capacity, and for central system load management.
- Generator set may be monitored by a facility monitoring system, or by an external monitoring system, such as for service contract facilitation.

In general, these communication tasks are handled by commonly available communication practices such as discrete signals or by digital communication such as RS485/Modbus[1] register maps. So the main concern in dealing with them is to simply plan for them carefully.

Picking the first generator to close to the bus

First Start control is handled in different ways by different vendors. Some suppliers simply use a dead bus sensor for each genset synchronizer, which allows each paralleling breaker to close to the bus if voltage is not sensed on the bus. This is a risky practice because it is quite possible that multiple generators can reach a decision to close to the bus at the same time, resulting in out-of-phase paralleling of the machines.

To prevent out-of-phase paralleling on energizing a dead bus, most systems provide a means to positively select the first generator set to close to the bus and prevent other machines from closing until the bus is energized and oncoming machines are properly synchronized. The devices and practices for providing this function are different between suppliers, and generally not compatible with one another.

A system designer can deal with this by preventing dissimilar machines from closing to the bus until at least one other machine has closed. This is a viable alternative if there are multiple machines available with compatible First Start systems, so that it is likely that the bus will be energized without the "odd" machine coming on line. It's also possible that a PLC-based program can duplicate the logic of one of the suppliers to get this detail covered.

Alarm and status information

Alarm and status information on generator sets has traditionally been provided with discrete (contact-based) signals that operate a relay and light a lamp if there is a specific alarm or status condition present. These signals are available on nearly any generator set and are compatible with most systems, so they don't represent serious issues, although there is a risk of incompatibility if planning is not carefully done.

Modern engines and the generator sets they are built with can have literally hundreds of alarm and status conditions, and the traditional conditions annunciated are not necessarily the most common or useful information to pass to the system operator. AC data and engine operating data are also useful in remote monitoring. Since most generator sets now are built with processor-based controls, most of this type of information is available via both digital communication mechanisms and traditional relay-based formats. The designer simply needs to decide what information is needed and specify what means are to be provided to pass the information to the user.

Options for remote monitoring include traditional alarm panels, alphanumeric displays, and touchscreen displays. Digital information is also easy to transfer into web-based monitoring systems and text-messaging systems.

About the author

Gary Olson graduated from Iowa State University with a BS in mechanical engineering in 1977, and graduated from the College of St. Thomas with an MBA in 1982. He has been employed by Cummins Power Generation for more than 25 years in various engineering and management roles. His current responsibilities include research relating to on-site power applications, technical product support for on-site power system equipment, and contributing to codes and standards groups. He also manages an engineering group dedicated to the design and development of next-generation power systems.

Recommendations

When paralleling dissimilar generator sets, a designer should:

- Verify that the existing generator set can carry full load with good voltage and frequency regulation.

- Review the transient performance of all the generator sets in the system and verify that the load steps (particularly load rejection) of all the gensets will not result in objectionable levels of reverse power.

- Verify that the pitch of all alternators is the same. Specify 2/3 pitch on all generator sets to avoid problems with this. Take mitigating steps if dissimilar alternators cannot be avoided.

In addition:

- For emergency/standby applications, load sharing controls (both kW and kVAR) should all be of the same manufacturer and model. Droop control may be suitable for some prime power applications and isolated bus kVAR load sharing.

- Attention should be given to the specific control interfaces to system master controls and facility management systems monitoring the generator bus. In general, these can be made to work in nearly every case, but it cannot be assumed that they will work without checking and verifying that the proper equipment is in place.

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[1]Modbus is a registered trademark of Group Schneider.

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