CATERPILLAR®

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Generator Set Transient Response

Introduction

The transient response of a generator set refers to the frequency deviations, voltage deviations, and the recovery time following a load change. Better response means smaller frequency or voltage deviations and a shorter recovery time.

This note is a discussion of the first-order issues involved in transient response and the available options. It applies mainly to 4-cycle diesel engines, because some of the issues differ with 2-cycle diesels or spark ignited engines.

Need For Good Response

The primary concern of the generator set purchaser is sufficient power. The transient response characteristics are important in situations where quick load changes may occur. In a standby installation, the generator set will be called on to accept a block load, which may be the full rated load, in one or more steps. Block loading will also occur where motors are suddenly loaded (the clutch on a blower is engaged, or a grinding mill is fed more material). The behavior of the generator set when starting a motor can not be predicted by observing its block loading behavior. When started, a motor demands power from the generator set at a very low power factor resulting in different generator set behavior. Besides the need for accepting load variations, loads like UPS systems or Variable Frequency Drives impose sometimes severe restrictions on the maximum voltage and frequency deviations.

A generator set is often required to demonstrate that it can recover from full load applied in a single step. This could be a real requirement, but it is also a frequent specification requirement which must be met even if it will not actually be experienced. The most common standards cited are NFPA 99 and NFPA 110, which merely require that the generator set not stall when full load is applied. In actual use, often only the most critical parts of the load are applied in one step.

Typical Transient Response

The generator set transient response to a single block load or motor start consists of up to three voltage dips and up to two frequency dips. Multiple loads applied at the same time behave similarly to an equivalent single load. The response to multiple loads applied staggered in time is a combination of responses to the individual loads. Removal of loads typically cause a single voltage and frequency rise.

The first dip is the generator's reaction to the load's instantaneous need for a lot of current. The generator voltage dip is a function of the generator subtransient reactance and the actual current required by the load. This voltage dip is so fast and of such short duration that the engine can not respond. The resulting frequency dip is minor.

The second voltage dip is caused by a drop in engine speed (frequency drop) as the engine slows down while developing the additional power required to handle the new load. The voltage drop is created by the voltage regulator trying to unload the engine and is proportional to the frequency drop when using a Volts-per-Hertz type regulator, like the VR3. The under-frequency characteristic of the VR3F and the Digital Voltage Regulator also behave in this fashion. As the engine catches up with the new load, it recovers to the original speed (frequency).

The third voltage dip is present when a reduced voltage motor starter is used. The reduced voltage motor starter brings the motor voltage to full voltage when the motor has reached a certain speed (usually 60 to 80% of rated motor speed). The applied full voltage is like a block load that demands an instantaneous jump in power. The generator set responds with another voltage and frequency dip while the engine catches up.

The relative size of the first voltage dip depends heavily on the generator's subtransient reactance. The second voltage dip depends on the amount of power the engine has available and the inertia of the generator set. The third voltage dip, if present, depends on the percentage reduction of the reduced voltage starter, the amount of power the engine has available, and the generator set inertia. An initial voltage dip like the first dip may occur at the start of the third dip, but this is unusual. If there is sufficient power available, this third dip is usually smaller than the second. If the third voltage dip is larger than the second, the engine is probably near it's limit in terms of power availability.

Generator manufacturers publish generator curves where they show voltage dip as a function of sk**V•A** produced in an attempt to provide customers with a voltage dip estimate. These curves assume a constant generator speed. When a generator is coupled to an engine, the speed drop discussed previously, can cause the voltage dip to be greater than shown by the generator manufacturer's curves. Many transient response performance specifications for packages are written based on these generator manufacturer's curves!

Causes of Transient Response Problems

A naturally aspirated (NA) engine pumps a fixed amount of air through the combustion space per minute. If the fuel supplied is just the right amount for the available oxygen (stoichiometric mixture), the engine will produce roughly its maximum output. If fuel flow is reduced, less energy is released and engine output goes down. If fuel flow is increased there is insufficient oxygen to consume it, burning is less efficient, the engine smokes, and the excess liquid fuel absorbs some of the heat energy released, which can reduce engine power output.

Maximum engine power is air flow limited; so the way to increase power is to increase air flow. Air flow is limited by engine displacement (the volume of a cylinder times the number of cylinders), the speed of the engine in rpm, and by the density of the air (i.e. kg of air per L of air).

For a given engine displacement, more speed produces more air flow, but only certain speeds such as 720, 750, 900, 1000, 1200, 1500, or 1800 rpm produce useful frequencies for power generation (50 Hz and 60 Hz). The only practical way to increase air flow is to increase the density of air entering the cylinders. This can be done by increasing air pressure (usually by compression with a turbocharger) or reducing air temperature. Compression increases air temperature, and is often cooled by means of a heat exchanger called an aftercooler using jacket water or radiator airflow. Turbocharger-Aftercooling (TA) an engine is a common and effective means of increasing engine airflow and power output. If done properly, output can be doubled or even tripled compared to a naturally aspirated engine of the same displacement.

The costs for the added output are an increased engine structure, the added turbocharging and aftercooler hardware, and slower response to large load changes. The governor can increase the fuel in a fraction of a second, but at no-load, engine air flow is similar to that of a naturally aspirated engine. Adding fuel increases exhaust temperature, causing turbo acceleration and increased air flow, but reaching full turbo speed may require several seconds. Meanwhile, the generator set is slowing because it's output is less than the applied load. If speed falls far enough (typically 30% at 60 Hz or 25% at 50 Hz), the generator set may have difficulty recovering. When the engine output (rating) is increased by turbocharging, the speed with which the engine responds to large load changes is slowed down. This is the result of the turbo lag. The rate of generator set speed change depends on the load applied and the inertia of the generator set.

Initial deceleration rates for typical Caterpillar generator sets with full load applied range from 50% per second on 3600 engines to 200% per second on 3208 engines. Deceleration continues until engine power increases enough to match the applied load. Further increases in engine output return the engine to rated speed.

Transient Response Improvement

Engine Displacement

It is almost too obvious to mention, but a bigger engine will respond better to a given load. There is no substitute for liters (or cubic inches).

Voltage Regulator

For years Caterpillar has used a Volts-per-Hertz regulator. As engine speed falls when a load is added, the voltage regulator causes the generator output voltage to fall by the same percentage. The lower voltage (to the load) reduces the power that the load absorbs, thus unloading the engine as speed falls, minimizing the speed dip. In spite of this, the latest round of rating increases has resulted in cases where the speed dip is too great to allow recovery when a full load is applied. To overcome this problem, we have developed a 2*V/Hz regulator, meaning that voltage falls off twice as fast as speed. The further reduction in voltage causes the engine to be unloaded even faster and all but eliminates cases where recovery is impossible. Exceptions include highly rated engines with heavy turbochargers when the load is applied immediately following a cold engine start.

Intuitively, the 2V/Hz voltage regulator would seem to cause much higher voltage dip during transients, which is undesirable. However, analysis and tests demonstrate that speed dip is improved so much that the voltage dip is far less than might be expected. In many cases, the voltage dip is less than it would be if the V/Hz voltage regulator was used.

Additional improvement can be achieved by using the Caterpillar Digital Voltage Regulator. The Digital Voltage Regulator under-frequency characteristic is programmable, which allows the characteristic to be matched to the engine, generator, and load combination.

Fuel/Air Ratio Control (FARC)

As mentioned earlier, excess fuel can cause smoke and reduce power. Highly rated turbocharged engines have much more fuel flow available than can be used effectively at no-load air flow, so they are subjected to over-fueling when load is added. The FARC is a device that senses air pressure from the turbocharger, and limits fuel flow to what can be consumed by the available air flow. The air pressure acts on a diaphragm balanced by a spring and a lever connected to the diaphragm prevents the governor from fully opening the rack until sufficient air is available to burn it. While effective, the device adds cost and complexity and is presently unavailable for certain governors such as the popular Woodward 2301. Adjustment is critical, too much fuel limiting also reduces power.

Waste Gate

Turbochargers can be made to run faster and therefore increase air flow by reducing the area of the turbocharger turbine inlet nozzle. A smaller nozzle increases no-load air flow and improves the ability of the engine to accept load. The difficulty is that the smaller nozzle causes the turbocharger to run too fast at rated load. A waste gate is intended to overcome this problem. It is a diaphragm operated device that has no effect at low loads. However, as the turbo accelerates and increases air pressure, the diaphragm opens a valve allowing part of the exhaust gas to bypass the turbocharger preventing turbo overspeeding. The difficulties with waste gates are added cost, complexity, and reduced engine efficiency. One concept to minimize performance penalties is to use the waste gate to increase turbine nozzle area instead of bypassing gas, but this further increases cost and complexity.

Generator Set Inertia

Since the engine deceleration rate is inversely proportional to the generator set inertia when a load is applied, frequency dip could be minimized by increasing inertia in proportion to rating increases. The most obvious method is with a bigger flywheel, but this adds cost and is likely to increase generator set linear vibration.

Air Impingement

Over 20 years ago, experiments with a portable air compressor improved engine response by injecting air from the air compressor through holes in the turbo compressor housing to accelerate the turbo. Caterpillar has since used this principle to start gas turbine engines and to substantially improve load acceptance on some 3500 and 3600 Engines. Care must be taken to size and locate the holes to maximize response and minimize opportunity for exciting compressor blade natural frequencies. A source of plant air is required. Control systems can be very complex, especially in multi-engine standby sites where the first engine to start is unpredictable.

Reduced Inertia Turbochargers

Most of the reason for slow response at high engine ratings is the amount of time required to accelerate the turbocharger. Since turbo acceleration torque is limited by safe exhaust temperatures, improved response has been sought by reducing turbocharger inertia. The compressor is already made of lightweight aluminum, so gains have been made by replacing the steel turbine wheel by one made of ceramic material. In one example, turbo inertia was reduced by about 40% and the rate of engine power increase rose by about 30%. This device is in production in a 3406 Truck Engine. Other technologies being considered include making a metal turbine wheel lighter by a process similar to sintering.

Turbo inertia can also be reduced by replacing a large turbo by multiple smaller ones. The transient response of the phase zero and phase one 3516 prime engines was improved by replacing the two turbos with four smaller turbos, effectively decreasing the turbo inertia.

Tuned Manifolds

If development cost is secondary to performance, improved response is possible by careful tuning of the length, volume, and shape of inlet and/or exhaust manifolds. Opening and closing inlet and exhaust valves causes pressure pulsations in the compressible manifold gases. If the manifolds are tuned, the pulsations can amplify manifold pressure and increase air flow, although each engine speed might require a different *optimum*. Tuned inlet manifolds alone can yield up to a 25% reduction in engine response time.

Conclusion

The transient response of a generator set is affected by many system components. Improving the response significantly requires a complete system redesign (3500B for example), but noticeable improvements can be made with a properly set up Digital Voltage Regulator.