SPECIFYING & VALIDATING MOTOR STARTING CAPABILITY

■ White Paper

By Gary Olson

Motor starting is probably the most complex interaction that occurs between a generator set and its loads because the results are a function of alternator capability (including both the stator and exciter), voltage regulator capability, engine capability and governing functions, as well as the motor and diverse characteristics of the loads that are actually driven by the motor. Starting a motor demands varying levels of both kW and kVar as a motor is starting and accelerating its loads to rated speed. Consequently, a critical evaluation of generator set ability when starting motor loads demands an evaluation of the ability of the entire system to serve all these time and magnitude-varying needs.
While most motor loads could be considered "easy to start," it's risky to simply assume that that they won't push a generator set to its limits (or beyond them), and leave a part of the building loads effectively unserved or cause an overload/shutdown of the genset.

Complicating the problem is the fact that there is no single standard that can be used to provide a basis for all necessary validation work. The industry currently depends on a critical evaluation of hardware primarily based on the requirements in NEMA MG1 Part 32, and NFPA 110.

This paper describes the motor starting process and its impact on generator sets and provides recommendations for verifying motor starting capability of specific generator sets for a specific application.

THE MOTOR STARTING EVENT

The load demand on the generator set package when a motor is starting can best be understood by a review of a typical motor starting curve. The peak kVA demand on the generator set during "across the line" starting occurs at the instant that the motor connects to the generator set, and continuously decays as the motor accelerates (top green line in Figure 1). Motor torque *available* starts at a level a bit more than rated and continuously increases to a peak between 85-90% of rated speed. On reaching about 90% of rated speed available, torque drops quickly to rated torque. Whenever the available motor torque exceeds the demanded torque, the motor will accelerate. The greater the difference between the two, the faster the motor will accelerate to rated speed. Conversely, if available torque is less than demanded torque, the motor will stall.

These characteristics are common in all motors, but actual values will vary considerably in magnitude depending on the characteristics of the specific motor selected. In particular, it's important to note that high efficiency motors typically have significantly higher peak kVA demands, so it's important to consider that when doing generator sizing calculations.

Note also that these curves *assume rated voltage is available* throughout the starting cycle. While that's not a bad assumption when powering the motor with utility power, a generator set's voltage while starting a motor is not constant and will decay significantly before recovering, especially when peak kVA is demanded. The actual voltage levels can vary considerably from machine to machine and supplier to supplier and it's important to verify not only the initial disturbance, *but also that voltage will actually recover*, since applied voltage directly impacts on the ability of the motor to deliver torque to accelerate the load.

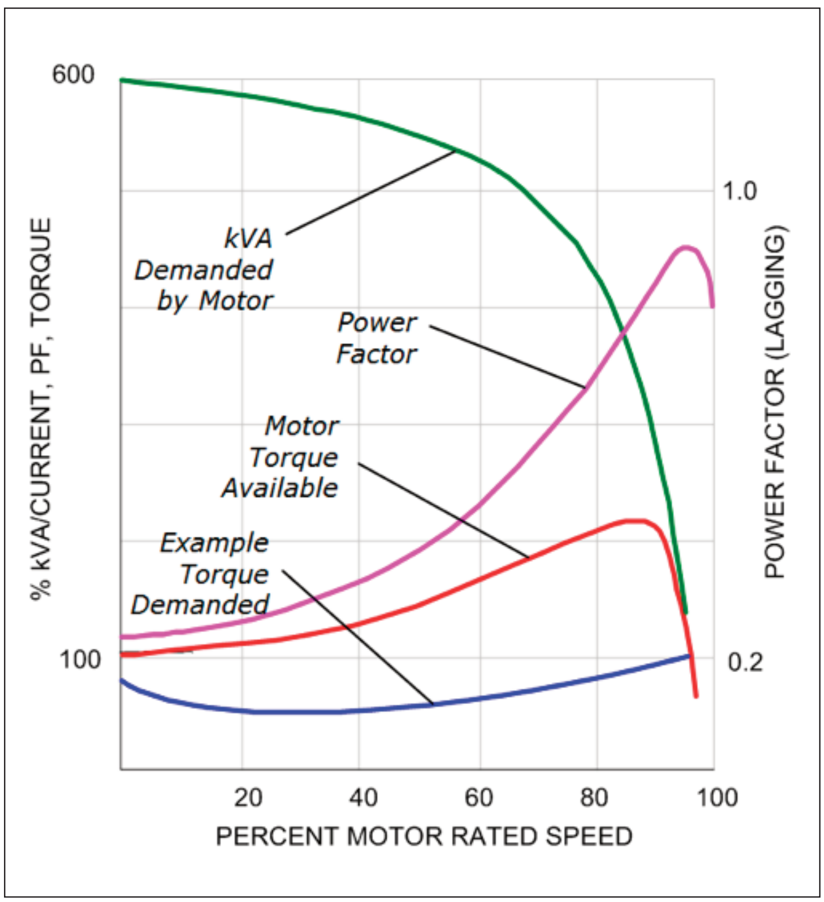

Figure 1 – Typical motor starting curve.

The initial voltage drop is a function of the alternator subtransient reactance[1]. Recovery to nominal voltage depends on the alternator/voltage regulator driving voltage back to normal levels. So, it's important to not only verify that the motor starting contactor (or other device) will stay closed during the initial voltage drop caused by the large initial kVA demand applied, but also so that the voltage will recover and drive the motor to rated speed. Commonly used standards for voltage drop are in the range of 20-30%. The biggest exception to this is that across-the-line starting fire pumps are limited by code to a maximum of 15% voltage dip while the fire pump is operating.

Documentation of generator set performance with applied motor starting loads varies dramatically by supplier. Many suppliers provide a "voltage dip curve", as shown in Figure 2. This curve is provided as a means of describing motor starting capability, and is based on transient reactance rather than subtransient reactance[2]. As with all data in NEMA MG1, it assumes frequency is constant throughout the starting cycle, which is unlikely to occur due to the changing magnitude of kW load applied to the engine as the motor is starting.

Another critical detail in motor starting with generator sets is driven by the fact that the available torque is a square function of the voltage available at the motor terminals. So, for example, a 30% voltage drop will result in less than half of available torque is available at normal voltage. Available torque will return to normal levels when (if) voltage recovers to a normal level.

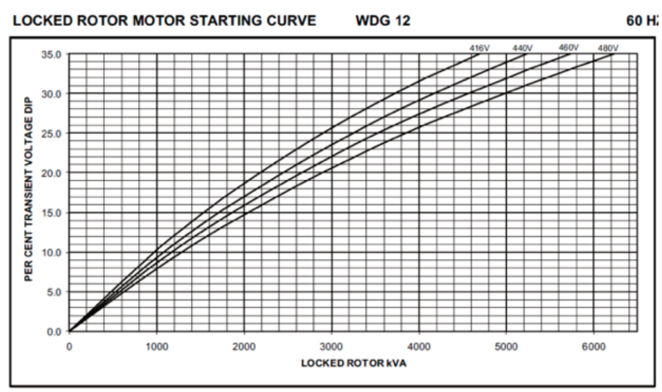

Figure 2 – Typical voltage dip (aka "motor starting") curve.

[1]The impact of the initial inrush occurs before the voltage regulator can sense it and respond, and it may or may not be the maximum voltage drop during the motor starting event.

[2]Since transient reactance is a higher value than subtransient, voltage dip will be indicated as a greater value.

Figure 3 illustrates a situation where actual torque demand exceeds available torque at the instant of load application and voltage does not recover until late in the starting cycle. The red dashed line is a rough estimate of available torque with an initial voltage drop that results in torque demand exceeding available torque from the motor. In this case, because there is not sufficient torque to begin rotation of the motor, the motor would not start. By contrast, if the motor did not have the high initial torque demand shown (in other words, if the blue line stayed below the red dashed line), it would start without a problem.

Figure 4 illustrates another concern: When the initial high kVA load is applied, there is a resulting voltage dip. As the kW demand on the engine increases, the speed drops, which will nearly always result in a second voltage drop. The magnitude of the initial voltage drop depends on the alternator subtransient reactance, while the second is a function of the engine speed drop (which causes voltage roll-off due to voltage regulator action) that will occur until the horsepower is delivered to accelerate the engine back to rated speed. Note that the initial voltage dip or the second dip due to engine speed drop can vary significantly in magnitude, so both need to be considered in the sizing process, as motors don't care why the voltage drops, they only care about delivered voltage.

Nearly all generator sets utilize a voltage roll-off function that intentionally drops voltage as engine speed drops, and builds it back up as engine speed recovers. This roll-off and recovery function varies somewhat between suppliers, but is critical in assuring that the engine will not stall due to a sudden load change.

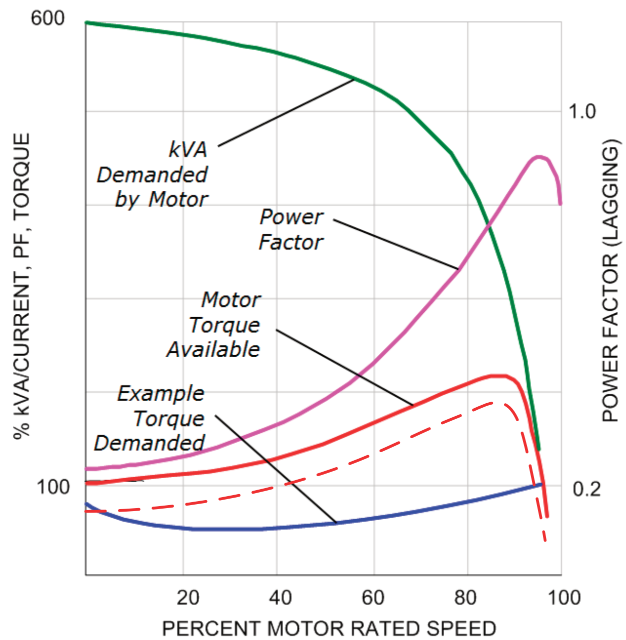

Figure 3 – Typical voltage dip (aka "motor starting") curve.

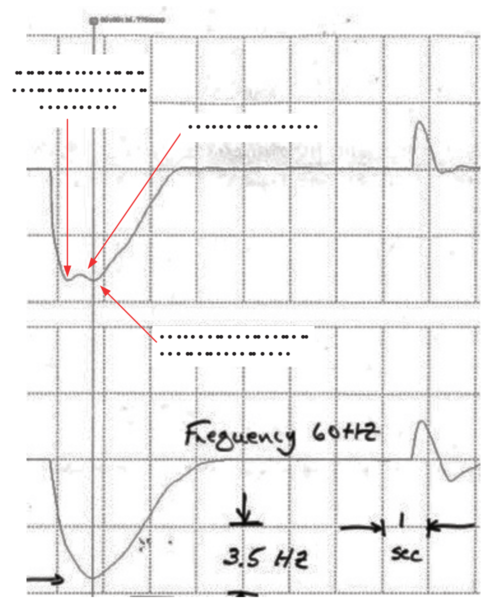

Figure 4 – Generator set performance on application of a block load. Note that voltage begins to recover by drops again due to engine speed drop.

The actual torque delivered to accelerate the motor is provided by the generator set engine, and varies significantly with engine speed. With most 1800 RPM engines the torque peak is at an engine speed greater than nominal alternator speed, so as engine speed drops, available torque drops. By contrast, if the torque peak of the engine was at a lower speed than 1800 RPM, available torque would increase as speed dropped. So, in most 1800 RPM genset applications, in addition to verifying the ability of the alternator/excitation system (including AVR) to deliver kVAR, it is important to know that the engine can deliver the available torque to accelerate the load when it is momentarily overloaded.

The torque demanded by the motor depends on the nature of the load attached to the motor. In Figure 5 (which is a clip from Figure 1), the torque demand of relatively difficult to start (high inertial) motor load is illustrated (red dashed line), along with a typical torque demand curve for a low inertial load (blue dashed line). Note that demand varies greatly depending on the nature of the load and the motor selected to drive the load. In either case, as long as the torque available is greater than the torque demanded by the motor, the motor will eventually start. However, if the voltage drops there will be less torque available, and consequently a motor will take longer to start on a generator that it does with a utility power supply.

It's worth noting that most loads could be considered "low inertia". As shown in Figure 5, a low inertial load (blue dashed line) does not require a large surge of torque to begin motor rotation. Low inertial loads are obviously easier to start than high inertial loads because they gradually load a generator as they accelerate. Many projects now utilize reduced voltage starting means (variable speed drives, IGBT drives, etc.) to take advantage of this characteristic to reduce power demand throughout the operating cycle of a motor. Also, since the low inertial load requires very little initial torque and gradually increases as it accelerates, it applies a ramping torque load on the engine, which will result in less speed change on the engine. This, of course, results in less voltage variation and often a smaller generator set will operate the loads.

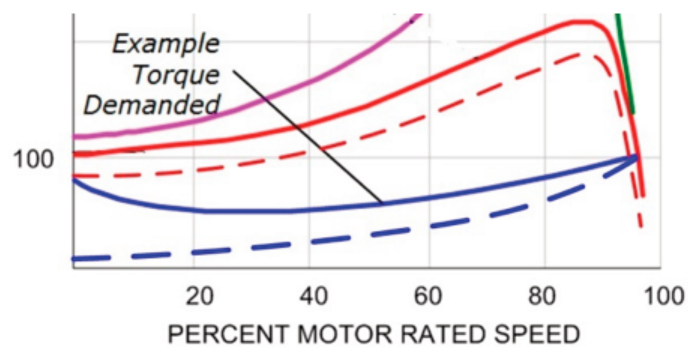

Figure 5 – Torque demand of different motors based on the nature of their loads. Dashed blue line shows torque demand of a low inertial motor load.

To review, motor starting depends on:

1. **Maintaining voltage during the initial inrush** at a level sufficient to prevent the motor starting contactor (or other device) from dropping out. This is primarily a function of the alternator reactance, which is an alternator stator measure[3].

2. **Recovering voltage after the initial inrush** at a level that is sufficient to develop necessary torque to accelerate the load. This is a function of the alternator stator, exciter, and voltage regulator (assuming engine speed recovers to nominal). Note that if the voltage drops further due to engine speed drop, the lower voltage level will become the "voltage dip" value that is important to the application.

3. **Accelerating the load to rated speed.** This is a function of the combination of the engine (including governing), complete alternator, and voltage regulator. However, note also that if the engine speed drops due to #1 or #2 above, the voltage may drop further before it recovers to rated conditions. So, the most accurate sizing recommendations will be based on actual generator set performance rather than alternator-alone data.

If a designer does not consider all of these factors, there is a possibility that the generator set package selected will not successfully operate the system loads under all conditions.

INDUSTRY STANDARDS

There is no single standard that covers all the technical demands that would validate the ability of an assembled generator set to start specific loads. Consequently, genset suppliers have been left with the responsibility of explaining the phenomena involved in motor starting with a generator set and providing designers with:

- guidance on how to validate the ability of a motor to start a load, and
- how to verify that a specific generator set will start that motor with the applied load.

The two standards that are most useful to guide designers understanding and specifying proper system performance when a generator is required to start motor loads: NEMA MG1 (Part 32 section 18) and NFPA 110.

NEMA MG1 Part 32 section 18 addresses the ability of an alternator to provide initial inrush current and to recover voltage after an overload condition. It is important to note that NEMA is considering the alternator and voltage regulator alone, and does not consider the interaction of this equipment with the engine/governing system. All NEMA MG1 materials assume constant speed operation, and all test data is required to be presented is based on constant speed. (32.18.1)

[3]NEMA MG1 32.18.5.2 notes: voltage dip at constant speed = (X'd)/[(Alternator kVArated)/(kVAload)] in percent. This should always be referred to as "calculated voltage dip".

Three terms are used in MG1 to describe the initial change in voltage that occurs due to change in load:

- Transient voltage regulation is the temporary change in voltage (usually expressed as a percentage) that occurs due to any load change (load addition or load drop). (32.18.2.1)
- Voltage dip is the initial change in voltage due to load addition before the alternator control system responds to the voltage change (32.18.2.2). Again, usually expressed as a percentage.
- Recovery voltage is defined as "the maximum obtainable voltage for the specified load condition." NEMA MG-1 also states "unless otherwise noted the percent voltage dip vs kVA load curve should provide a voltage recovery to at least 90% of rated voltage[4]."

Of these, voltage dip is most commonly used to describe the initial disturbance on motor starting. It is particularly important to note that voltage dip is only a function of the alternator reactance, so the maximum voltage dip on an alternator data sheet is strictly a function of only applied load and the alternator reactances. If there is a further drop in voltage due to engine speed change, that might be described as transient voltage regulation or may be completely ignored, depending on the supplier practice. Since voltage dip calculations are based on alternator reactance only, this parameter can only tell you what the alternator can do, and ignores the impact of the voltage regulator, excitation system, and impact of engine speed change. If that is done, the user has effectively assumed that voltage will always recover and there is no engine speed change.

In order to affirm that the voltage will recover after an overload condition, NEMA MG1 includes requirements to document recovery voltage capability of an alternator. Documenting recovery voltage provides a means to determine if the voltage will recover to nominal levels with a specific short duration[5] overload on the alternator.

Whenever the kVAR load on an alternator increases, the voltage regulator has to increase excitation power in order to maintain or recover voltage. In Figure 5 you can see what amounts to an "overload curve" for an alternator, exciter and specific voltage regulator operating at constant speed. kVA load is shown on the X axis, and per unit voltage is shown on the Y axis. In this example, voltage remains at a constant level for up to around 3800 kVA. This is reflective of the fact that alternators are actually designed to operate for a short period of time under overload conditions. For example, if an alternator will operate at no load with a voltage regulator duty cycle of 7%, its full load duty cycle might be only 35% while the peak duty cycle might be 60%. So, in every excitation system there is inherent ability to operate in an overload condition at some level for some period of time. The higher the duty cycle it can run at, the harder it can "push" the load to recover voltage—but as noted, at some point it will be at a peak level, and at that point adding additional load results in voltage drop.

[4]With 90% of nominal voltage available from a generator, any load that works when powered by a utility service will work on the generator. Higher voltage levels allow the motor to produce more torque and make it easier to accelerate the load. Looking back at Figure 1, one can see that if the worst case torque/kW load occurs at 85-90% of nominal speed, any generator that maintains at least 90% of rated voltage at that load level will always recover to nominal voltage quickly after that peak demand passes, since torque and kVA demand dramatically drop at that point.

[5]short duration" is variable, but is limited to the time it takes to actually start a motor

In Figure 6, at about 3800 kVA the voltage regulator is literally running at maximum allowable output, so any additional load increase results in voltage drop because excitation can't be increased to a higher level. When load is increased further and voltage drops to 90% of nominal, per NEMA MG1 32.18.5.1, the reported value is corrected to 1 per unit voltage, resulting in the reported recovery voltage kVA of a little over 5000kVA[6].

Determination of recovery voltage kVA should be demonstrated by an alternator/voltage regulator test at constant speed and power factor less than 0.3[7]; and documented by a field forcing capability curve as shown in Figure 5 if recovery voltage kVA is not published. This can be done if a low power factor load is gradually applied (over 5-10 seconds) to the generator set.

Since NEMA MG1 only deals with the alternator and voltage regulator operating at constant speed, it must be understood that verifying alternator/exciter/voltage regulator capability is not sufficient to determine whether or not a specific generator set can successfully power the applied load.

NFPA 110 (along with NEMA MG1) can be used to describe requirements for the generator set package as a whole. NFPA 110.5.2.3 (2) requires prototype testing to demonstrate the ability of the generator set package to pick up motor starting loads (part of that is covered by testing that fully complies with NEMA MG1), and to demonstrate the ability of the generator set to pick up loads in a full load test during installation acceptance (7.13.4.3).

There are no voltage dip requirements in NFPA 110 for the full load test, just a requirement that voltage recovers to nominal levels. This is usually not a problem since the actual kW applied is based on 1.0 power factor. So, this test just demonstrates that the engine will recover speed on a kW overload condition up to rated load, which does not put the maximum kVAR load on the generator (that part has been demonstrated in the MG1 tests) but does demonstrate that the maximum kW load applied the engine will recover to rated speed. The kVA level at which the 90% voltage recovery is reached is always higher than the kVA applied in a full load site test.

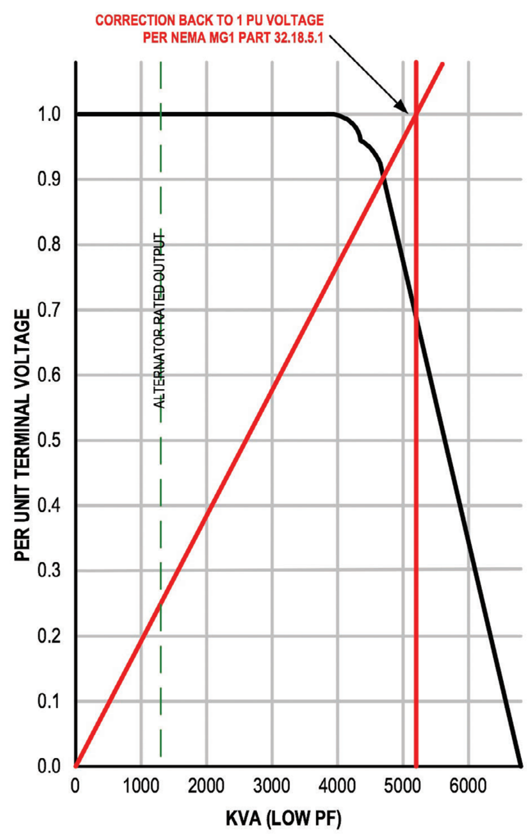

Figure 6 – Field Forcing Capability Curve for a 1250kVA generator set.

INDUSTRY ISSUES

The response of the various generator set suppliers to these requirements varies dramatically, making it difficult for designers to verify proper performance of a generator set for starting specific motor loads. The only saving grace to the situation is that since many motors actually drive low inertial loads, overload demands are limited and the starting cycle is often relatively easy for a generator to manage. However, much of the technical literature on this topic is often technically flawed at best, and definitely reflects a lack of understanding of all the physics of motor starting while ignoring code requirements.

The major issue with most generator set supplier recommendations is that recommendations are done based on initial voltage dip[8] at constant speed (which implies steady state kW load) without consideration of other major factors in motor starting:

- **engine speed drop which usually drives voltage regulator "roll off" in voltage**
- **ability of the excitation system to recover to nominal voltage after the initial inrush occurs**
- **ability of the generator set to pick up surge kW load with an acceptable transient voltage regulation that occurs due to initial kVA inrush due to acceleration of the motor load**

These practices greatly simplify the recommendation process and often work simply because most motors are commonly attached to low inertial loads. It also simplifies the sizing process by eliminating the need to verify the impact of calculated load on a specific assembled engine, alternator and voltage regulator, thus eliminating the need to include actual generator set performance as a part of the sizing practice.

If voltage dip calculations are based on alternator reactance alone, you can generate all the motor starting curves based on nothing more than alternator data. In essence, they have told you what the alternator can do, but not what the alternator, exciter, and voltage regulator can do together running at constant speed. It is simply assumed that the voltage will always recover, when in fact, that is not always true.

Finally, since a motor requires a short burst of kW greater than its steady state kW demand, it's important for a generator set to demonstrate its ability to pick up the transient load and recover to rated speed. Since this is a function of only available kW, a simple block load test on the generator set can be used to demonstrate that the generator set is suitable for a specific application. Most generator sets can pick up rated load in a single step, so prototype testing or factory testing demonstrating load pick up capability can be used to verify that the generator set will properly recover when a specific motor is started.

[6]The actual calculation is based on the current drawn at rated voltage and corrected with the ratio of Vrated voltage/ Vrecovery voltage.

[7]This is recognition that the core parameter in the test is kVA (kVAR) and that power factor is not important, except to allow the power source driving the alternator to be reasonably limited in size.

[8](as calculated by applied kVA load vs. either transient or subtransient reactance)

To summarize:

Accurate and reliable sizing of a generator set requires consideration of initial voltage dip, recovery of the voltage delivered to the load to at least 90% of nominal voltage as the motor is accelerating, and the ability of the generator set to pick up the kW load applied.

- Alternator locked rotor kVA curves provide initial voltage dip assuming constant speed
- Ability of the excitation system to recover from a defined overload requires use of a recovery voltage kVA curve
- A simple full load test on the genset demonstrates the ability of the genset to recover from a rated kW load step

RECOMMENDATIONS

1. The initial voltage dip of the alternator should be specified in terms of voltage dip at constant speed and a specific kVA level. A supplier should document performance to the requirements with either a voltage dip curve which charts voltage dip vs. kVA, or with reactance data from an alternator data sheet.
2. The designer should demand compliance to NEMA MG1 requirements for reporting of recovery voltage kVA. This can be done via an alternator data sheet, and if that is not available, via an actual test demonstrating the field forcing capability of the alternator/exciter/voltage regulator proposed. The level of recovery voltage kVA required is a function of the actual load demands. However, it would not be unreasonable to generally require recovery voltage kVA of at least three times rated kVA (based on the generator set, not alternator rating). That being said, five times rated kVA is not an unusual performance level.
3. The sizing practice used for selecting a generator set should incorporate not only the alternator performance but also the expected voltage dip when picking up the loads while operating on the generator set package; as this value is different than the constant speed data provided with the alternator alone. Remember that the motor performance depends on the delivered voltage which includes voltage roll-off due to engine speed drop during load pick up.
4. Factory and field testing[9] should demonstrate the ability of the generator set to pick up rated load in one step, and document the expected voltage and frequency variations with that level of load step applied, both at 1.0 and 0.8 power factor. Note that NFPA 110 requirements have been "softened" on this point, so it's important to specify the ability to pick up rated load in one step when that is needed for the application.
5. When doing sizing calculations for selection of a generator set, it's best to do the final selection based on assembled generator set performance, rather than individual component performance.

[9]Factory testing verifies that the machine has been built correctly and performs as well or better than the prototype. Field testing verifies that the machine has been installed correctly. Since kVAR output will not vary due to installation, it is reasonable to eliminate the kVAR-related testing in the field.

RECOMMENDED PROJECT SPECIFICATIONS

The following text should be in the alternator specifications:

The steady state kVA rating of the alternator shall be XXXX kVA with a maximum temperature rise of 80/105/125[10] C based on specified maximum site ambient conditions. Provide derating calculations for all applications with ambient temperature greater than 40C (104F) and site altitude great than 305M (1000ft) based on alternator manufacturer's published documentation.

The alternator shall accept a full load step at rated kVA with a maximum voltage dip of XX percent based on the transient reactance of the alternator proposed. Provide documentation (with calculations if necessary) demonstrating compliance to this requirement.

Alternator provided shall provide recovery voltage kVA of XXXX[11] kVA per the requirements of NEMA MG1 Part 32 section 18.2.2. "Motor starting kVA" based on any other practice is not acceptable and will result in rejection of the proposed alternator. Provide published documentation of performance or a test procedure, compliant to the requirements of NEMA MG1 part 32, for a factory test that will be performed documenting required performance.

Generator set specification text should include:

The generator set shall pick up a block load equal to the specified kW at 0.8 power factor at rated site conditions and recover to rated voltage and frequency.

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[10]The temperature rise choices noted are for Class F insulation, which is most commonly used for line voltage applications. Note that as temperature rise increases, alternator becomes smaller and reactances increase and voltage dip increases. Maximum temperature rise generally used in UL2200 generator sets is 125C.

[11]This value should be adjusted based on the needs of the application and the supported by documentation from a manufacturer's sizing program to verify validity of the system performance.

ABOUT THE AUTHOR

Gary Olson is a 40-year+ veteran of the power generation industry with more than 30 years or service prior to retiring from Cummins. He is an expert in the application of emergency/standby power generation equipment and in the interaction of this equipment with both load devices and utility distribution systems. He is now an independent consultant working primarily with Cummins distribution.

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Gary has many published magazine articles and white papers. Many of these can be found on cummins.com. He has contributed much of the content of several of the Cummins technical application manuals, including T-030 (Gensets), T-016 (Paralleling), and T-011 (Transfer Switches).

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