Alternator Designs for Non-Linear Loads

The nature of loads within facilities have changed dramatically over the last 30 years, with facilities designed for nearly 100% linear loads (such as across-the-line motors and incandescent lighting) now giving way to designs that must accommodate nearly 100% non-linear loads. In addition, the public expectation for the reliability of power in facilities is increasing, and the revenue lost due to failed utility service in many cases justifies use of “full facility” standby designs.

These changes drive the need to specify and use the best possible alternator/excitation control system designs available. This paper covers recommendations for alternator design requirements in systems with predominantly non-linear loads.

Basic Alternator Control

An alternator is an electromechanical device that converts mechanical energy (usually from an engine) to electrical energy. The design rests on the physical principal that when a rotating magnetic field is moved through a stationary coil voltage is produced that allows production of electrical power. The magnetic field is produced by a brushless excitation system composed of an exciter and rectifier that provides DC power to the field of the machine. With a constant load, voltage will increase and decrease as excitation power to the field is increased and decreased. Conversely, as load changes, the voltage will change unless the excitation power level is changed to match the load requirements.

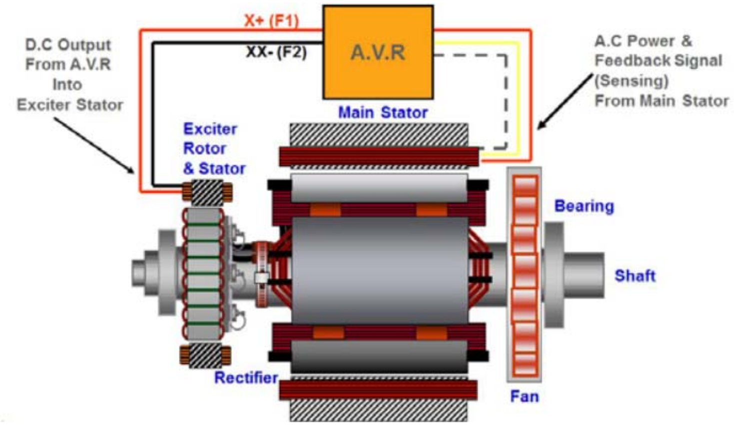

Figure 1: Figure 1: Alternator cut-away showing major components. Note that the AVR provides DC power to the exciter, which produces an AC voltage to a rectifier assembly. The rectifier provides DC power to the main alternator field.

Figure 1 shows how these principles are applied in hardware. The design shown is termed “self-excited” because the source of power for the voltage regulator (AVR) is residual voltage present in the main field (main stator) of the alternator. This cut-away drawing shows an alternator main stator with a rotating field within it on a rotating shaft; and an exciter composed of a stator/rotor with rectifiers to provide energy to the main field. Power from the AVR is provided to the exciter stator, which forms a magnetic field which produces an AC voltage waveform in the rotating part of the exciter. A rectifier assembly converts the AC power from the exciter into DC power which provides energy to the main field.

So, the AVR changes the amount of energy sent to the exciter to make necessary changes to the voltage of the system in response to load changes.

Figure 1 also shows that the input power and voltage sensing to the AVR is taken off the main stator assembly. AC voltage is produced by the alternator, which goes into the AVR. The voltage regulator often provides this function through use of a SCR (silicon controlled rectifier), which turns on at a time period after a zero crossing, and turns off as the voltage waveform approaches zero. The energy that is routed to the exciter is represented by the area under the curve at each point in the voltage waveform, as shown in Figure 2[1]. If the AVR senses low voltage it turns on sooner so more energy gets to the exciter and a stronger field is produced in the alternator. If the voltage

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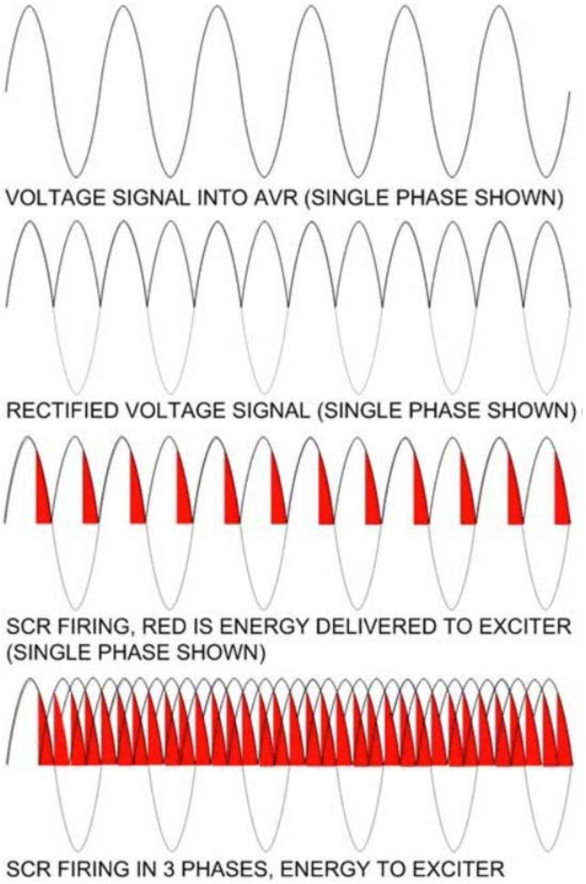
[1] Figure 2 shows a full-wave rectified system. In a half-wave rectified system only the positive portion of the waveform is used for excitation power, so there is half as much energy available to direct to the exciter.

is sensed high, the time delay to turn on the SCR is longer, so less energy reaches the exciter, the field strength drops, and the voltage goes down.


VOLTAGE SIGNAL INTO AVR (SINGLE PHASE SHOWN)

RECTIFIED VOLTAGE SIGNAL (SINGLE PHASE SHOWN)

SCR FIRING, RED IS ENERGY DELIVERED TO EXCITER (SINGLE PHASE SHOWN)

SCR FIRING IN 3 PHASES, ENERGY TO EXCITER

Figure 2: Excitation pulses in a 3-phase sensing full-wave rectified excitation system.

In “half wave rectified” designs the AVR uses only the positive portion of the sensed waveform, and sometimes only used a single phase of the 3-phase voltage, so there was a finite amount of energy available to drive the exciter field, and it was relatively easy to disrupt, since there was only a single SCR firing per each electrical cycle. It could also be noted that whether a half or full wave rectified signal is used, there is a finite amount of power available to the exciter, so any sufficiently large load may prevent voltage from recovering to rated levels.

For example, on application of a 3-phase fault, or even a large motor load, voltage would collapse on the terminals of the alternator, and the machine could not increase excitation to a sufficient level to recover voltage or drive sufficient current to clear downstream protective devices. So, self-excited machines are sometimes termed “inherently protected” since are not able to provide sufficient current to damage themselves on a 3-phase fault.

When the alternator is providing power to non-linear loads the distortion of the voltage waveform used for the power supply to the AVR (especially notching close to zero crossing points) could make it difficult for the voltage regulator incorrectly detect the zero crossing point. When the SCR fires at the wrong time either too much or too little energy reaches the alternator main field, causing the load applied to the engine to pulsate. If the load pulsates, the engine speed pulsates, making even more difficult for the AVR to properly operate.

Improving on the Basic Design

In alternators used for critical applications with significant levels of non-linear load, the SCR-type AVR is often replaced with a 3-phase sensing and FET[2]-based AVR with separately excited design (rather than self-excited). In a 3-Phase sensing design the AVR commands are based on the average of all sensed voltages rather than a single (or 2-phase) sensing level. Because the voltage is regulated based on an average voltage, instantaneous disruptions on one phase are less of an impact than with a single phase sensing system. As illustrated in Figure 2, a three-phase sensing system can also deliver more power to the field of the alternator for better transient load performance.

The addition of an isolated excitation system power supply is also important in the improvement in performance when serving non-linear loads. A common choice is the addition of a permanent magnet generator (PMG). The rotating permanent magnet produces a magnetic field that is moved through a stationary coil to produce a high

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[2] A FET is a field effect transistor design that provides a pulse-width modulated signal to the exciter. This signal is not dependent on sensing the zero crossing point, but rather provides a commanded number of pulses per second. Consequently, distortion does not impact on the ability of the AVR to provide a stable output voltage.

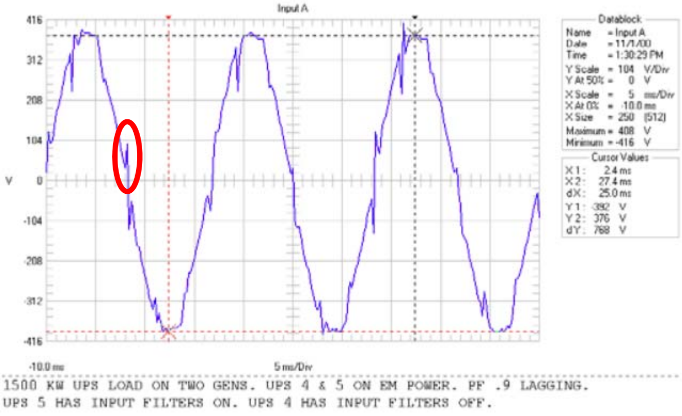
frequency AC voltage that is used to provide power to the voltage regulator. This power source is available (at full power) whenever the engine is rotating.

Since the only load for the PMG is the voltage regulation system, the power source is completely isolated from disruptions that may be caused by non-linear loads or even severe disturbances such as bolted fault conditions. Consequently, a constant power supply drives the field of the machine and the alternator can safely operate a higher percentage of non-linear loads. Another advantage of this feature is that the alternator can provide power under short circuit conditions for a longer period of time, so that downstream circuit breakers are more likely to trip under fault conditions, allowing the balance of loads in the system to be served, rather than shutting down the generator set.

Alternator Design

Alternators used in demanding applications need to replicate the capability of the utility service in order to successfully operate demanding loads without dramatic over-sizing of the alternator. So, in general, the most important action will be to reduce the impedance of the alternator, so that any sudden change in load on the alternator will result in the minimum disruption of the voltage waveform. Another way of describing this is that the alternator will be “stiffer” relative to the load.

Many non-linear loads are derived from SCR’s, which as shown in Figure 2 put a sudden load pulse on the alternator and then quickly remove it. This happens so quickly (within a single half of an electrical cycle—0.008 seconds) that the required energy is taken from the stored energy in the field of the alternator before the AVR starts to respond, so the voltage waveform can be very distorted even though the average voltage appears to be normal. (Figure 3)



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1500 KW UPS LOAD ON TWO GENS. UPS 4 & 5 ON EM POWER. PF .9 LAGGING.
UPS 5 HAS INPUT FILTERS ON. UPS 4 HAS INPUT FILTERS OFF.
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Figure 3: A voltage waveform taken from a generator set powering a non-linear load. Note that the waveform includes many notches rather than having a smooth shape. The notches are caused by SCR firing in the load (in this case, a 6-pulse UPS). When firing is close to a zero crossing point, the SCR can have difficulty in detecting the zero crossing point.

Reducing the impedance of a specific alternator design is done by making the alternator relatively larger compared to the load. In order to avoid gross over-sizing of the alternator it is important to start with an alternator design which has a low subtransient reactance by nature of its design. A good guideline is to drive for a maximum subtransient reactance of 0.12 per unit. (Subtransient reactance is like a golf score—lower is better.) On larger machines a more practical level may be 0.15 per unit.

The design of the alternator may be either “wire-wound” or “bar-wound”. Wire-wound designs are those that use round, insulated wires to make up the coils of the alternator stator. Bar-wound designs use rectangular bars to make up the coils of the alternator. Wire-wound designs will generally result in lower subtransient reactance (assuming similar material content/cost), so are superior for non-linear load applications. Bar-wound designs are best for loads that put sudden, quickly-repeated mechanical loads on a generator set. These include applications such as some cranes, and some oil rig applications.

Alternators of nearly any size for standby applications are now available with Class H insulation, which has superior capabilities and can operate at higher temperatures than earlier machines with Class F insulation. This is important because the notching causes incremental heating in the alternator that can shorten the life of the alternator. By starting with good insulation (Class H), and then limiting the full load temperature rise (how much the temperature inside the alternator increases with load application) to a maximum of 105 °C[3], the life of the machine is unaffected by the stresses placed on the alternator by the load and the overall level of distortion caused by non-linear loads or other suddenly applied loads (such as motor starting) is minimized.

Recommendations

Generator sets for demanding applications should include the following capabilities:

- The alternator should have a low subtransient reactance (0.12 per unit, maximum)
- The alternator should utilize Class H insulation and have a temperature rise of not more than 105°C
- The voltage regulation system should be 3-phase sensing and include a permanent magnet generator for excitation support.
- In any application with significant levels of non-linear loads, the voltage regulator should be a FET-type design that provides a pulse-width modulated output to the alternator exciter.

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[3] Class H insulation is rated for continuous operation at 125C temperature rise.

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