Application Guidance Notes: Technical Information from Cummins Generator Technologies

AGN 048 - Rubber Tyred Gantry (RTG) Cranes

BASIC CONSIDERATIONS

Generating Sets used in RTG Crane applications are invariably sited in coastal regions. These Generating Sets often become problem units, because of the arduous ambient environmental conditions of their location site. The ambient conditions encountered at the dockside locations where most RTG Cranes operate are known to be particularly arduous for electrical machines - crane drive motors and the ac generator (alternator).

Cummins Generator Technologies therefore expect the nominated alternator to be incorporated within a Generating Set canopy designed specifically for the application, and sensibly located on the RTG such that it will offer good environmental protection for the alternator with regard to:

- High saline humidity,
- Good vibration isolation from the Generating Set prime-mover.
- Good shock and vibration isolation from RTG dockside motion/activities.
- Protection against the effects of exhaust fumes from other dockside vehicles.

Ensuring reliable satisfactory service requires careful consideration being given to the ventilation systems that will be shared by both alternator and engine. Simplifying the considerations to just deciding to have a relatively simple canopy with large openings for the benefit of the engine, and then considering the alternator satisfied by the fitting of low cost air-inlet filters, will result in operating problems.

Decisions at the Generating Set design stage, regarding the Generating Set Canopy design and airflow control, must include discussions with the alternator manufacturer to ensure that the appropriate optional extra air filter / louvre kit is nominated and that a bespoke maintenance regime is implemented for the complete Generating Set.

The RTG Crane application is a quite unique situation. For reasons of making the alternator output characteristics suitable to power the Crane's drive motor, combined with the duty cycle of the variable crane motor load, the alternator is usually operating with quite low levels of winding temperatures. Whilst this low temperature situation would normally be considered to be beneficial, it does introduce a problem when the operating environment is high humidity, and even worse if this is combined with a salt laden atmosphere.

The winding temperature at which moisture is driven from the windings is accepted as being 100degC. However, experience gathered from the actual operating temperatures of the alternators nominated for the Non Linear Loads (NLL) associated with RTG Crane applications, suggests the windings never reach this temperature for a period long enough to begin the 'drying out' process.

Now consider a situation of the alternator's windings contaminated with deposits from a high humidity and salt laden atmosphere, combined with the dust and pollutants around a working dockside, plus RIC engine port vehicles emitting exhaust gas by-products, and the effects these all present in the form of a winding contamination problem. Add to this, additional atmospheric moisture associated with local weather conditions, and the dew point situations created within the canopy, and how all these elements combine to create the forming of moisture and particulate contamination on the surface of all wound components. And then, these wound components not reaching a working temperature hot enough to drive away moisture, thereby leaving a winding insulation system with much reduced dielectric 'barrier' capabilities.

Whilst the above considers the contaminants that weaken the winding insulation system. The following explains the additional electrical stresses associated with the Variable Speed Drive units used to power the various crane movements. These VSD's are NLL, with quite high levels of harmonic distortion. The resulting harmonic voltage distortion results in transient Voltage conditions that may well be twice the peak value that the alternator would experience under normal linear load conditions. These high transient voltage spikes stress the electrical insulation system, with which a clean uncontaminated winding insulation system can cope. But a contaminated winding will find such transient voltage spikes difficult to contain, followed inevitably by the breakdown of the insulation barrier and winding short circuit.

Nomination and incorporation of an alternator for a severe environment

This AGN goes on to cover the nomination and incorporation of an alternator designed specifically for a severe environment, as typically encountered by an RTG Crane application. It expands the technical considerations of various routes aimed at offering a Generating Set package suitable for the purpose.

The alternator's air inlet cooling air management is an important factor that must be considered very carefully. Then, there is the problem with salt, with its moisture absorbing film of contamination on the alternator's winding. When the alternator is working and the windings are hot, the moisture is driven off the windings surface, and the insulation resistance - IR - will be high enough to ensure that no insulation breakdown or surface tracking occurs. But as soon as the alternator is stopped, the alternator's local environment becomes extremely humid. It is at this point the hygroscopic layer of salt that has formed on the windings, will absorb moisture and this will result in the windings IR value being reduced to a low level, and so trigger an inability to insulate/isolate phase to phase and phase to earth. Therefore, when the alternator is next started and it excites to the normal working voltage - electrical pressure - there is a real risk that an insulation failure will occur as a result of insulation breakdown initiated by surface tracking.

What can be done? Well, the ideal is to filter the salt from the Generating Set cooling air. But the practicalities must include control of the humidity level of the alternator's environment, and this involves far more than the fitting of an anti-condensation heater to the alternator. The most successful schemes involve a fan heater blowing several kW's of hot air around the alternator 'chamber' to keep the humidity RH% as low as possible. Obviously this needs an electrical power supply when the Generating Set is not running and so may well not be an easy option.

There may be a way of running-on the Generating Set after its programmed service duty. This would be in a way devised to keep hot dry air circulating whilst the whole Generating Set area temperature is gradually reduced to stop the sudden increase in RH% that occurs around Generating Set when it is stopped and left trapped in its 'sweat box' canopy.

Conclusion on basic considerations

Most Generating Set manufacturers have historical experience of problem applications, and will appreciate the areas of 'risk'. This should never be reduced to a fundamental approach of believing that just changing the manufacturer of a troublesome component within a Generating Set will immediately solve the failure problem. Therefore, it is never good engineering practice to simply rush forward with an alternator nomination for problem applications where other alternator manufacturer's products have failed.

The introduction of a carefully considered air inlet filtration system is a step in the right direction, but not a total solution. Canopy/housing design, and therefore Generating Set environment control, are critical factors for Generating Set components for units that will be installed and operated on 'problem sites'.

Refer to AGN 072 – Environmental Conditions – for further information.

Further on in this AGN, there are a number of alternator technical features that must be considered to mitigate all probable environmental issues.

GENERATING SET CONSIDERATIONS

In addition to the basic considerations for the operating environment, there are other considerations relating to Generating Set suitability for supplying the many and various loads that are typical of a RTG Crane application.

Engine Loading Levels

Most RTG Crane manufacturers quote the Hoist, Trolley, and Gantry motor sizes in kW but do not qualify whether electrical, or mechanical and just where in the system this power [kW] is required. A trend seems to be emerging that the quoted powers are based on the calculated required power output from the drive motor into the mechanical movement's gearbox. Unless appropriate guidance is provided, the efficiency of the motor and its power system must be assumed, along with the operating power factor of the motor - drive system. Assumptions made are as follows:

Hoist

Typically assumed values for a steady state full load running condition are: 90% system overall efficiency and 0.9 p.f.

So; stated kW x 1.23 = Full Load running kVA @ 0.9 pf.

To establish Engine load, the above Full Load running kVA must be considered as the alternator output, therefore alternator efficiency at this loading level must be taken into account.

A typical alternator efficiency is ~92%.

Therefore: **Engine power kWm** = $\frac{\text{Full Load running kVA x 0.9}}{\mathbf{0.92}}$

Acceleration of the Hoist drive system is usually conducted under a controlled linear ramp rate achieving the maximum required mechanical power level within a period of some 3 < 4 seconds. This seems to result in the load appearing to the Generating Set as a gradual, linearly increasing load, not a single step impact load.

Typically, the peak acceleration power is some 1.3 x normally required full load running system power. The drive system efficiency, for simplicity, is assumed to stay the same 90%, although the power factor will now be assumed to be at 0.4 p.f. lag.

So; $\frac{\text{stated kW x 1.3}}{\mathbf{0.4x\ 0.9}}$= stated kW x 3.61 = Peak Acceleration kVA @ 0.4 pf.

To establish Engine load, the above Peak acceleration kVA must be considered as alternator output, therefore, alternator efficiency at this loading level must be taken into account.

A typical alternator efficiency is ~85 %.

Therefore: **Engine power kWm** = $\frac{\text{Peak Accel.kVA x 0.4}}{\mathbf{0.85}}$

Trolley

Typically assumed values for a steady state full load running condition are 90% system overall efficiency and 0.9 p.f.

So; stated kW x 1.23 = Full Load running kVA @ 0.9 pf.

To establish Engine load, the above Full Load running kVA must be considered as alternator output, therefore, alternator efficiency at this loading level must be taken into account.

A typical alternator efficiency is ~92%.

Therefore: **Engine power kWm** = $\frac{\text{Full Load running kVA x 0.9}}{\mathbf{0.92}}$

Acceleration of the trolley is never found to be a particular problem and this may be simply due to the relatively small motor kWm used for this system. It is expected that the start factors are very similar to the hoist motors, but it is unlikely to have such a sophisticated ramp and control scheme as the hoist.

Gantry

Typically assumed values for a steady state full load running condition are 90% system overall efficiency and 0.9 p.f.

So; stated kW x 1.23 = Full Load running kVA @ 0.9 pf.

To establish Engine load, the above Full Load running kVA must be considered as alternator output, therefore, alternator efficiency at this loading level must be taken into account.

A typical alternator efficiency is ~92%.

Therefore: **Engine power kWm** = $\frac{\text{Full Load running kVA x 0.9}}{\mathbf{0.92}}$

Acceleration of the Gantry has been found to be an area where quite high torque requirements may have been found, but this situation varies with different types of control systems and different RTG manufacturers.

High torque requirements seem to be demanded of the Gantry drive system to overcome the initial stiction of the Crane wheels to start movement of the RTG along the dockside.

It seems that many crane schemes do incorporate a controlled rate of acceleration of the RTG gantry, but the load often seems to be presented to the Generating Set as a large step load demanding instant torque / power to initiate RTG movement, with a peak impact kVA demand of 2 x stated full load running condition, at 0.6 power factor – to produce m.m.f. (magneto motive force) and motor torque – and a transient characteristic that subjects the Generating Set to an initial block shock load condition.

From data received to date, it seems that although the Gantry Motor is usually sized in kWm terms at approximately 80% of that quoted for the Hoist Motor, the acceleration load of the Gantry Motor, for the reasons stated above, is often more demanding than the Hoist Motor.

Typically, the peak acceleration power is some 2.0 x normally required full load running kVA. The drive system efficiency, for simplicity, is assumed to stay the same [90%], although the power factor is now assumed to be at 0.6 p.f. lag.

So; $\frac{\text{stated kW x 2.0}}{\mathbf{0.6\ x\ 0.9}}$ = stated kW x 3.7 = Impact kVA @0.6 pf.

To establish Engine load, the above Impact kVA must be considered as alternator output and alternator efficiency at this loading level must be taken into account.

A typical alternator efficiency is ~90%.

Therefore: **Engine power kWm** = $\frac{\text{Impact kVA x 0.6}}{\mathbf{0.9}}$

If possible the Crane Manufacturer should always be requested to provide a LOAD DIAGRAM for the Crane system showing motor acceleration, motor run and if possible, combinations of individual drive systems.

Alternator Loading Levels

The power electronic schemes, whether involving ac or dc Motors, associated with the variable speed motors employed for RTG Crane drive systems, will constitute a Non Linear Load [NLL] for the alternator.

A NLL will cause non-sinusoidal current waveform, with a high harmonic content, to flow from the alternator and this in turn, will distort the generated output voltage waveform causing it to have 'harmonic content'.

Whilst this will not cause the alternator any particular problems, the levels to which the voltage waveform can be allowed to be distorted, with harmonic content, is set by the Motor's Drive System power electronics associated control equipment's level of tolerance to harmonic distortion. The level of harmonic Voltage distortion is a product of the level of harmonic Current distortion combined with the source impedance of the electrical supply.

If an alternator is the source of supply, then the source impedance can be related to the sub-transient reactance [X"d]. To calculate the level of harmonic Voltage distortion on the system it is necessary to have the following information regarding the Drive System.

- Number of pulses [i.e. 6 or 12] in the power electronics converter stage.
- Level of current distortion produced by the load [known as I.dist% or THDi%].
- Are harmonic filters fitted?
- Maximum level of voltage distortion acceptable to load [V.dist%]. Operating input voltage and frequency.
- Operating input power factor.
- Operating system efficiency.
- Clarification of any kW figures: 'where in system' and are the figures in kWm or kWe?

If actual values of current distortion are not known, then the following typical values can be used once the overall scheme has been identified. Typical current distortion figures for unfiltered systems are as follows:

- 12 pulse - 14%
- 6 pulse - 30%
- 2 pulse - 45% (single phase)

Most motor drive systems can tolerate a level of harmonic voltage distortion [V.dist] in the order of 15%. This value greatly depends on the guidance supplied by the Drive Manufacturer. Under acceleration conditions, it is often possible to allow the harmonic voltage distortion levels to go up to 20% V.dist. When the Crane has a base auxiliary load that may include high efficiency [latest technology] lights, there is a considerable risk that these lights and perhaps other elements of the base load, will be adversely affected by high levels of V.dist%.

In order to maintain good voltage regulation, even though the voltage is grossly harmonically distorted, it is necessary to fit an AVR that is both three phase sensing and R.M.S. sensing to maintain the required nominated output voltage based on a true R.M.S. value. A digital or MX321 analogue AVR is required, which has to be used in conjunction with the PMG. Simple overall guidance regarding alternator types required for typical RTG Cranes is not possible with guidance based on the above required data.

Commissioning

With the Motor Drive System having so many variables such as; acceleration ramp rates, motor static ‘torque’ levels, stability time constants of closed loop control systems and these ‘stability levels’ also needing to be set for Engine governing and the alternator AVR, each needs to be set with relative consideration to ensure compatibility of the total System.

The STAMFORD range of alternators is favoured, for RTG Crane applications, throughout the world. Port Authorities often specify them; as do crane manufacturers and those associated with the assembly of the main power packs.

The duty for the power pack is particularly arduous, because of the harsh environment and the nature of the load. A saline laden atmosphere, exhaust fumes and a potentially dusty atmosphere, all have a detrimental effect on the winding insulation.

Most cranes incorporate 6-pulse thyristor drive systems on the hoist and trolley, creating two types of problems to the alternator:

- The first is the high transient voltage levels seen when the thyristors operate (switch), which can cause problems to the voltage control system. The diodes, in the rotating rectifier assembly, are the most vulnerable and must be adequately protected to ensure continuous operation.

- The second consideration is the current and voltage distortion due to load induced harmonics. The switching of the load creates the harmonic disturbance; this distorts the current waveform, which in turn distorts the voltage waveform. The alternator can tolerate a large degree of harmonic distortion but the load usually needs a sinusoidal (harmonic free) waveform to facilitate the current switching control circuits. The maximum percentage of load distortion generated by the load and the distortion level acceptable to the drive system, should be supplied, to help determine alternator selection.

To be sure of the correct alternator selection, all odd and even numbered harmonics to a high order are considered. Application Engineering offer a service, of providing customers with a second check to their sizing calculations, to enable us to ensure that we offer the most cost effective solution within the given technical parameters.

We are now finding that enquiries are stipulating the maximum levels for Transient Voltage Dip [TVD] on application of peak load and also the direct Sub-Transient Reactance [X”d] against given load levels, which help to dictate the alternator size. In some instances, we have been specified a minimum alternator size!

There is no substitute for the practical experience of the crane manufacturers and we must accept their views and size the alternator accordingly, but in all cases we will endeavour to offer a technically acceptable machine with the most cost effective frame and core size.

Alternator Technical Features

If a STAMFORD alternator is nominated for a RTG Crane application, a recommendation for the design of that alternator will include the following technical features:

PMG Excitation

Separate excitation using a Permanent Magnet Generator [PMG] system provides isolation from the effects of a distorting voltage waveform, caused by power electronics - thyristor loads.

2/3 Pitch Winding

The 2/3 pitch winding design used in all STAMFORD alternators eliminates all triplex harmonics; the 3rd order harmonic has the greatest heating and distorting effect on the alternator.

AVR Selection

STAMFORD alternators are available with a wide range of AVRs. A digital or MX321 AVR is recommended, to ensure a 3 phase sensing with isolation from the magnetic influence of the alternator for RTG Crane application. The digital and MX321 AVRs work with the PMG to give outstanding performance. Over voltage protection is included as standard. All AVRs are isolated from the effects of vibration from the drive train by specially selected anti-vibration mountings, eliminating the potentially damaging frequencies.

Diode Protection

Thyristor loads cause very high transient voltage levels when operating, which can damage diodes in the rectifying assembly. Twin Varistors (suppressors) and used on the rectifying assembly to protect the diodes and ensure continuous operation of the crane.

Severe Environment

Guidance on protection against the environmental conditions is provided at the beginning of this AGN. The main stator windings of the STAMFORD alternators recommended for RTG Crane applications are Vacuum Pressure Impregnated (VPI) with epoxy protection resin. The epoxy resins have high mechanical resistance to airborne particles, such that no further over-coat of epoxy is needed.

There are other technical feature for the STAMFORD alternator that may be considered for very arduous RTG Crane applications:

Louvres

The addition of louvres to the air inlet and air outlet, will provide drip proof protection to 60 degrees and depending on the canopy design, may act as a baffle to dirt ingress in the canopy.

Note: The air inlet louvres are likely to increase the overall dimensions of the alternator. Also, most Generating Set canopy designs have air inlet at the alternators end of the canopy, so side air inlet on the alternator adds to the torturous path that dirt particles must take.

Air Inlet Filters

Air inlet filters may be added to the alternator air inlet to increase protection of the stator and rotor windings, by offering a barrier to dry dust particles. The filter is not a coalescer and will not protect against excessive amounts of moisture. However, on a fully enclosed canopy, i.e. not open bottom, the filters will provide a barrier to any slight water vapour suspended in the air entering the canopy.

Manometers

Air inlet filters, when fitted, may cause more problems than they save and if they are not maintained and changed regularly, they become blocked to an unacceptable degree. The use of manometers fitted in close proximity to the filters are highly recommended. The manometers should be mounted on the alternator to give the crane operator a visible indication of when the filter pads should be changed.

Note: Pressure differential switches may be provided for remote indication in the operator's cabin.

Temperature Monitoring

Temperature monitoring options are available for thermistors or RTDs (Resistance Temperature Detectors) to be fitted, to monitor the winding temperatures.

Anti-condensation Heater

It is recognised that in some instances, it is not possible to connect temporary power to a mobile crane when not in use. However, an alternator when not in use and unheated suffers more damage by moisture than one in continuous operation. So wherever possible, heaters should be fitted and power connected, either by mains cables or small mobile generators, to ensure longevity of the alternator.

OPERATING DEMANDS

The RTG Crane application is one of the most arduous applications for an alternator. So far in this AGN, we have looked at the harsh operating environment and we have looked at the loading that is typical for this type of application. There are further operating demands placed on the Generating Set that must also be considered.

Variable Speed Operation

RTG Crane manufacturers are currently developing the next generation of cranes where the Port Authorities need to reduce dock side emissions and container handling operational costs.

Technical discussion is on-going, with a long debate with regard to the limitations of trying to ‘force’ an alternator to operate at a fixed voltage over a speed range. The discussion so far, has centred on practical considerations associated with the alternator’s internal magnetic circuits and their performance capability described by various magnetisation curves and the resulting performance limitations imposed by magnetic saturation.

The following technical comments cover the same subject area. Once the following comments have been read, it becomes imperative to fully discuss the technical needs of the RTG Crane manufacturer and make their engineering team fully aware of the practical limitations, which must be considered and accepted.

A commonly made mistake is that by careful choice, a suitable AVR can be fitted to the alternator and this excitation control module will ‘force’ the alternator to maintain a constant voltage over a speed range.

The performance capability of an AVR should not be confused with the inherent limitations associated with an alternator’s electro-magnetic circuits and the characteristics of magnetic circuit saturation.

An AVR has a clearly defined and simple task and that is to maintain the alternator’s set output voltage. Therefore, an AVR has zero sympathy, or knowledge, of a magnetic circuit being pushed into saturation.

One slight correction to that statement is, that well designed AVR’s have an Under Frequency Roll Off (UFRO) function that introduces an overriding feature, to reduce the alternator’s output voltage, should the operational running speed fall below a pre-set UFRO knee point - typically at 95% rated speed.

The UFRO feature makes the AVR introduce a controlled amount of reduction in the alternator's output voltage, achieved by reducing the operational level of excitation, thereby ensuring the excitation system is not forced into an unacceptable level of magnetic circuit saturation and by so doing, activate a protection system to safeguard against overheating of the excitation system, which includes the main rotor winding assembly.

The Principles and Limitations associated with Magnetic Flux Levels

When designing an alternator it is a fundamental requirement that the alternator's required output voltage range – at the appropriate harmonized frequency – will be generated within an acceptable bandwidth of operational magnetic flux levels.

For reasons of simplifying the subject of complex electro-magnetic flux levels, it is customary to consider operational flux levels in percentage terms around a base level of 100% flux level being the equivalent to an ideal operating condition. Indicating the many and varied flux paths in technically correct unit-terms of Tesla would complicate the following low level technical explanation.

It is generally accepted that an alternator can be operated over a flux range of 95% to 105 % flux level without discomfort, thereby making it possible for an alternator to provide a reasonable voltage range for a given 50Hz or 60Hz frequency mode of operation.

For example, a 50Hz European application will be expected to operate at 380V-400V-415V.

This exact same alternator can be offered at 440V-460V-480V for an American site, where the harmonized system is based on a 60Hz system. With the alternator running faster – 60Hz (1800rpm) rather than 50Hz(1500rpm) - the flux emanating from the rotor is 'cutting' the stator winding at a higher speed, due to the rotor's increased circumferential speed. Under the ideal operating flux level, the identified 50Hz voltages can be increased by a factor of 60 / 50 = 1.2.

This means that, at 60Hz, the ideal operating flux level offers a voltage range of:

- 1.2 x 380 = 456 (which becomes 'rounded-up to 460V)
- 1.2 x 400 = 480V,
- 1.2 x 415V = 498V (which is not an internationally harmonized voltage).

Consider trying to operate the same alternator at a speed of 40 Hz (1200rpm). To keep the magnetic flux levels within 'designed' ideal operating flux levels, the output voltages must be now reduced from the 50Hz voltage levels by a factor of 40 / 50 = 0.8. This now identifies the 'ideal flux level' will generate a voltage range of:

- 0.8 x 380 = 304V
- 0.8 x 400 = 320V
- 0.8 x 420 = 336V

By now an understanding should be forming of why there are finite limits regarding the operational envelope of the magnetic circuit, involving careful considerations for the electro-magnetic circuits and resulting problems associated with forcing an alternator to maintain a constant output voltage over even a relatively limited speed range of 1200rpm to 1800 rpm (40Hz to 60 Hz). Across such a speed range, the flux level will vary inversely with speed and so, will result in 120% at 40Hz and 80% at 60Hz.

Considering the alternators limits under a 1200rpm condition

Operating at a 120% flux is a saturated condition, which can be achieved under a 'forced' condition, using an unsympathetic AVR. This will result in the excitation current being increased considerably above the 'ideal' level.

Fundamental considerations regarding the expected increase in the level of excitation current can be mathematically considered using a cube law factor. This 'factor' indicates that the rotor winding will be forced to carry some 1.2^3 = 173% of designed ideal excitation current in order to create sufficient flux to achieve the expected fixed voltage at the reduced speed.

The increased excitation current will create extra heat within the rotor winding and again, this introduces an additional square law factor to be used and so, 1.73^2 equates to an increase in rotor winding losses (heat) of a factor of 3, therefore indicating three times the normal heat (losses) will be created within the rotor winding assembly when compared with operation under the ideal magnetic flux level condition for the No-Load output voltage condition.

Diagram 1 – further on in this AGN – shows Magnetisation Curves with a typical Saturated condition added as an extension to the Open Circuit Curve (OCC).

Considering also, the alternator's cooling system

This 'forced' condition of generating the 480V at 40Hz is under an operation condition where the alternator's shaft mounted cooling fan is rotating at only 1200rpm. The result is reduced cooling air flow, in terms of volume, plus this reduced quantity of air is moving across the wound component's surface at a slower speed. Therefore, the heat transfer from the wound assembly to the cooling air has become seriously compromised.

Diagram 2 – further on in this AGN – indicates the level of miss-match between an ideal flux level operating condition and one where the forced excitation maintains a constant voltage across speed range. The above explained fundamentals of magnetic circuits found within an alternator offer an overview relating to why there is a defined limit to the operating +/- bandwidth for the output voltage range can now be progressed to offering an explanation of the characteristics, which occur under the effect of load current flowing through the stator winding.

Now considering the effect of the 'forced' output voltage being applied to a load

The next technical area for consideration begins with an explanation of the effect of load current flowing through the alternator's stator winding. The result of current flow is an electro-magnetic field. Connected load's current flowing within the alternator's stator winding creates an electro-magnetic field, which opposes the No-Load flux and so, is said to create a de-magnetising flux called 'armature reaction'.

Load current armature reaction opposes the fundamental flux associated with generating the No-Load voltage required level. So, unless the excitation current is increased to counteract the effect of an applied load's current and resulting armature reaction, the alternator's output voltage will be reduced.

The AVR's function is to 'automatically' maintain a constant output voltage and this is achieved as the AVR dynamically adjusts the operational level of excitation; more excitation being required to maintain the 'set-level' of alternator output voltage, as load is connected and a reduced level of excitation as load is disconnected.

The following data is based on HC4F, but is technically relevant for any alternator.

Diagram 1: Magnetisation curves:

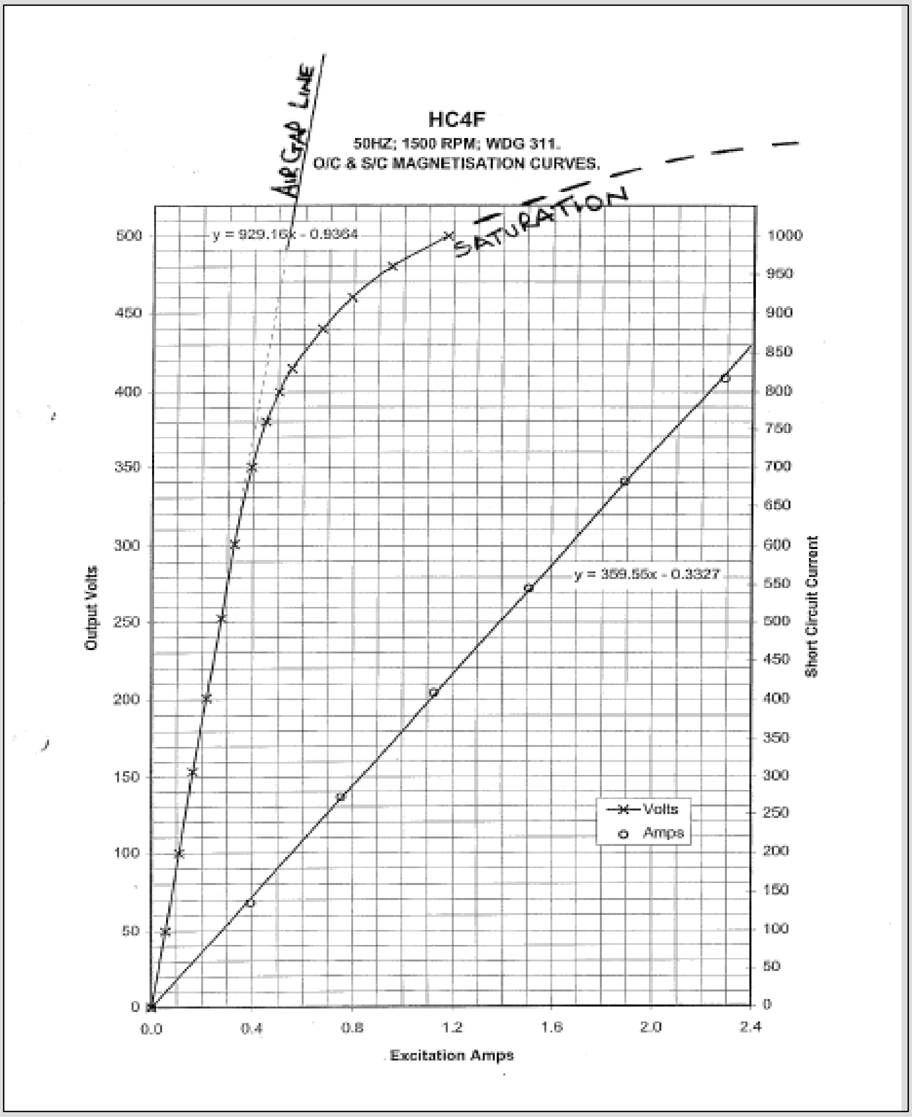
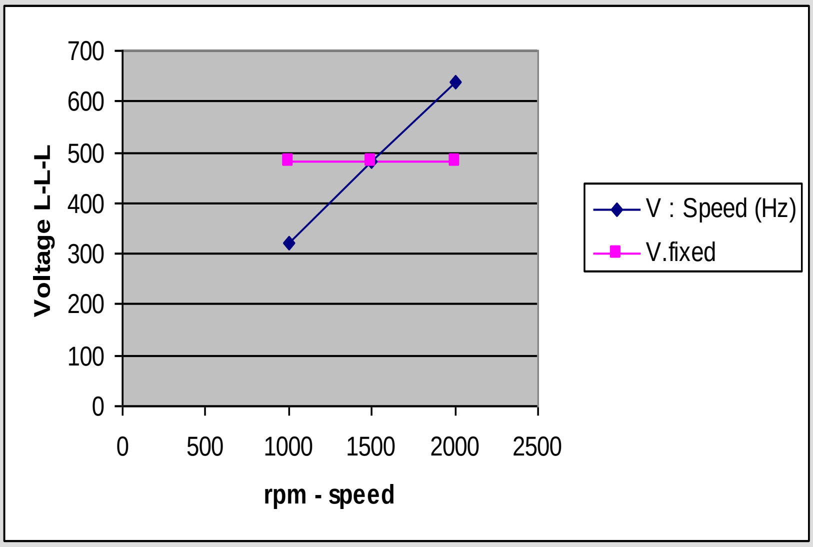


Diagram 2:



The 'Blue (diagonal) line' shows the ideal flux level being maintained when output voltage is proportional to speed. The 'Pink (horizontal) line' indicates a fixed voltage across the speed range.

Note; the miss-match between the two lines at the extreme ends of the speed range.

Summary of above explanations

Each design of alternator has a well-defined maximum level of excitation, which can be applied to that design of alternator.

- **Long term threshold:** The long term threshold being a function to limit the heat created within the excitation systems wound components and also the heat created within the stator winding assembly's lamination steel, resulting from sustained high levels of magnetic flux and lamination steel eddy-current losses.

- **Short term threshold**: The short term threshold being related to the excitation ceiling level, which the AVR can apply to excitation system for short term momentary overload or fault condition 'clearing'.

Hopefully, the above has offered an insight into why the excitation level and the resulting electro-magnetic circuits have inherent limitations, which require careful consideration. Therefore, for a given operating condition the required level of excitation must always be identified.

Even so, the level of excitation being identified as required will encounter finite electro-magnetic limitations shared between:

- Fundamental flux level required to achieve the No-Load voltage level.

- On-load excitation required to overcome armature reactance.
- Operational rotor speed and associated pole face circumferential speed.

All the above conditions will encounter and therefore, must include the inevitable magnetic circuit saturation factors. Finally, all the above must take into account the shaft mounted fan's rotational speed, the resultant airflow quantity and the achievable thermal transfer cooling effect.

Constructing a vector diagram for the Excitation components

The graph on Diagram 1 has details of the level of excitation current required when the alternator is under a test condition of delivering current into a short circuit applied across all three phases. The contained test results provide fundamental data required to establish the winding design's Magnetisation Curves.

Using the Open Circuit Curve (OCC), and the Short Circuit Curve (SCC), it is possible to construct an excitation vector diagram for any alternator's proposed operating condition. By comparing the resulting vector diagram for the proposed condition with a reference vector diagram for the alternator under a known operating condition, a correlation regarding the alternator's ability to operate under the proposed condition is possible.

It must be stated that this method of comparing comparative operating conditions and resulting operational excitation levels is not an absolute method. It will not predict the alternator's thermal continuous rating for the proposed condition - factors associated with an abnormal heating effect within lamination steel's magnetic circuits and a cooling fans thermal heat transfer characteristic are not considered.

But it is a good method to identify how hard the excitation will be required to force the alternator to operate at the proposed condition and so useful as a guide with regard to the alternator's short term capability to operate under this condition for a low level duty cycle period.

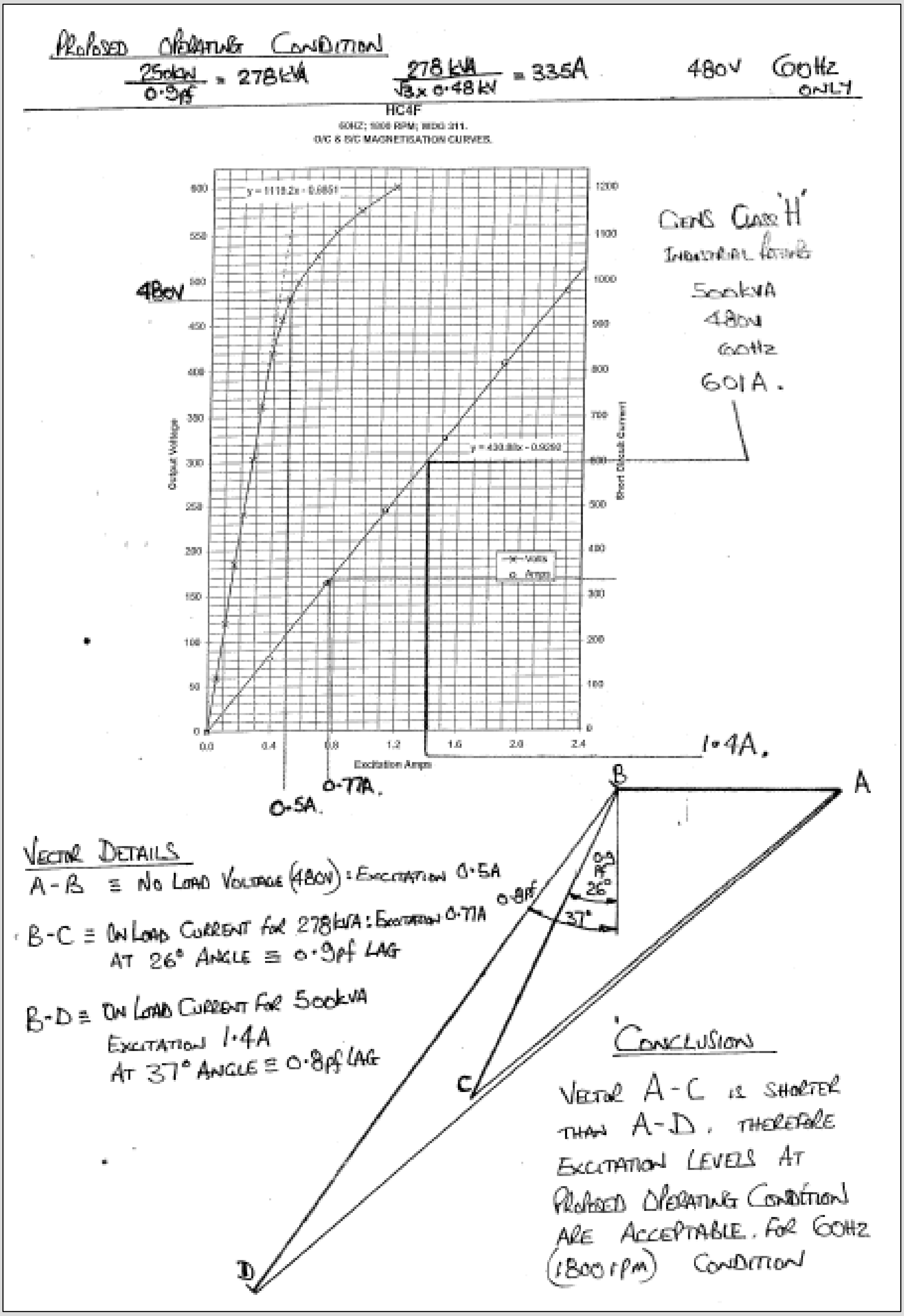
Considering an example 480V at 250kW mode of operation

An excitation vector diagram has been created in the following **Diagram 3.** This shows the proposed 1800rpm, 60Hz, 480V, 250kW (assumed to be at 0.9pf lag) operating condition. The comparative excitation vector diagrams indicate that at 1800rpm the proposed 480V, 250kW (278kVA) condition is acceptable.

An excitation vector diagram constructed for the 1500rpm (50Hz) at the same 480V indicates that 480V, 278kVA, 0.9pf is within the excitation systems capability. However, considerations regarding the likely operating temperature of the stator assembly's lamination steel under a continuous level of magnetic flux density associated with operation at 480V, 50Hz raise serious concerns.

An excitation vector diagram for considering the capability of the excitation system to maintain the identified 480V at 1200rpm (40Hz) identified this to be an **unacceptable mode of operation**.

Diagram 3: Summation of excitation vectors for the no-load voltage and on-load rated current at rated power factor:



Alternative winding designs

The above explanation makes reference to the output voltage range of an alternator having quite a limited bandwidth, which is in fact typically +/-5%. This means that to satisfy each harmonized voltage and frequency sector commonly encountered throughout the world, there needs to be a number of winding designs for a type of alternator. For example, the winding designs for a typical STAMFORD alternator include:

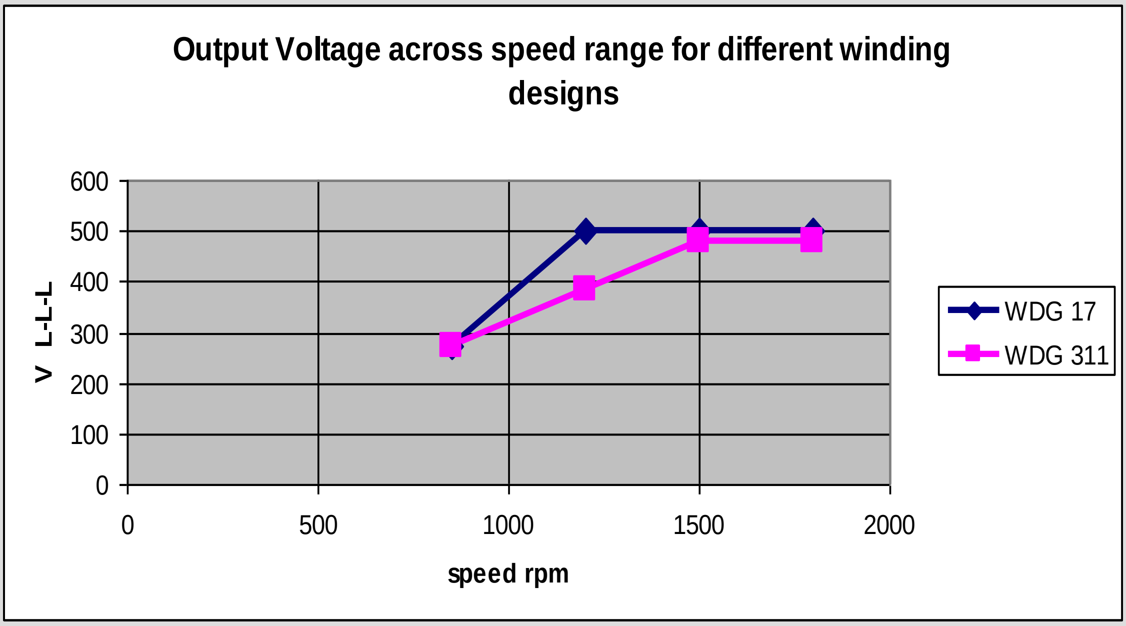
European nominal 400V at 50Hz ……………………….Stator winding design 311
European industrial 690V at 50Hz ……………………..Stator winding design 26
North American 480V at 60Hz………………………….Stator winding design 311
Canadian 600V at 60Hz …………………………………Stator winding design 17
Middle East 380V at 60Hz ………………………………Stator winding design 14
Off shore & Marine 690V at 60Hz ………………………Stator winding design 28

There are many more!

It therefore figures; that considering the use of a different stator winding design may help to solve the problem of unacceptably high flux density levels when trying to nominate an alternator for this with this fixed voltage across the speed range.

Consider the graph below and note how the stator winding design Winding 17 allows the fixed voltage to be held over the speed range of 1200rpm to 1800rpm.

Yet the Winding 311 design can only maintain the fixed voltage over the 1500rpm to 1800rpm range and below 1500rpm, the output voltage must be reduced and this will be achieved by correct adjustment of the AVR.



The graph on the previous page indicates a way forward for a fixed voltage across a speed range application. It indicates that over the 1200rpm to 1800rpm speed range, a constant voltage is possible. The technical explanations in preceding parts of this document have explained how the excitation system will be used to adjust the level of operational magnetic flux in order to maintain a constant voltage over a speed range.

It has already been explained how the ideal level of magnetic flux is identified as being 100% and that the electro-magnetic design criteria is always to achieve this 100% flux level for the output voltage at the centre of an allowable operating bandwidth, e.g. 400V +/-5% for a 50Hz (1500rpm) fixed speed design. The electro-magnetic designer achieves this design balance by careful choice of performance specification and quantity of the active material. This means electrical steel and copper windings.

When considering applying the 'ideal' fixed speed design for a variable speed application, which will involve forcing this alternator's components to operate at a flux level considerably different to the 'ideal' flux level of 100%, with a +/- 5% bandwidth, there are several practical points to be considered:

Stator assembly lamination steel temperatures

Operating at flux levels above 110% significantly increases the temperatures of the lamination steel as a result of magnetic saturation and associated losses. There is always a risk that the lamination steel temperature will reach a level which could thermally degrade the stator winding insulation materials. An absolute maximum flux level above 120% must never be exceeded.

An added complication with the proposed fixed voltage across a speed range application, is the highest operating flux levels will be encountered at the slower running speeds, where the thermal heat transfer characteristics of the cooling air are much reduced.

Harmonic distortion created by the power electronics incorporated within variable speed drives

Dock-side container handling equipment employs VSD's to power the various drives; hoist, gantry, trolley, travel, etc. The expectations of the VSD is that it will be supported by an electrical power supply system that provides a power quality, which will provide a stable supply of voltage and frequency, which resists harmonic distortion. In technical terms, such a supply is described as having a 'Low Source Impedance'.

The need for a low source impedance supply - often called a stiff supply - is primarily to resist harmonic distortion of the voltage waveform resulting from the non-linear current consuming characteristics of the power electronics, within the variable speed drive packages.

A low source impedance supply is achieved by choosing an alternator with low reactance values and the easiest way to achieve this is use an alternator that has a stiff electromagnetic design and so, an operating flux level of some 103% to 108% flux level. An alternative way involves grossly over sizing the alternator.

As the above technical explanation has explained and graphically illustrated, the constant voltage over a speed range requirement will result in an alternator that has low flux levels – therefore, high reactance levels - at high speed and high flux levels at low speed – therefore, low reactance levels.

This means that at high speed where the engine is developing the most power, the alternator has a low flux level, therefore low reactance and so, will be unable to resist harmonic distortion of the voltage waveform. Yet to meet the higher levels of power demanded by the various VSD's incorporated within the crane, the electrical power supply will be handicapped by being forced to operate at low flux levels. Over sizing the alternator to achieve a low source impedance supply for the high speed condition, would not result in a cost effective container handling package.

Consider the graph on the previous page, which shows the allowable voltage across a speed range for a Winding 311 and then Winding 17 design, and summarised in the following table:

Speed(rpm)	Voltage winding 17	Flux level % winding 17	Voltage winding 311	Flux level % winding 311
850	340	120	274	118
1200	480	120	385	118
1500	480	99	480	118
1800	480	79	480	98

Note; how the wider speed range at the constant voltage is achieved by the Winding 17 design, but the flux level at 1800rpm is a very low at 79%, which equates to a very high reactance, high source impedance (soft) supply.

Conclusion on the requirement for Variable Speed Operation

The need for a variable speed Generating Set for incorporation within a dock-side container handling equipment package is well understood and must be provided before environmental legislation forces the issue. Operating a variable speed alternator at a constant voltage, over a high proportion of the proposed speed range, must be reconsidered with the above technical explanation considered by the suppliers of the VSD manufacturers specifying this requirement.

Providing a low source impedance – stiff supply – alternator for a Non Linear Load application, but allowing the alternator's output voltage to be Voltage proportional to Speed, must be proposed to the VSD designers and manufacturers.

Development of a variable speed Generating Set for this application should be in conjunction with the VSD manufacturer's investigation into a power electronics package, which can accept a variable voltage input, ideally V: Hz.

A full understanding needs to be established for the proposed engine's capability to accept load steps expected for the torque demand by various crane drives. The engine's torsional behaviour should also be investigated to identify compatibility calculation to be conducted by the engine manufacturer and therefore, offer guidance regarding the suitability of a single, or two, bearing construction alternator.

An operational duty cycle chart (Load Diagram) should be established to ensure that under slow speed running, therefore high flux conditions, the alternator windings are not becoming overheated.

A harmonic analysis should be conducted under various operating conditions, to ensure the level of system harmonic voltage distortion is acceptable to all connected electrical components – including the alternator.

This is where Application Engineering are available to offer assistance in conducting a sizing exercise for variable speed application. Contact applications@cummins.com.

Non-Standard Voltage Operation - High Flux

Another issue that may need addressing, is the requirement to operate at an unusual – fixed – voltage and frequency configuration. 460V at 50Hz is most commonly required for an RTG Crane application. This simple assumption is based on experience of these applications and the knowledge that electrical equipment manufacturers would not have a standard product range for this high voltage for 50Hz operation. It is further confirmed by experience that some VSD motor control units, especially in the Far East area of the world, use this voltage to power the VSD systems used on RTG Cranes.

At 460V, 50Hz, the alternator's excitation is high, consequently the working Flux level is high. This results in the stator lamination steel running at correspondingly high magnetic flux levels, which cause the stator lamination pack to run hot. In fact, there is a risk that the resulting high stator core pack temperature will damage the stator insulation slot liner.

For example: a HCI634J with standard Winding 312, operating at 460V, 50hz, has a Flux level of 111%. This high flux requires 50% more excitation current – at no load – than the designed ideal 100% flux level at 415V, 50Hz.

To take into account this high flux and associated operating temperatures, the alternator must be de-rated. For a flux level of 111%, a reasonable de-rate is between 20% and 25% below the normal 415V, 50Hz Class H temperature rise continuous base rating.

In addition, the characteristics of the load that the alternator is to support must also be considered. If it is a VSD or UPS, therefore a Non Linear Load, therefore with harmonic current and voltage distortion, this will add to the overall heating effect within the machine, and then an even greater de-rate is required.

In the case of an RTG Crane, the 'Duty Cycle' of the load characteristics is very variable as hoist, trolley, and travel, each accelerate, and then run as individual drives or as combinations of operating drives. This means that the actual heating effect within the alternator caused by this very variable load, is not a real 'continuous' problem.

A further consideration for an RTG Crane application is the fact the alternator has been chosen to offer a low source impedance supply to ensure minimal harmonic voltage distortion, whilst supporting the harmonically distorting VSD NLLs. To achieve this, it will mean that the alternator will be operating at a considerably higher loading level than its full continuous 'thermal rating', and coupled to an engine that could not support the full thermal rating.

Conclusion on non-standard voltage operation

If the example HCI634J Winding 312 is to be used for an RTG Crane application, then there will not be a service problem for the alternator to operate at 460V, 50Hz, and have a name plate rating of 20% less than its normal 415V, 50Hz continuous Class H temperature rise continuous rating. Therefore 1000 x 0.8 = 800kVA is an acceptable nameplate rating at 460V, 50Hz.

If however; the alternator is expected to run at 460V, 50Hz continuously supporting a steady state industrial 'prime' type load, then we may have to consider a 25% to 30% de-rate and therefore nameplated accordingly.

The conclusion here is; that a risk assessment must be carried out. Application Engineering are available to offer assistance in conducting this risk assessment exercise. Contact applications@cummins.com.

REGENERATIVE LOADS

Yet another potential issue; where certain loads feed-back mechanical power to an electrical supply system as a characteristic of their normal mode of operation. A RTG Crane hoist motor, for instance, may have a regenerative braking system to slow and stop the hoist.

Other connected loads sharing the same electrical system may absorb this 'reverse-power' and so the Generating Set may only have to reduce its contributed power output level during these 'reverse-power' occurrences. Unusual in RTG Crane applications, but situations can occur where the level of 'reverse-power' actually exceeds that being consumed by other connected loads and so, regenerated power is actually pushed into the terminals of the alternator.

For further guidance on this potential issue, refer to AGN 018 – Regenerative Loads and Reverse Power.

MAINTENANCE REGIME

There is, without doubt, a need for comprehensive maintenance on a Generating Set used in a RTG Crane application and a Generating Set manufacturer who is experienced in RTG Crane installations will know the extent of maintenance required. From an alternator manufacturer's viewpoint, this is based on the guidance offered in this AGN. For the alternator, in particular, the main stator winding is the most vulnerable area of concern that requires special attention to maintain serviceability. Maintenance advice is offered on the next page.

Alternator Main Stator Winding Insulation System

The only way to check on the condition of the winding insulation system is by introducing a regular procedure to check the stator winding Insulation Resistance [IR] value, and although not normal practice for a low voltage scheme, the Polarisation Index [PI] should be measured.

At the first sign that the IR and PI are low, the alternator stator winding must be cleaned. This check of IR and PI need only be carried out to the stator winding. The spinning of the rotor, and the fact that it operates at a low voltage, means that it is not as much at risk.

However the exciter field is another ‘at risk’ component, and the fact that it operates with dc, means that it has a high risk factor due to its operation with fixed polarisation. If the exciter field insulation fails, it will also take out the AVR.

Realistically, the chances of the local maintenance team being able to do a PI test is perhaps unlikely, but this does not mean that some form of convenient maintenance tool should not be provided for IR/PI measurement. For example, a Megacon Isoguard type system.