Application Guidance Notes: Technical Information from Cummins Generator Technologies

AGN 182 – Operating Efficiency of an Alternator

ALTERNATOR COMPLIANCE WITH CODES, STANDARDS AND DIRECTIVES

Alternators are designed to comply with the various national and international engineering standards associated with rotating electrical machines. The performance of AvK and STAMFORD alternators complies with the 60034-1. In terms of the origin and use of this Standard, there is a traceability from IEC, through EN to BS, as follows:

- IEC 60034-1 is the Standard being managed at the global level
- EN 60034-1 is the version of the IEC standard adopted by the EU
- BS EN 60034-1 is the version of the standard adopted by UK

This international engineering standard for Rotating Electrical Machines details aspects of operational expectations and is entitled ‘Rating and Performance’. It is this engineering standard that defines all the necessary guidance regarding the operating efficiency of an ac generator (alternator).

This IEC 60034 approach introduces the concept of ‘Typical’ efficiency that, when stated and supported as a measured value maintained within set parameters held within a library of test data which is continually updated as the manufacturer of that product, conducts regular quality sampling test work as part of their ISO 9001 quality plan.

When an alternator is specified with a requirement for a ‘Guaranteed’ efficiency value, that individual alternator’s likely efficiency will initially be considered, based on test data library information correlated to quality sampling and the known performance trend of active material presently being used for product manufacture. This allows a best value to be identified, which will be duly adjusted to ensure a guaranteed value will be satisfied. In most cases, that alternator will be selected for verification and validation testing before despatch.

OPERATING EFFICIENCY OF ALTERNATORS

The 60034-1 describes a test method for establishing alternator efficiency, along with introducing realism regarding the performance variances that will inevitably be present resulting from unavoidable material specification tolerance bandwidth associated with the active materials incorporated within volume manufactured rotating electrical machines. The 60034-1 introduces allowances for the resulting bandwidth of measured efficiency values for volume manufactured alternators by introducing an allowable variance in the value of the stated losses. These are indirectly stated in the alternator's published Technical Data Sheet, but readily identified as the difference between 100% minus the alternator's stated efficiency percentage.

- For alternators with rated output <150 kVA, the allowable tolerance for efficiency is -15%
- For alternators with rated output >150 kVA, the allowable tolerance for efficiency is -10%

Section 12 of the 60034-1 contains a table, which identifies the tolerance on values and quantities.

Item	Quantity	Tolerance
1	Efficiency η	
	– machines up to and including 150 kW (or kVA)	–15 % of $(1 - \eta)$
	– machines above 150 kW (or kVA)	–10 % of $(1 - \eta)$
2	Total losses (applicable to machines with ratings >150 kW or kVA)	+10 % of the total losses

Explanation

To explain further; it must be accepted that, for a given alternator, the materials, construction and operational conditions will all be subject to tolerances and variances, which cumulatively combine to have an influence on the actual operating efficiency of a specific alternator powering a specific application's load.

Those manufacturers of alternators claiming adherence to IEC 60034 will have conducted the necessary engineering test work to verify and validate each product's performance for the proposed operational envelope. With regard to efficiency levels, several samples will have been tested to establish a typical operating efficiency level, which is then included within the alternator's published Technical Data Sheet. Quality sampling then ensures continued adherence to the standard and the published data. This typical efficiency level is advisory.

Example

Consider the published efficiency value for an alternator rated at above 150kVA. The tolerance advises that losses can increase by 10%. If the typical efficiency is advised as being 92%, then invoking the -10% consideration suggests:

- The total losses could be = 1.1 (1 – 0.92) = 0.088pu.
- Therefore the operating efficiency could be = 1 – 0.088 = 91.2%
- With the alternator still adhering to IEC 60034-1.

Alternator Losses

As described previously in this AGN, alternators are designed to comply with IEC 60034 and the published technical data advises 'typical' efficiency values. The total losses associated with the operating efficiency of an alternator can be broken down into six distinct areas. The following identifies each area and includes a brief explanation.

Friction and Windage Losses

- **Typically represent 10% of the alternator's total losses.**

- These losses are associated with spinning the unexcited rotor assembly at rated speed. The power taken to drive the fan and so move the required cooling air through the various air flow paths will represent the major part of these losses, although the irregular construction of the salient pole rotor and rotating diode assembly does add to windage losses.

- The frictional losses associated with the shaft supporting bearing(s) is very low and for this reason the efficiency of single and two bearing alternators are not differentiated.

- The fan performance in terms of air flow volume and speed, and the resulting thermal heat transfer characteristics via the designed air flow paths over back iron, through and around out-hangs and through the stator bore, have been developed for each alternator frame size for the IC01 indirect cooling system, to ensure good rotor to stator thermal balance under the prescribed continuous output rating. Such considerations take into account the changes to air circuit resistance encountered as core pack lengths vary for a given alternator frame size.

Iron Losses

- **Typically represent 12% of the alternator's total losses.**

- The losses associated with the stator core pack's laminated steel assembly are linked with the choice of the electrical steel, the specified form of inter lamination insulation, steel thickness, combined with the designed slot form and resulting operational magnetic flux paths and levels. Summed together, these factors combine to introduce complex considerations that affect magnetic circuit behaviour with defined losses.

- Flux levels must be set to enable the alternator to have output voltage stability across 0<100% rated load conditions, plus acceptable capability under transient, momentary and short term overload conditions, as encountered with fault clearing, load step changes and forced excitation conditions when motor starting, etc.

- Such operational considerations can be taken to extremes when, for example, supporting a Non Linear Load (NLL), or the alternator is ‘embedded’ with a network with an operationally wide voltage range.

- A change to lower loss electrical steels introduces a complex design process, accepting the stator core losses will be reduced, but at the expense of requiring increased magnetising effort, which increases the rotor current, therefore increased the rotor losses.

Stator Winding Copper Losses

- **Typically represent 45% of the alternator’s total losses.**

- The loss associated with the stator winding is based on I^2R. Where: ‘I’ is considered by the ‘amps’ being delivered to the connected load and so ‘flowing’ through the stator winding. ‘R’ being the stator winding resistance, which must take into account the ohmic value of the windings will increase in proportion with winding temperature, which in turn has a direct relationship with the level of load current being delivered.

- Engineers recognise that the stator winding copper losses represent the majority of the alternator’s inefficiency. Therefore; operating the alternator under a loading level where the output current ‘I’ is comfortably within the alternator’s thermal limits will keep ‘R’ as low as possible and thereby aid the drive towards operating at peak efficiency.

- For most industrial alternators, operating within the region between the Class B temperature rise rating (80C rise / 40C ambient) and the Class F temperature rise rating (105C rise / 40C ambient) will be rewarded by operating in the envelope of peak operating efficiency.

Stray Losses

- **Typically represent 12% of the alternator’s total losses.**

- This category covers a complex mixture of losses that electro-magnetic design engineers assign as ‘stray’; it being a convenient place to attribute complicated unknowns.

- What is accepted, is that the majority of stray losses occur in and around the region of the stator winding out-hangs at each end of the stator and rotor lamination core packs. Here complex electro-magnetic circuits abound, associated by the load current flowing in the stator windings, and stray magnetic fields from the excitation system. Controlling winding out-hang dimensions, and careful management of their shape and proximity is beneficial, but as the stray losses are proportional to the stator winding copper losses, the real benefit comes from operating the alternator at a conservative rating.

Rotor Copper Losses

- **Typically represent 18% of the alternator's total losses.**

- The losses associated with the rotor winding are based on I^2R. Where: 'I' is the rotor winding current required to achieve the rotor circuit's Ampere–Turns required to produce the electro-magnetic field to excite the stator. 'R' is the rotor winding resistance. The rotor winding current level is set by the need to provide an air gap flux, which maintains rated output voltage under the operating conditions set by the current consuming characteristics of the connected electrical load. Rotor current levels increase generally in proportion with rated output, and increase again if that load has power factor (pf) that is not at unity pf.

- If the alternator is forced to operate outside the ideal voltage range for that alternator's stator winding design, or the load has a low lagging power factor or high harmonic content, then levels of magnetic saturation will be encountered, which cumulatively result in even higher levels of rotor current being demanded. Such situations result in increased rotor temperature that inevitably radiates and increases the stator temperature and so stator winding 'R'.

- Once again, operating the alternator within the region between the Class B temperature rise rating (80C rise / 40C ambient) and the Class F temperature rise rating (105C rise / 40C ambient), at a power factor as close to unity (1.0) as possible, improves alternator efficiency.

Exciter Losses

Typically represent 3% of the alternator's total losses.

In a brushless alternator, the incorporated 'exciter' provides the necessary amplification between the low power levels from the AVR into the high power level required by the main rotor's windings. The power required for this – rotary – amplification stage is directly provided by the Generating Set's prime mover.

The exciter's losses include a product of copper losses and iron losses, but exciters must be designed to perform under conditions of alternator load step changes, momentary overload conditions and steady state overload conditions without encountering magnetic saturation. This requires the exciter design to be generously designed with regard to iron and copper content and thereby has inherent low I^2R losses.

Conclusion

The drive to create a cost effective alternator design; where economic use of active materials – copper and lamination steel – are minimised in order to achieve the highest possible **kVA output per kg of active material,** will not result in an alternator with high operating efficiency at its published Class H temperature rise Base Continuous Rating. This situation can be redressed by due reference to the efficiency curves and by choosing to operate the alternator at a de-rated output that coincides with the alternator's peak efficiency.

Efficiency curves are included in each alternator's published Technical Data Sheet (TDS).

OPERATING EFFICIENCY OF GENERATING SETS

Optimising the overall operating efficiency of a Generating Set has always been important. An objective to identify areas of inefficiency, associated when the spectrum of fuel input against electrical power output is to be considered, challenges engineers across many specialist fields of mechanical and electrical engineering.

The work of these engineers must include considerations and due concern with regard to a broad base of practical engineering and international legislative requirements that may force emphasis of key performance parameters to take precedence over achieving optimum efficiency.

Even the most simplistic approach for contemplating overall Generating Set efficiency quickly identifies the reciprocating internal combustion engine (RIC engine) as being the most inefficient component, accepting the overall efficiency of Generating Sets does improve as power levels increase. Even so, for an RIC diesel engine, the operating efficiency broadly falls within the bandwidth of 30<40%, with the alternator's typical efficiency bandwidth being 80<97%.