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Application Guidance Notes: Technical Information from STAMFORD | AvK

AGN025 – Non Linear Loads

DESCRIPTION

A Non Linear Load [NLL] is a load with current consuming characteristics that do not follow (mimic) the same fundamental shape as the applied voltage waveform. Technically, this situation is examined by conducting a voltage and current harmonic analysis. This data provides details of the predominant current harmonics and the resulting harmonic distortion to the applied voltage waveform.

There are many commonly encountered Non Linear Loads. There are NLLs that consume continuous current, examples being lighting units associated with discharge lamps, and then discontinuous current associated with power electronic devices.

The most troublesome Non Linear Loads incorporate power electronics devices. Examples being: phase controlled thyristor bridges, transistors – insulated-gate bipolar transistors (IGBTs) or diodes – as in an uncontrolled bridge. All such devices will generate harmonic current distortion, which in turn will distort the applied A.C. voltage waveform.

We are often asked, What level of ‘over-sizing factor’ should be used when offering a Generating Set for loads such as Variable Speed Drives (VSD), Uninterruptible Power Supply (UPS), or even a sports stadium lighting system, where all introduce concerns regarding system operational levels of harmonic distortion?

The short answer is, there is no single ‘over-sizing factor’ suitable to cover all applications involving loads that generate harmonic distortion. Each application consideration must begin by establishing an understanding of the operational characteristics of the proposed NLL equipment in terms of the level of harmonic current distortion, plus identification of the total connected load's peak and steady state kVA level. As there are many types of NLL's resulting in many different operating characteristics, it figures that there will be many over-sizing factors.

It must be appreciated that when considering the characteristics of a Variable Speed Drive [VSD], or an Uninterruptible Power Supply [UPS], it is the characteristics of the converter stage that affect the alternator. What happens in the inverter stage is of interest, but may well have little effect on the resulting level of harmonic voltage distortion generated within the applied voltage waveform from the power supply (alternator).

If the level of harmonic voltage waveform distortion is allowed to become too high it will lead to either a malfunction of the NLL power electronic system, or instability of the alternator's excitation system.

Non Linear Load's are now common place and so alternators are available 'fit for purpose'. A suitable excitation system will be available, sometimes listed as an optional extra, or even a retro fit kit, which will maintain a stable generated RMS output voltage, despite the voltage waveform distortion caused by the NLL. However, experience suggests that long before a correctly specified alternator has problems with harmonic distortion, the NLL's electronic power devices and their associated phase angle control system will begin to malfunction.

SIZING AN ALTERNATOR FOR SUPPLYING NON LINEAR LOADS

There is a logical route that will provide an engineered solution for the nomination of a suitable alternator for any application where complex loads including NLL's are to be considered. The following explanation describes a route that has been broken down into parts in an attempt to provide a progressive understanding of the issues involved.

Part 1. Fundamentals

It must be accepted that when supplying a load with inherent current waveform distortion, the supply voltage waveform will become affected and so will also become harmonically distorted. Therefore consideration must always be given to identifying an acceptable level of harmonic voltage distortion. Many types of electrical equipment have a finite tolerance to a distorted level voltage waveform above which equipment is likely to malfunction or component failure occurs.

Once the percentage levels of Total Harmonic Distortion (THD%) for both the current and voltage waveform have been identified, then the operational characteristics of the required electrical power supply can be fully considered, and so the alternator nomination exercise can begin.

A fundamental approach involves considering the relationship between harmonic current distortion, harmonic voltage distortion and in turn power supply (alternator) source impedance in terms of Ohms Law.

Where; the supply source impedance R = V.dist% / I.dist%

For an alternator, the parameter which best ‘describes’ source impedance for consideration of voltage waveform distortion is the sub-transient reactance X”d.

This basic level approach simply provides a relationship comparison as a route towards identifying a suitable level of alternator impedance (sub-transient reactance actually), and so a ‘rule of thumb’ guidance regarding the level of ‘specialness’ required when comparing the required ‘special’ alternator to normal industrial prime rated Generating Set’s engine and alternator combination.

If nothing else, this explains the importance of gathering data regarding the characteristics of the NLL and then to also consider the needs of **all** connected loads before the quest for alternator sizing and nomination can begin.

Part 2.1. Types of NLL’s and typical characteristics for current waveform harmonic distortion

Some electrical loads draw continuous current over the period of each applied voltage half wave, but due to their complex current consuming behaviour, which results in the generation of a complex current waveform with individual harmonic orders, which combine to give the fundamental current waveform a high harmonic content. An example of such a load is:

- Discharge lamps.

Some electrical loads draw discontinuous current for each applied voltage half wave. Such loads incorporate power electronic packages. The action of this discontinuous current is to generate a pronounced level of harmonic distortion which can vary considerably as the absorbed kVA varies over the equipment’s operating range. The following are common types of Non Linear Loads that incorporate electronic power devices:

- Rectifiers
- UPS systems
- Variable Speed Drives (VSD) and Variable Frequency Drives (VFD)
- Soft start systems
- Switch mode power supplies

Obtaining data regarding the harmonic current distortion characteristics of a proposed load can be difficult, and so the following section provides key questions, and then suggestions regarding typical values should assumptions need to be made.

Part 2.2. A questionnaire to identify technical characteristics of the NLL

To establish acceptable levels of voltage waveform distortion, it is important to know the type of NLL to be powered. The following details regarding the characteristics of the NLL are required;

- Number of pulses associated with the converter stage. This is normally 6 or 12.
- Level [%] of harmonic Current distortion generated by the NLL.
- Are harmonic filters fitted to reduce the level of Current distortion?
- Maximum acceptable level of harmonic Voltage distortion.

- If UPS, then peak input under battery recharge condition.
- If VSD, then motor starting peak kVA condition.
- Operating Voltage and Frequency.
- Operating Power Factor and efficiency.

When actual data cannot be obtained then assumptions must be made and the following offers typical values for types of NNL's.

Typical Levels of Total Harmonic Current Distortion

Current Distortion on a NLL is referred to THDi or Idist and is given as a percentage:

- 12 pulse - 14% (also considered appropriate for modern IGBTs)
- 6 pulse - 30%
- 4 pulse - 45% (single phase equipment)

Typical Acceptable Levels of Total Harmonic Voltage Distortion

If no specified levels for system harmonic voltage distortion can be provided then the following typical levels can be assumed, but the customer should be made aware that assumptions are now replacing real engineering data.

Voltage Distortion created by a NLL is referred to THDv or Vdist and is given as a percentage:

- UPS Systems - 10%
- Inverter Drives - 15%
- Soft Start Systems - 20%
- Rectifiers - 20%

<u>Part 3. The Behaviour of Non Linear Loads and Alternators</u>

The chosen alternator must have a low enough 'source impedance' to ensure that the resulting level of system harmonic voltage distortion will be acceptable to the NLL and this may also mean acceptable to any 'normal' load being supplied.

As a general rule, the following basic formulae can be used to gain an appreciation of the behaviour of Non Linear Loads and alternators.

It must be accepted that these 'Rules of Thumb' should not be misused by making guaranteed promises to customers based on the answers provided by each simple rule, nor should the answer be taken to a number beyond one decimal place and the answer should always be rounded up rather than down when being applied to the alternator selection process.

General Rule

This rule assists with the identification of the required level of alternator source impedance, as measured by the required level of sub-transient reactance (X"d) for the alternator under consideration, in order to achieve a required level of harmonic voltage distortion. Remember the alternator must always be nominated based on a class ‘F’ (105/40°C) rating to ensure the extra heating effect of the harmonics does not force the alternator to operate above the class H (180°C) thermal limit for the insulation system.

X”d % = (V.dist% / I.dist%) x (Pn / 6) x 10

Where:

X”d is the sub-transient reactance level required for the proposed alternator.
V.dist% is the required level of harmonic voltage distortion.
I.dist% is the level of harmonic current distortion the NLL operates with.
Pn is the number of pulses associated with the converter stage of the NLL.

Example:

The NLL is 6 pulse, with 30% I.dist, and a specified level of V.dist at 10%:

X”d % = (V.dist% / I.dist%) x (Pn / 6) x 10

X”d% = (10 / 30) x (6 / 6) x 10
X”d% = 0.33 x 1 x 10
X”d% = 3.3%

The Class ‘F’ temperature rise [105/40] rating of the alternator will have an X’’d greater than 3.3% - usually around 12%. It will be necessary to de-rate the kVA output of the alternator to reduce the X’’d to 3.3%.

By transposing the formula, the level of V.dist% for a situation where the alternator X”d% is already known, can be calculated;

V.dist% = (X”d% x I.dist% x 6) / (10 x 6)

Based on using the same values:

V.dist% = (3.3 x 30 x 6) / (10 x 6)

V.dist% = 10%

Part 4: Associated considerations when supporting NLL

So, nominating a ‘fit for purpose’ alternator starts with considering the characteristics of the NLL. This includes the identification of input kVA and typical level of harmonic current distortion. This information is then computed against the ‘source impedance of the supply’ and for an alternator, this means considering the value of the alternators sub-transient reactance [X”d].

Once the correct alternator has been identified the appropriate excitation system can be included in the final alternator's specification. The excitation system must include Auxiliary Winding technology or a PMG and MX321 AVR or DM110 AVR, as appropriate.

Thermal considerations – The heating effect of harmonics

Harmonic distortion as a result of Non Linear Loads will generate extra heating in the power supply system that is being used to support them. The current harmonics will cause extra non power producing current to flow and as a result; will increase the heating in all supply cables and of course, the alternator stator windings.

The effect of extra [harmonic] current flowing through the stator windings will result in increased armature reaction occurring within the alternator and this will require the alternator excitation system to operate at higher than normally expected levels, with the result that the main rotor windings will be hotter than expected.

A side issue of this activity is that the damper cage may also be affected by the harmonics, which may result in unexpected continuous current flowing through the damper cage and therefore, more heat.

The effect of the resulting harmonic voltage distortion occurring on the generated voltage waveform will be for these higher than fundamental voltages to promote extra heating within the stator lamination steel.

The combined effect of the extra heating effect due to the alternator powering a NLL is very dependent upon the level of harmonics present within the system and we all know that this is directly proportional to the characteristics of the NLL, combined with the source Impedance of the supply, which we always relate to the value of the alternator's X"d.

For this reason, the total continuous load should never exceed the alternator's Class 'F' temperature rise [105/40] rating.

This will result in the **real** total heating effect within the alternator being such that the alternator stator and rotor components will be operating at temperatures just below a full Class 'H' rating level.

Excitation system:

To ensure the alternator's excitation system remains stable under the imposed levels of harmonic distortion created by the NLL, an isolated and so stable power supply must be incorporated within the alternator to provide the AVR with an excitation power source. Ideally this should be based on a PMG pilot exciter, although a well-designed auxiliary stator winding can provide acceptable levels of performance.

NLL's with harmonic filters:

Harmonic filters designed to reduce the effective level of system harmonic distortion are available specific to the characteristics of each type of NLL. The latest technology is based on 'Active-Filters' which are active harmonic compensating systems with the ability to maintain the voltage to virtually a pure sine-wave. NLL's operating in conjunction with active filter will operate at very close to 1.0pf, and so engine nominations need to take this into account.

Well-designed traditional harmonic filter packages consist of a combination of capacitors and chokes as tuned LC circuit. Low cost filters are likely to be capacitors only, and these can cause operational problems for the alternator's excitation system, due to a self-excitation effect should the total connected load become a very leading power factor (kVAr lead) condition. Most alternators can only tolerate a low value of leading kVAr (Zpf lead capacitive current) and typically this is in the order of 25% of the alternator's industrial rated kVA.

Inclusion of any form of harmonic filter package therefore needs technical consideration to ensure problems do not occur during the NLL's 'start-up', when the active power is virtually zero, and the alternator may only be supplying only a leading pf load.

Part 5: Sizing the Alternator

At this stage, it is important to note that the NLL will always be the most susceptible part of the site equipment package should unacceptably high levels of supply system harmonic voltage distortion be allowed to occur. It is never a malfunction of a correctly 'sized' Generating Set.

At this stage, we now have the key information regarding operational parameters. We have gathered and considered data for the proposed NLL and the normal (linear) loads. We have applied typical acceptable levels of system harmonic distortion when no information is available. We have determined the required level of source impedance of the alternator by calculating the alternator's sub-transient reactance (X''d). And we have considered the alternator design specification. We can now conclude the 'alternator sizing' process.

The 'basic level approach' covered in Part 1 has a formula which introduces the term R as a route to provide an indication of power supply (alternator) source impedance. When the level of harmonic current distortion is high yet the required level of harmonic voltage distortion is low, then the source impedance of the supply system must be very low. In practical terms this means that an alternator must be selected with very low levels of reactance, thereby a very low level of sub-transient reactance X"d will be achieved.

Engineers use complex computations to consider the effect of voltage and current harmonic distortion levels, distribution system impedance, and the consequence of operational linear loads that inevitably will be sharing the electrical system. However, in an attempt to keep it simple, we apply an uncomplicated two-step approach. Firstly, in Part 3, we calculated a value of X"d. Now, secondly, we must relate this X"d towards a route for alternator nomination.

The X"d% value in Part 3 now needs to be corrected to the base kVA level of the proposed NLL input kVA. This is a simple 'correction' calculation to identify the NLL's base kVA level:

(NLL input kVA / Alternator's published kVA for published value of X"d) x **Published value of X"d.**

To more effectively illustrate the sizing process, it is better to use an example:

Example*: 415V 50Hz system, a mixed load of some 450kVA which includes a UPS identified as having a maximum input demand of 300kVA, 6-pulse with 30% harmonic current distortion and the advised maximum level of harmonic voltage distortion is 10%.*

Source impedance considerations:

The alternator must have a Class F temperature rise rating of at least 450kVA, and so this a fundamental starting point for alternator consideration:

From our example in Part 3, we know the alternator will require X"d to be no more than 3.3%.

From a data file, an alternator is found with a Class F temperature rise rating of 475kVA, with an identified X"d of 12% for this base rating at 415V 50Hz

Now we correct this published X"d for the 'F' rating to a recalculated for X"d against a base rating associated with the UPS input kVA:

UPS base level X"d = (300/450) x 12% = 8%

As the required alternator must have an X"d of up to 3.3%, this alternator is unsuitable.

From a data file, another alternator is selected. This alternator has a Class 'F' rating of 850kVA and published X"d of 9% at 415V 50Hz.

Again, we correct this published X"d for the 'F' rating to a recalculated for X"d against a base rating associated with the UPS input kVA:

UPS base level X"d = (300/850) x 9% = 3.2%.

This alternator is suitable.

Excitation system considerations:

The alternator must be fitted with a suitable excitation system and AVR, specifying the need for an isolated power supply for the AVR by preferably PMG pilot exciter, alternatively a stator auxiliary winding system.

Practical considerations **regarding Generating Set design must now be considered:**

As the correctly selected alternator is an 850kVA design, yet the application is identified as 450kVA, and so an appropriate engine for a 450kVA Generating Set is all that is required. The miss-match of large alternator to small engine forces the Generating Set designer to consider special Engine-Alternator base frame design, torsional compatibility, starter motor torque, alternator's inherently high fault current levels and an electrical protection system, and on-site installation scheme, that will duly consider the operational harmonic distortion levels and any resulting EMC contravention.

Based on the above calculation the following list provides reference values for typically encountered NLL applications:

Consider a 6 pulse unfiltered NLL with some 30% harmonic current distortion:

To operate with the harmonic voltage distortion in the region of 10%, then X"d ~ 3.3%

To operate with the harmonic voltage distortion in the region of 15%, then X"d ~ 5.0%

To operate with the harmonic voltage distortion in the region of 20%, then X”d ~ 6.7%

Consider a 12 pulse unfiltered NLL with some 14% harmonic current distortion:

To operate with the harmonic voltage distortion in the region of 10%, then X”d ~ 14%

To operate with the harmonic voltage distortion in the region of 15%, then X”d ~ 21%

Part 6: Existing and Old Alternators

Identifying the capability of existing / old alternators to support newly installed NLL’s requires all the above outlined operational information to be gathered and taken into account for the proposed NLL. This information then needs to be considered against the existing alternator’s value of sub-transient reactance [X”d] calculated against a ‘base level’ for the proposed NLL’s operating kVA.

If the NLL is likely to result in generating a level of harmonic voltage distortion above 5% then the alternator will need to be fitted with an excitation system that is isolated from the alternator’s main output connections. In the case of a STAMFORD alternator, this can be achieved by the fitting of a PMG and MX321 type or digital type AVR.

CONCLUSION

The above technical explanation has purposely been kept at a level that provides a simple explanation, which hopefully will remove some of the mystery that often surrounds a Generating Set sizing exercise, when complex combinations of mixed loads that include NLL’s are specified. The described calculations have purposely been kept simple. Their roots are the results of years of experience making complex calculations that lead to an observation that for the vast majority of typical NLL’s, a ‘fast-track’ calculation could be used and this experience is now shared.

RECOMMENDATIONS

The harmonic distortion adds to the alternator’s operating temperature and therefore, the total continuous load should never exceed a Class ‘F’ temperature rise [105/40] rating.

Once information is available for the above key points for the Non Linear Loads, the Application Engineering Department will be able to quickly nominate a suitable alternator for any type of Non Linear Load. Email, applications@cummins.com.

It is important to accept that it is the NLL that will be the first item to malfunction under conditions of unacceptably high levels of harmonic Voltage distortion, not the alternator.

Refer to AGN026 Harmonic Voltage Distortion, for further information on acceptable levels of V.dist%, the heating effects on an alternator and ways to reduce distortion.

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