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Application Guidance Notes: Technical Information from STAMFORD | AvK

AGN 034 – Alternator Reactance

DEFINITION

Reactance Periods

Inherent to the design of an alternator are certain internal dynamic characteristics that influence the performance of the alternator under momentary and steady state load conditions. These characteristics can be individualised to identify behaviour at specific times following load level changes and are collectively referred to as reactances. Each individual reactance characteristic can be influenced at the point of alternator electro-magnetic design.

When the alternator's load conditions are suddenly changed the alternator's resulting performance deliberations begin by considering:

- The sub-transient reactance for 'time zero' response.
- As time elapses beyond half a cycle, the transient reactance.
- And finally, the resulting steady state conditions are identified by a qualification of positive, negative and zero sequence components.

Sub-Transient Reactance [X"d] - 'The Kick'

During the first few milliseconds of a sudden load change, the characteristics attributable to X"d will result in a response that promotes a rather aggressive reaction to the load change. In the case of a short circuit fault occurring, high levels of current will be generated, which momentarily reach the equivalent to the full load current multiplied by the reciprocal of the sub-transient reactance. If the sub-transient reactance is 12%, the peak values will be some 8 x rated current and this is described as being the symmetrical condition, with the asymmetrical - absolute maximum - being twice the symmetrical value.

Transient Reactance [X'd] - 'The Follow Through'

After the first few milliseconds of X"d influenced behaviour, the alternator's performance becomes dominated by X'd and appropriate time constants. In the case of a short circuit fault condition, the high current levels associated with X"d decay at a rate controlled by X'd in conjunction with various alternator time constants.

Synchronous Reactance [Xd] - 'The Push'

Modern alternators, fitted with a control system capable of supporting a sustained steady state short circuit current, will typically sustain 2 to 4 x rated current under a steady state three phase short circuit condition. This means that Xd should not be used to determine the third period fault current level, but engineers can deduce a great deal about an alternator's 'capability' from Xd.

Xd is, in fact, established by the ratio of the excitation levels established by SCC and OCC tests.

The Effect of Reactances

The performance of each alternator under short circuit conditions is presented on the alternator's Short Circuit Decrement Curve and this displays the effects of X"d, X'd and excitation forced, fault current (rms) levels over time.

Zero Sequence Reactance [Xo]

When an alternator has a grounded Neutral and a fault occurs, thereby shorting phases together and to-earth, resulting phase fault-currents will become in phase: *zero phase angle displacement.*

Negative Sequence Reactance [X_2]

This reactance is used to establish alternator performance under unbalanced load, or fault conditions, thereby generating a contra-rotating to normal operation: *negative phase sequence*.

AN ALTERNATOR AND ITS REACTANCES

This section is based on a question about the differences between the overload and fault contribution of the UCI or UCM 224G. The answer below explains how a thermal rating does not change the inherent performance of a particular alternator design. The answer covers the UC 224G alternator but is applicable to any STAMFORD or AvK alternator.

The UC 224G alternator is a standard STAMFORD product with the G being the core length identifying the amount of 'active material' - in the form of lamination steel and copper wire that will be used to build this G core length of frame type 224 alternator. For additional information; the winding number and design for the alternator decides the number of turns required [to give the voltage required] and therefore, this controls the allowable cross sectional area of the conductor for each winding coil turn, that can be fitted into the space available in the stator winding slot, but [almost] regardless of winding design - and so output voltage level required - the active material will always be fully utilised. This is how we design in order to make a cost effective alternator.

A decision now has to be made regarding whether the alternator will be operated at the absolute maximum allowable temperatures for the insulation materials and winding assembly, as would be the case with a standard Industrial UCI [I for Industrial] or operated at a reduced and specified operating temperature in order to be compliant with a marine classifying society and so be offered at a lower kVA and therefore, become a UCM [M for Marine]. So these basic considerations and factors are used and so, set the alternator's continuous thermal rating – nameplated kVA.

We must remember; it is still the same amount of active materials inside the alternator, so when this machine is subject to an impact load, an overload, or a fault condition, the alternator will always behave in the same way regardless of its nameplated kVA or identified application - UCI or UCM. The stored energy dealing with the suddenly changed load condition comes from within the alternator as a product of the active materials within that alternator and a UC 224G, whether it’s a UCI or UCM makes no difference.

Things that do make a difference:

- **The operating magnetic flux levels.** If the UCI and UCM are both working at the same voltage and frequency, the situation is nullified, as the flux levels will be the same. The expressions used to describe an alternator’s 'reaction' to a sudden load step change are the ‘Reactances’ and ‘Time Constants’. Perhaps the most commonly used measure of an alternator’s capability to respond to a load step change is the value of the alternator’s sub-transient reactance X"d. The value of X"d takes into account the operating magnetic flux level therefore, the operating voltage level and frequency, and then this is referred back to a 'base' rating kVA, maybe the nameplated kVA rating, but on data sheets it is usually based on the Industrial kVA rating.

So consider the UC 224G operating at 415V, 50Hz;

As an **Industrial** alternator it has a class H rating of 85kVA and a published value for sub-transient reactance X"d of 11% at a Class H temperature rise continuous (base) rating of 85kVA. The same alternator has an industrial Class F temperature rise rating of 75kVA. X"d at the Class F rating is therefore; equal to [75/85] x 11 = 9.7%.

The same alternator as a **Marine** alternator has a Class F temperature rise continuous marine rating of 65kVA and so X"d at this marine rating is equal to [65/85] x 11 = 8.4%. At the Class B marine rating of 60kVA, the X"d is equal to [60/85] x 11 = 7.8%.

The above explains how as the same alternator has different values of X"d at different kVA outputs. But when the 'time zero' fault current is established using the basic formula of [1 / X"d] x base rated current [Amps], the answer will always be the same value of 'symmetrical' fault current for any of the above industrial or marine ratings. This is correct, because it is the same active materials that will use their energy to generate the fault current.

If the alternator is operated at a voltage other than the normal voltages for which data is published, then again, the reactance values will change correspondingly. Let's say an alternator with standard Winding 311/312 has reactance values published at 480V 60Hz, but the alternator is to be operated at 380V 60Hz. We could simply calculate the reactance value at 380V by [380/480] x value at 480V = value at 380V.

The sum of the detail in the section is therefore; a combined multiplier for reactance adjustment, which considers both the kVA change (reactance is proportional to kVA) and voltage change (reactance is inversely proportional to the square of the voltage).

Under these change circumstances, the following formula should be used to re-calculate reactance values:

$$X_2 = X_1 * \left(\frac{kVA_2}{kVA_1}\right) * \left(\frac{V_1}{V_2}\right)^2$$

- **The alternators excitation system**

If the alternator does not have an excitation system that is able to support a steady state short circuit current, then once the 'stored' energy of the magnetics in conjunction with the amount of active material have been expelled, the alternator will stop giving an output. For example; if the AVR type is an AS or an SX type but is not connected to an auxiliary winding. Such an alternator would give a time zero fault current appropriate to its value of X"d and the decay from this initial high value to zero would be described by calculations involving the alternator's transient reactance X'd and various time constants. Note; other reactances would form part of the calculations required to fully display the fault level capabilities of the alternator.

If the Excitation system has an AS AVR with Auxiliary winding or MX type AVR [powered by PMG] or Transformer controlled and therefore, a compounded system, then this constitutes an excitation system that will force a sustained short circuit current to be generated.

For an example of the UC 224G Winding 311 operating at 50Hz, refer to the Short Circuit Decrement Curve for the appropriate AVR in the alternator's Technical Data Sheet.

CHANGING REACTANCE VALUES

We have determined that reactance values are a measure of an Alternator's 'magnetic stiffness' and are used as a mathematical modelling tool to help describe the performance of an alternator under the different stages of behaviour during fault conditions. The reactance is 'set' by the electrical design used for the alternator and is a product of the amount of active [electrical] components used within the alternator. Usually, the main requirement of a design is to be as cost effective as possible; provide the maximum kVA for the minimum kg of materials; combined with achieving the **lowest** possible reactance values to provide the best possible performance against modern electronic power controlled Non Linear Loads.

Having achieved the above, it often comes as a surprise when **higher** reactance values are specified. The reasons, allied to the distribution system, are well understood.

Unfortunately, it is not possible to INCREASE the reactance of an existing cost effective design. Reducing reactance is achieved by going to a LARGER alternator.

Offering an alternator to comply with all the requirements of Marine Authorities requires **low** reactance in order to satisfy the specified short circuit performance, and transient voltage regulation limits set for during motor starting.

REACTANCE VALUES FOR PARALLEL ALTERNATORS

The performance of alternators operating in parallel is always an interesting topic. Fundamentally, when considering parallel running Generating Sets, it must always be accepted that, under steady state load conditions, a well set-up parallel running alternator should be set to share the total in proportion to the alternators rating. For example; a 500kVA in parallel with 1000kVA Generating Set should both be running at 50% rated kVA to support 750kVA of total load.

It is worth pointing out at this stage; Engines share the kW, excitation systems share the kVAr, thereby Generating Sets share kVA.

Under load step changes or fault conditions, this transient load will not be shared equally. Here source impedance up to the PCC has a significant effect. Even two similar sized alternators will not equally share an applied 'step-load'. In fact, the share will typically be more like a 45% and 55% contribution.

When considering ‘power system’ reactance values for parallel running Generating Sets, the approach should be similar to considering resistors in parallel and so a reciprocal factor should be used after the reactances for each alternator have been corrected to the base kVA of the total system. For example, consider two Generating Sets:

G1: 1000kVA output at 415V, 50Hz with X"d of 14%.
G2: 500kVA output at 415V, 50Hz with X"d of 12%.

G1 & G2 in parallel: Base level 1500kVA

G1 now has X"d of 21% (0.21pu)
G2 now has X"d of 36% (0.36pu)

The 'effective' X"d for the above pair of alternators based on their combined capability of 1500kVA = $(0.21^{-1} + 0.36^{-1})^{-1}$ = 0.133pu = 13.3%.

SATURATED AND UNSATURATED REACTANCES

The table on the next page provides the multiplying factors for each reactance in order to convert that reactance from its Saturated value to its Unsaturated value. For S-Series alternators (S0-S9), please refer to the datasheets for the most accurate saturated and unsaturated values:

Reactance - Saturated value		Unsaturated value - multiplying factor		
		S0-S7	P80	AvK
Direct Axis Synchronous Reactance	Xd	1.2	1.15	1.11111
Direct Axis Transient Reactance	X'd	1.15	1.235	1
Direct Axis Sub-Transient Reactance	X"d	1.17	1.22	1.11111
Quadrature Axis Reactance	Xq	1.03	1.03	1.03
Quadrature Axis Transient Reactance	X'q	1.03	1.03	1.03
Quadrature Axis Sub-Transient Reactance	X"q	1.2	$\frac{X2\ (unsat) \times X2\ (sat)}{X''d\ (sat)}$	1
Leakage Reactance	XL	1.13	1.13	N/A
Negative Sequence Reactance	X2	1.2	1.165	1.11111
Zero Sequence Reactance	X0	1.17	1.15	1.11111

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