Application Guidance Notes: Technical Information from STAMFORD | AvK

AGN 005 – Fault Currents and Short Circuit Decrement Curves

DESCRIPTION

To facilitate the correct design of an electrical protection system and to determine the electromagnetic and mechanical stresses imposed on an alternator during fault conditions, the short circuit performance of the alternator during the early stages of a fault condition must be established.

The Short Circuit Decrement Curves represent the alternator's fault current during Sub Transient, Transient and Sustained periods of the fault condition.

For reasons of clarity, the Decrement Curves display the performance of the alternator for a three phase short circuit condition, with descriptive notes being provided to enable the calculation of single phase, or phase-to-phase fault currents.

The levels of fault current are decided by the armature reaction being created by the effect of the fault current flowing through the stator windings and the resulting effect of de-magnetising Ampere Turns on the rotor flux. The armature reaction to a 3 phase fault is a condition that involves all 3 phases, therefore, all the stator windings and a displayed sustained fault current is an indication of the achievable fault current demagnetising armature reaction in terms of sustainable Ampere Turns.

This same level of Ampere Turns if only occurring in a 2 phase (L-L) fault should result in some 3/2 times more current than a 3 phase short. Similarly the L-N single phase fault should give 3/1 times more current, but due to the pulsating flux of this very unbalanced condition the resulting fault current is typically 2.5/1 times the 3 phase level.

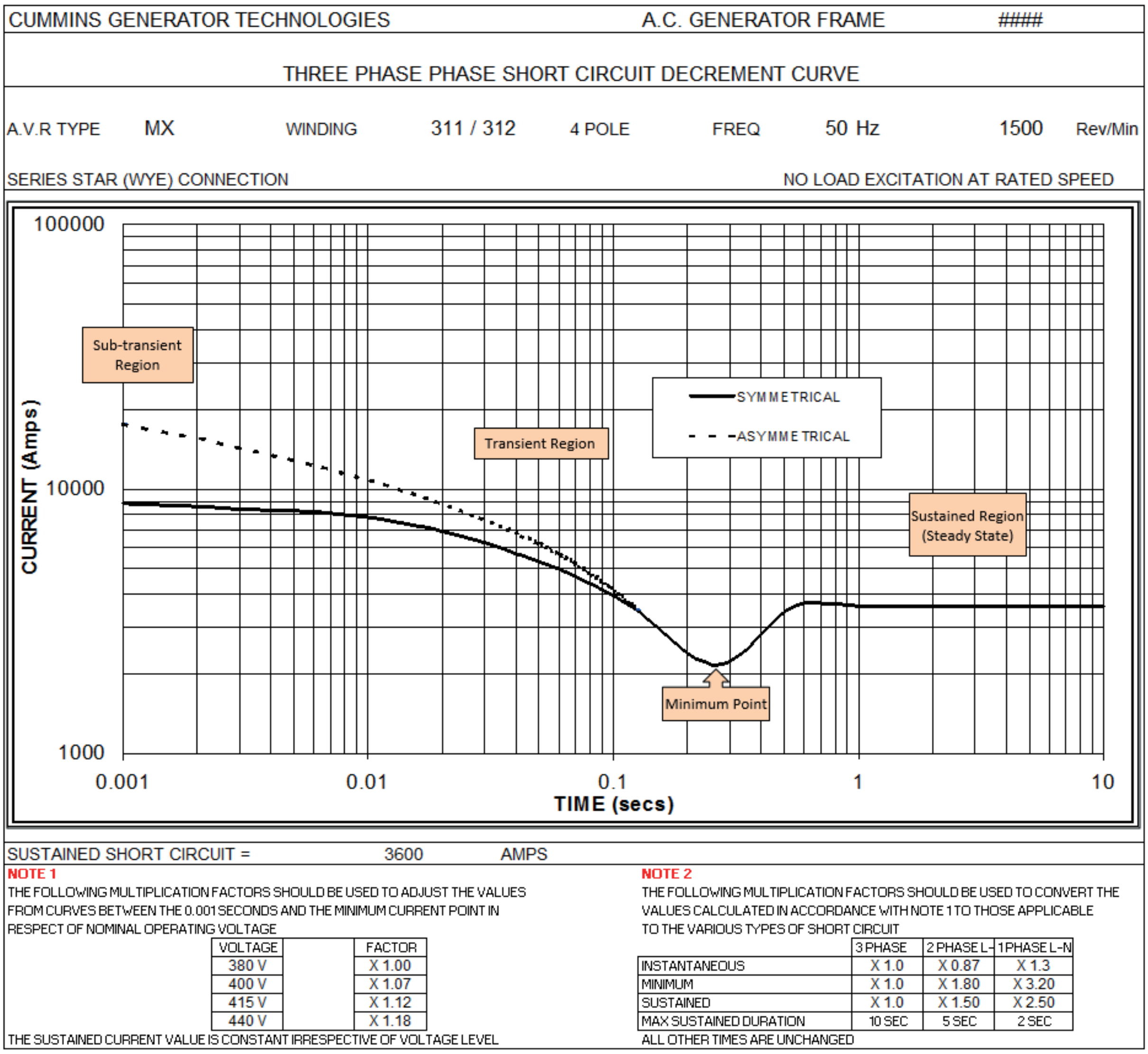
The graphically advised performance of the alternator under short circuit fault conditions is based on the fault occurring at, or very close to, the terminals of the generating set.

A generating set operating in service will be connected to a distribution system serving the connected load[s]. This distribution system will have impedance (Z), and so will introduce a value of Z between the alternator terminals and the point at which the ‘fault’ has occurred. The ‘fault’ will also have a value of Z, and if the nature of the ‘fault’ is an ‘earth-fault’, then the ‘earth-return’ path will also have a level of impedance.

The total fault loop impedance of the electrical distribution system will lower the actual level of fault current from that displayed on the alternator’s published Short Circuit Decrement Curve.

SHORT CIRCUIT DECREMENT CURVES

An example of a typical Three Phase Short Circuit Decrement Curve is shown in Figure 1.


CUMMINS GENERATOR TECHNOLOGIES A.C. GENERATOR FRAME ####

THREE PHASE PHASE SHORT CIRCUIT DECREMENT CURVE

A.V.R TYPE MX WINDING 311 / 312 4 POLE FREQ 50 Hz 1500 Rev/Min

SERIES STAR (WYE) CONNECTION NO LOAD EXCITATION AT RATED SPEED

SUSTAINED SHORT CIRCUIT = 3600 AMPS

NOTE 1

THE FOLLOWING MULTIPLICATION FACTORS SHOULD BE USED TO ADJUST THE VALUES FROM CURVES BETWEEN THE 0.001 SECONDS AND THE MINIMUM CURRENT POINT IN RESPECT OF NOMINAL OPERATING VOLTAGE

VOLTAGE		FACTOR
380 V		X 1.00
400 V		X 1.07
415 V		X 1.12
440 V		X 1.18

THE SUSTAINED CURRENT VALUE IS CONSTANT IRRESPECTIVE OF VOLTAGE LEVEL

NOTE 2

THE FOLLOWING MULTIPLICATION FACTORS SHOULD BE USED TO CONVERT THE VALUES CALCULATED IN ACCORDANCE WITH NOTE 1 TO THOSE APPLICABLE TO THE VARIOUS TYPES OF SHORT CIRCUIT

	3 PHASE	2 PHASE L-	1 PHASE L-N
INSTANTANEOUS	X 1.0	X 0.87	X 1.3
MINIMUM	X 1.0	X 1.80	X 3.20
SUSTAINED	X 1.0	X 1.50	X 2.50
MAX SUSTAINED DURATION	10 SEC	5 SEC	2 SEC

ALL OTHER TIMES ARE UNCHANGED

Figure 1 Typical Three Phase Short Circuit Decrement Curve

On first viewing a Decrement Curve it can seem to be unnecessarily complex, it is hoped that the following explanation will simplify the information illustrated.

The sub-transient and transient regions, as indicated in Figure 1, deliver fault current resulting from the energy within the magnetic field strength associated with electromagnetic circuits prevailing within the alternator associated with an excitation system operating to maintain rated output voltage, whilst supporting the connected electrical load. When the fault initially occurs, this store of energy begins to be dispersed, initially driving the high levels of current associated with the sub-transient region, then continuing to force a decaying level of fault current through the transient region until eventually the store of energy is drained.

Sub-Transient Region.

The sub-transient time period is typically no more than two cycles (40ms @ 50Hz). This region of an alternator’s performance is mathematically considered by use of the Sub-transient reactance (X”d). The Symmetrical level of time zero fault current for a three phase fault condition can be calculated by multiplying the alternator’s rated output current by the reciprocal of the value of X”d as a value in per unit (pu) terms.

Example: Where the alternator’s rated full load current is 1443A and published sub-transient reactance for 400V, 1000kVA is 0.15pu (15%), the time zero symmetrical fault current = (1/0.15) x 1443 = 6.66 x 1443 = 9619A.

It can be seen that at time zero each of the fault conditions begin at two individual points from which two converging curves meet after some 0.1s (5 x AC cycles). The lower curve for each condition describes the level of fault current associated with a Symmetrical fault current waveform, a condition where each half of the ac current waveform is equal about the zero crossing line. The higher curve describes the level of fault current associated with an Asymmetrical current waveform, a condition where the first cycle of sinusoidal current waveform is wholly displaced to one side of the zero crossing line.

The Asymmetrical level of fault current for the three phase fault condition is often the subject of academic debate. One reason for identifying this value is related to considering the power source capability with regard to the designed ‘rupturing capacity’ of associated electrical conductor assemblies, including bus-bar chambers and switchgear. Therefore, the asymmetrical value most often quoted for 3 phase and 2 phase fault conditions is based on a factor of twice the calculated symmetrical current level. In a practical situation, the likelihood is that 99.9% of all fault conditions will occur somewhere between perfect symmetry and perfect asymmetry and so, actually subjecting a distribution system to the advised asymmetrical value is most unlikely.

Transient Region.

The time from the sub transient region onwards, to the convergence of the symmetrical and asymmetrical curves and on to the point after which the fault current begins to increase, is referred to as the transient region. Through this transient region the AC sine wave of the fault current resolves to align equally about the zero crossing mean line. The alternator’s performance throughout the transient region can be mathematically described by due reference to the alternator’s transient reactance (X’d) related to various time constants.

It should be noted that self-excited alternators fitted with an AVR that is powered by the output of the alternator’s main stator winding and therefore, does not have an independent power supply, are inherently unable to force the alternator to deliver a steady state level of 3 phase fault current. Therefore, the transient region ends with zero fault current, meaning the alternator has effectively stopped working after a period of typically 0.35s. Such alternators do have a certain ability to provide a limited forcing capability when that alternator is subjected to single phase fault conditions.

The Short Circuit Decrement Curve caption in Figure 2 shows that there is a point where the transient regions falling fault current level is caught (minimum point) and the fault current level increases to a point where a steady state level of current is achieved and maintained.

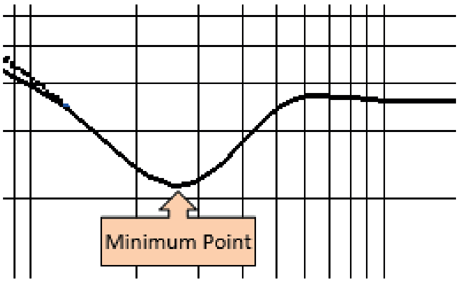


Figure 2 Short Circuit Decrement

This behaviour is the result of an AVR being supplied by a dedicated power source, such as a Permanent Magnet Generator (PMG), stator auxiliary winding, or battery supply. Despite the fact that the AVR immediately recognises the alternator's output voltage being below nominal level, due to the short circuit and responding instantly by beginning to increase the level of excitation to correct that situation, there is a finite time taken by the exciter and main rotor electro-magnetic circuits to reach a level of field strength to make a positive contribution to supporting a positive fault current level. The decrement curve portrays this with the indicated level of fault current beginning to increase. The increase then reaches a point where the fault current is held at a constant level. This constant fault current level is a product of the excitation system reaching its maximum forcing capability.

Sustained Region (Steady State).

With regard to the sustained region level of fault current, this area is often referred to as the steady state or synchronous region. With the current level in this region being multiples of rated output current, the alternator is clearly operating under a condition of forced excitation; therefore, no effort should be made to determine the level of steady state fault current level by a calculation using the alternator's advised value for the synchronous reactance (Xd).

An alternator's actual sustained short circuit current level is displayed on the individual Decrement Curve for that alternator design. The generating set industry 'standard' of expecting a 300% short circuit current is no more a 'given' than it is likely that the connected electrical loads will result in the alternator operating at only 0.8pf lag.

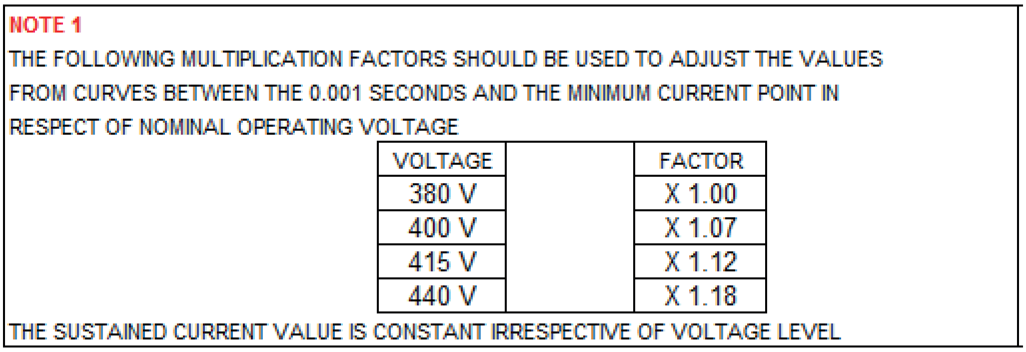
Multiplying factors.

The intent of a Short Circuit Decrement Curve is to provide information regarding the performance of an alternator under fault conditions. It has become common practice to display in a graphical form the alternator's performance under a 3 phase [L-L-L] short circuit condition where the prospective fault current is the result of a fault occurring directly at the alternator's stator winding terminals, and so effectively of zero impedance.

In order to keep the Decrement Curve graph as simple as possible tabled 'Notes' have been included to provide multiplying factors to be used for the establishment of prospective fault current levels under a phase to phase [L-L] zero impedance fault condition, and also a single phase [L-N] zero impedance fault condition.

The Notes are located below the Three Phase Short Circuit Decrement Curve, labelled Note 1 and Note 2.

Note 1:



NOTE 1

THE FOLLOWING MULTIPLICATION FACTORS SHOULD BE USED TO ADJUST THE VALUES FROM CURVES BETWEEN THE 0.001 SECONDS AND THE MINIMUM CURRENT POINT IN RESPECT OF NOMINAL OPERATING VOLTAGE

VOLTAGE		FACTOR
380 V		X 1.00
400 V		X 1.07
415 V		X 1.12
440 V		X 1.18

THE SUSTAINED CURRENT VALUE IS CONSTANT IRRESPECTIVE OF VOLTAGE LEVEL

This table advises nominal operating voltage mathematical factors, which should be applied to the graphical curves over the region from 'time zero' to the point of minimum current level.

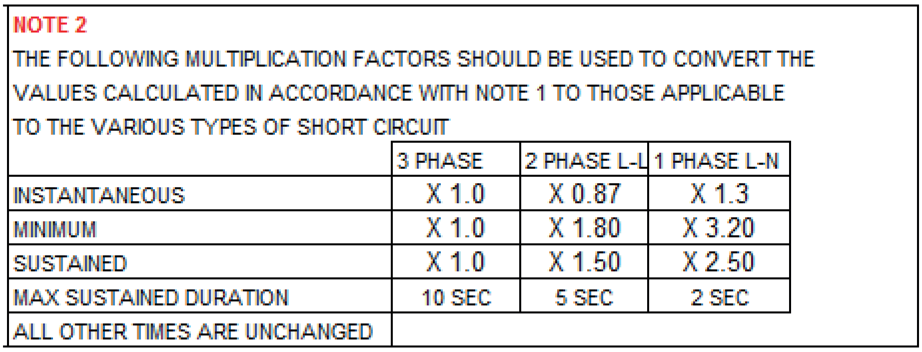
Example:

Assume a 400V alternator:

The graphically displayed SYMMETRICAL 'INSTANTANEOUS' value taken from the graph is 9000A, therefore introducing the advised 1.07 factor becomes 9000A x 1.07 = 9630 A

Note 2:

The values shown in 'Note 2' for 2 phase (L-L) and Single phase to Neutral (L-N) fault conditions have been chosen for mathematical simplicity, considering the multitude of different designs of alternators manufactured, combined with experience of alternator performance.



NOTE 2

THE FOLLOWING MULTIPLICATION FACTORS SHOULD BE USED TO CONVERT THE VALUES CALCULATED IN ACCORDANCE WITH NOTE 1 TO THOSE APPLICABLE TO THE VARIOUS TYPES OF SHORT CIRCUIT

	3 PHASE	2 PHASE L-L	1 PHASE L-N
INSTANTANEOUS	X 1.0	X 0.87	X 1.3
MINIMUM	X 1.0	X 1.80	X 3.20
SUSTAINED	X 1.0	X 1.50	X 2.50
MAX SUSTAINED DURATION	10 SEC	5 SEC	2 SEC
ALL OTHER TIMES ARE UNCHANGED			

In order to keep the Short Circuit Decrement Curve graph as simple as possible, Note 2 has been included to provide multiplying factors that are to be used for calculating of prospective fault current levels under a phase-to-phase [L-L] zero impedance fault condition, and also a single phase [L-N] zero impedance fault condition.

Example:

Consider a single phase to neutral fault:

- The graphically displayed **SYMMETRICAL** 'INSTANTANEOUS' value taken from the graph is 9000A, therefore introducing the advised 1.3 factor becomes 11700 A
- The graphically displayed **ASYMMETRICAL** 'INSTANTANEOUS' value taken from the graph is 18000A, therefore introducing the advised 1.3 factor becomes 23400 A
- The graphically displayed **MINIMUM POINT** current value taken from the graph is 2100A, therefore introducing the advised 3.2 factor becomes 6720 A
- The graphically displayed **SUSTAINED** value taken from the graph, confirmed in text is 3600A, therefore introducing the advised 2.5 factor becomes 9000 A
- The maximum sustained duration for a phase to neutral fault is 2 seconds

With regard to the 2 phase (L-L) fault condition; and the 'Instantaneous' (time zero) moment. The stated factor 0.87 is strictly only applicable for an alternator with a design where the value of X"d and X_2 are equal, and this would be true for a cylindrical rotor design and nearly true for a salient pole design with an idealised and perfect design of damper cage.

For the majority of the CGT alternator designs, it seems that X_2 are some 1.5 x X"d. This then changes the standard formula as follows:

$$X''d_s = [X''d + X_2] \;/\; 1.732 = 2 \times X''d / 1.732 = 1.15 \times X''d$$

And so the fault current $I''d_s = 1/1.15 \times I''d = 0.87 \times I''d$

Into a specific formula where $X_2 = 1.5 \times X''d$, of :

$$X''d_s = ([X''d + X_2] / X''d) \;/\; 1.732 = 2.5 \times X''d / 1.732 = 1.44 \times X''d$$

And so the fault current $I''d_s = 1/1.44 \times I''d = 0.7 \times I''d$

When considering the variability of the values of symmetrical up to asymmetrical level of I"d current, and then the small variation between multiplying a chosen value of I"d Amps by either 0.7 or 0.87, the decision to use 0.87 on all Decrement Curves becomes justified.

As further justification for supporting simplified mathematical factors in the L-L and L-N columns, the following variability's should be considered.

A generating set operating in service will be connected to a distribution system serving the connected load[s]. This distribution system has impedance, and so will introduce a value of Z between the alternator terminals and the point at which the 'fault' has occurred. The 'fault' will also have a value of Z, and if the nature of the 'fault' is an 'earth-fault', then the 'earth-return' path will also have a level of impedance. The total 'fault' circuit / loop impedance value will much modify the actual level of alternator fault current displayed on the alternator's published Short Circuit Decrement Curve.

Curves are drawn for Star (Wye) connected machines. For other connections the following multipliers should be applied to current values:

Parallel Star = Curve current value x 2
Series Delta = Curve current value x 1.732

Maximum sustained duration. Note 2 also details the maximum sustained duration of a fault condition that the alternator can withstand. The disconnection time from the fault is critical to prevent damage to the alternator winding. Safe guidance is considered to be: < 10sec for a fault across 3 phases (L-L-L), < 5sec for a fault across 2 phases (L-L) and < 2 sec for single phase to Neutral fault (L-N).

FAULT CONDITIONS

The performance of an alternator under fault conditions is described by the Short Circuit Decrement Curve, which forms part of the technical publication provided by manufacturers of the alternator. The favoured method seems to be a graphical representation of the alternator's fault current performance, therefore in general terms, aligns with the technical data provided by the manufacturers of over-current protection devices.

For reasons of clarity, the decrement curves display the performance of the alternator for a three phase short circuit condition. Calculations have been made, using the descriptive notes associated with the decrement curve, to facilitate the single phase, or phase to phase curves to be determined and manually added. For the following example, such an exercise has been undertaken, with the addition of red and blue curves.

The example Decrement Curve in Figure 3 on the next page is applicable to a typical industrial alternator rated at 1000kVA, 400V, 1443A, 50Hz:

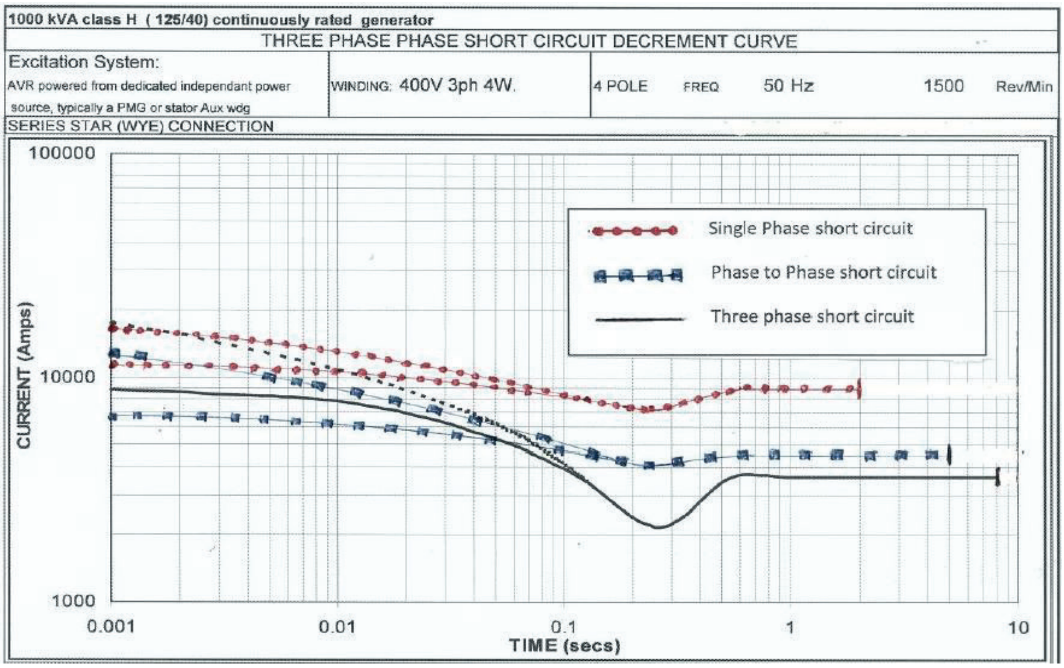


Figure 3 Short Circuit Decrement for Multiple Fault Conditions

Note that at the end of each line a 'stop' has been indicated to provide guidance regarding the maximum duration the alternator can tolerate that fault condition. This time limit is yet another important factor which must be considered with regard to the trip settings for Circuit Breakers, as the alternator depends on effective fault discrimination and thereby removal of the faulted circuit to be effected within the ac alternator manufacturers allowable duration time. Alternator manufacturers can provide a separate document which displays Thermal Damage limits.

Once again, the type of fault condition is influential when determining the choice of a Circuit Breaker. The disconnection time from the fault is critical to prevent damage to the alternator winding. An initial guide is: < 10sec for a fault across 3 phases (L-L-L), < 5sec for a fault across 2 phases (L-L) and < 2 sec for single phase to Neutral fault (L-N).

Of course in the real world there will be distribution system cabling and the faults impedances to consider and so, the actual fault current will be less than those indicated on the Short Circuit Decrement Curve.

However, the part of connected electrical network where the fault has occurred will no doubt be protected by a cascading distribution system of Circuit Breaker's with lower current ratings and so, are likely to be easily tripped by the generated fault current, which should occur almost instantly - for reasons of less interference to all other connected loads - because the affected circuit and its Circuit Breaker will be tripped by the X"d fault current level in that affected circuit.

Mechanical Stress.

Worthy of inclusion to add to the above electrical engineering explanation is some comment with regard to the momentary **mechanical stress** a short circuit condition imposes on to the mechanical structure of a generating set. When designing the mechanical components for an AC generator (alternator), the momentary peak torque levels – think in terms of torque reaction - under a short circuit situation or a crash synchronisation event* must be identified and included in the structural design considerations. Typically, the factor used for the alternator’s frame and stator core assembly, and this includes the holding down fasteners employed at the frame feet to genset structure, is 12 times the alternator’s continuously rated power level. For the region associated with the coupling to the engine’s flywheel and flywheel housing, the factor employed is 8 times rated power level.

Engineers with experience of watching a generating set being subjected to short circuit testing will have witnessed the dynamic forces that cause the generating set to rock about its axis in a violent manner, even lift from the ground on one side if not anchored securely and recall the audible experience of equipment suffering severe levels of imposed stress. In fact, it is the unbalanced short circuit conditions that impose the greatest forces.

*Crash synchronisation event: Consider alternators’ operating in parallel and a fault occurs within the electrical system they are supporting. If that fault is close to the alternators, therefore very low impedance, furthermore the fault condition is not immediately disconnected by a discriminating circuit breaker; it is very likely that the system voltage will be suppressed to a level which makes it difficult for the alternators to remain in perfect synchronisation. When the fault is cleared, the resulting behaviour of the individual generating set control functions for speed and excitation may have performance differences. These performance differences result in the generating sets being forced to realign and return to perfect synchronism under what is often termed a ‘rough synchronising’ event. Such a scenario imposes a doubly stressful event on to the equipment.

On-Site Fault Current Levels.

Parallel Operation. A simplistic starting point is to look at the Short Circuit Decrement Curve for each alternator that is working in parallel, and then consider 'simply adding' each of the alternator’s predicted 'ideal' fault currents together.

However, this will give a higher value than will actually be achieved in a real installation, but this will give a worst case 'rupturing capacity' current, which may be what the installation engineer needs to identify, because of concerns about a delicate installation network.

On site situations. Let’s start with just one solo alternator on a real site fault condition. In truth the Decrement Curves are based on the short circuit being right at the terminals of the alternator. In service of course this is hardly likely to where the fault occurs, so then the installation engineer must introduced the distribution systems circuit impedance (Z). It is worth repeating this is in the series path of the ‘Generator to Fault' current flow, and so will reduce the 'ideal' Decrement Curve fault current level, to real on-site conditions. The ‘fault’ will also have a value of Z, and if the nature of the ‘fault’ is an ‘earth-fault’, then the ‘earth-return’ path will also have a level of impedance. The total ‘fault’ circuit / loop impedance value will much modify the actual level of alternator fault current displayed on the alternator’s published Short Circuit Decrement Curve.

When operating in parallel, each generator is coupled to the on-site system common bus-bar by conductors of no doubt different lengths, so different impedance, therefore this introduces an initial 'in-series' impedance from generator to common bus bar. From common bus bar through the site distribution network and out to the fault, introduces a second impedance, which a value based on the Site system. All these in series impedance’s reduce the fault current level from that which are shown on the Decrement Curves.

A **Rule of Thumb**; providing the generating sets are not too far away from the common busbar, assume the fault level at the bus bar will be 90% of the simple sum total of each generating set fault current, as shown on each alternator's Decrement Curve. The installation engineer must then worry about the distribution systems impedance, which will further reduce the busbar fault current level, and so set what will be available to trip the installed over current protection devices.

Other considerations.

There is a misconception that all alternators - fitted with an appropriate excitation system - will generate at least 300% short circuit current under the steady state condition associated for a balanced 3 phase short circuit condition. It is a commercially conscious market place that has forced cost effective engineering to be applied to standard industrial products with the consequence that many industrial Prime rated (125/40) type alternators now fall short of delivering such performance. For the generating set manufacturer this may set a challenge when selecting a circuit breaker with adequate fault discriminating capability, when a low level of fault current is available. The positive is that most electrical system faults are phase to earth, or phase to phase, furthermore the very high fault currents associated with the sub-transient and initial stage of the transient regions should be quite capable of providing sufficient tripping capability and enable the minimum disruption time for the healthy connected load.

Marine Classifying Societies still specify a 300% requirement and here the selection of the alternator includes due consideration of Decrement Curves for alternators under review, with the 300% I.s/c. function being the critical sizing parameter.

stamford-avk@cummins.com

www.stamford-avk.com

STAMFORD | AvK ™

POWERING TOMORROW, TOGETHER