

Calculating generator reactances

> **White paper**

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Generator reactances are used for two distinctly different purposes. One use is to calculate the flow of symmetrical short circuit current in coordination studies. A second use for generator reactances are in specifications that limit the sub-transient reactance to 12% or less in order to limit the voltage distortion induced by non-linear loads. For either short circuit or harmonic distortion analyses, the stated reactances will need to be converted to a common base to make valid comparisons. Typically, generator reactances are published in per unit values on a specified base alternator rating. Where the generator set rating differs from the alternator base rating it will be necessary to convert the per unit values from the alternator base rating to the generator set rating. For selecting circuit breakers with adequate AIC rating the maximum asymmetrical short circuit current to flow in the first half cycle may be approximated from the generator sub-transient reactance (x''_d) and a factor to account for DC offset.

The flow of current in an AC circuit is controlled by impedance. When a short circuit fault occurs in a distribution system the fault current that flows is a function of:

1. the internal voltage of the connected machines in the system (generators and motors),

2. the impedance of those machines,
3. the impedance to the point of the fault, mostly cable impedance,
4. and the impedance of the fault, if arcing.

The generator internal voltage and generator impedance determines the current that flows when the terminals of a generator are shorted. The effect of armature reaction on the generator air gap flux causes the current to decay over time from an initial high value to a steady state value dependant on the generator reactances. Since the resistive component in generators is negligible, for practical purposes it may be ignored and only the reactances need be considered. Generator reactances, as determined by tests with fixed excitation, are:

Name Importance	Symbol	Range ¹	Effective Time
Sub-transient reactance Determines maximum instantaneous current and current at time molded case circuit breakers usually open.	X''_d	.09 – .17	0 to 6 cycles
Transient reactance Determines current at short time delay of circuit breakers.	X'_d	.13 – .20	6 cycles to 5 sec.
Synchronous reactance Determines steady state current without excitation support (PMG).	X_d	1.7 – 3.3	after 5 sec.
Zero sequence reactance A factor in L-N short circuit current.	X_0	.06 – .09	
Negative sequence reactance A factor in single-phase short circuit current.	X_2	.10 – .22	

¹ Reactances shown are typical per unit values for generators ranging from 40 to 2000 kW.

Sub-transient reactance

With a generator operating at full voltage, a symmetrical 3-phase short circuit at its terminals will cause a large amount of current to flow. This initial current is used to determine the required interrupting rating of overcurrent devices, circuit breakers and fuses, located at the generator(s). The initial instantaneous current value (ISC_{Sym}) is controlled by the sub-transient reactance (X''_d) and is expressed by the voltage divided by the sub-transient reactance, or:

$$ISC_{Sym} = E_{AC} \div X''_d$$

In per unit, assuming a 0.10 sub-transient reactance, the initial symmetrical short circuit current expressed in multiples of full load current:

$$ISC_{Sym} = 1.0 \div 0.10 = 10 = 1000\% \text{ of full load current}$$

Reactances, including the sub-transient, are expressed with a plus or minus tolerance of 10%, typically. Determination of the maximum current should use the worst case tolerance of minus 10%. The maximum symmetrical current from the example above becomes:

$$ISC_{Sym} = 1.0 \div (0.10 - 10\%) = 11.1 = 1110\% \text{ of full load current}$$

The peak current in the first half cycle will also include a DC component, the magnitude of which depends on the point in the cycle when the short circuit occurs. A DC component offsets the symmetrical current around the zero axis resulting in asymmetry. If the short occurs at point where voltage is at its peak, the DC component will be zero. If the short occurs at the point where voltage is at zero, the DC component will be at its maximum, and the peak current will be almost two times the symmetrical current.

In practice the actual DC offset will likely range somewhere between zero offset and the maximum offset. However, for the purpose of selecting the interrupting rating of circuit breakers the assumption that the DC offset will be at maximum is a safe and conservative assumption ($ISC_{Sym} \times 2$). Generally, circuit breaker interrupting ratings are expressed in RMS Symmetrical Amperes and are tested to achieve near maximum offset at that symmetrical current magnitude. Select breakers, then, based on the maximum allowable generator symmetrical short circuit current.

GENERATOR SHORT CIRCUIT CURRENTS

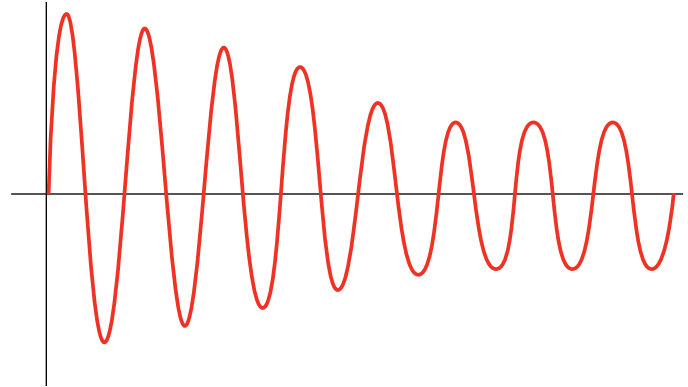


FIGURE 1 – Symmetrical current

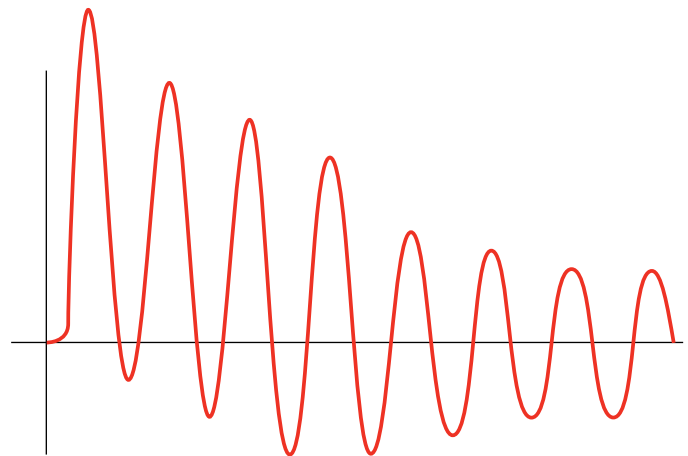


FIGURE 2 – Asymmetrical current

Calculating per unit sub-transient reactance

Cummins Power Generation publishes generator reactance values in Per-Unit (P.U.) to a base alternator rating as specified on the alternator data sheet. The generator sets however, have various base ratings, and so there is a need to convert from the alternator base to the generator set base. This conversion is accomplished using the following formula:

$$P.U.Z._{new} = P.U.Z._{given} \left(\frac{\text{base kV}_{given}}{\text{base kV}_{new}} \right)^2 \left(\frac{\text{base kVA}_{new}}{\text{base kVA}_{given}} \right)$$

About the author



Timothy A. Loehlein is a graduate of the University of Minnesota with a Bachelor of Electrical Engineering and a PE in Minnesota. Tim has been a Cummins Power Generation employee since 1976 in positions as Application Engineer,

Design Engineer, Technical Project Leader and Project Manager. His current position is a Technical Specialist-Electrical in application engineering for Cummins Energy Solutions Business, supporting combined heat and power (CHP) and peaking applications.

For example, suppose you want to find the sub-transient reactance (X''_d) in Per-Unit for the 105°C rise, 480 volt alternator on a 750 kW DFHA generator set. From the generator set specification sheet, S-1132, the alternator data sheet is ADS-311. ADS-311 shows a sub-transient reactance of 0.16 P.U. based on the 125°C alternator base rating of 1300kVA. The base kVA rating of the 750DFHA is 938 kVA. Using the formula, calculate X''_d on the generator set base as follows:

$$X''_{d(\text{Genset})} = X''_{d(\text{ADS})} \left(\frac{\text{kV}_{\text{ADS}}}{\text{kV}_{\text{Genset}}} \right)^2 \left(\frac{\text{kVA}_{\text{Genset}}}{\text{kVA}_{\text{ADS}}} \right)$$

$$X''_{d(\text{Genset})} = 0.16 \left(\frac{0.48}{0.48} \right)^2 \left(\frac{938}{1300} \right)$$

$$X''_{d(\text{Genset})} = 0.115 \text{ P.U.}$$

Limiting voltage distortion

It is becoming commonplace for consulting engineers to limit sub-transient reactance in specifications to 0.12 per-unit or less to limit generator voltage distortion caused by non-linear load induced harmonic currents. The alternator source voltage distortion induced by the harmonic (sub-cyclic) current distortion is directly

related to the generator set sub-transient reactance. The higher the reactance is, the higher the voltage distortion. Reducing the source impedance (reactance) reduces the voltage distortion. This calculation will need to be used to check and compare suppliers' submittals against specifications. In the example, while a 125°C rise alternator may have been specified, 105°C alternator would have to be supplied to meet a 0.12 per-unit or less sub-transient reactance requirement.

Summary

The sub-transient reactance of a generator set is used to calculate the maximum available short circuit current for selecting circuit breakers with adequate interrupting rating. Since nearly all of the generator impedance is reactance, addition of the DC component for the first few cycles may almost double the symmetrical value of current. Specifications that limit the sub-transient reactance (X''_d) to 12-per-unit or less limit the voltage distortion caused by non-linear load currents. Calculation of the available short circuit current using per-unit values may require converting from the alternator base rating to the generator set base rating using the formula provided.

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