

Generator Specifications for Planning, Operations Planning, and Real-time Models

Steady-state ratings

Dynamic parameters

Capability curves

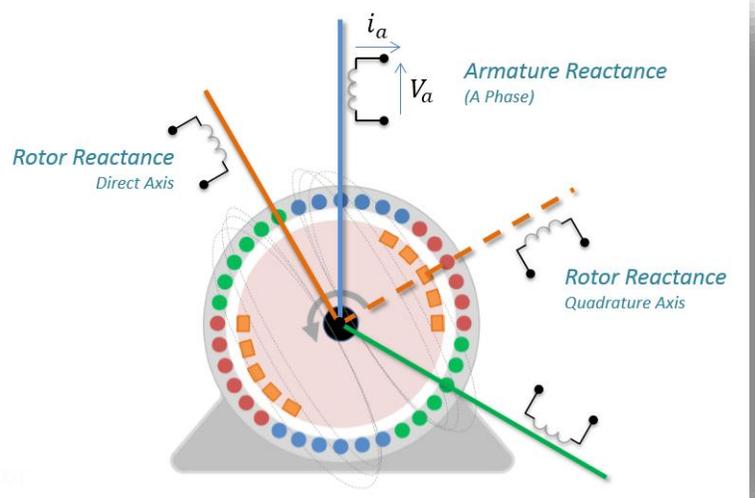
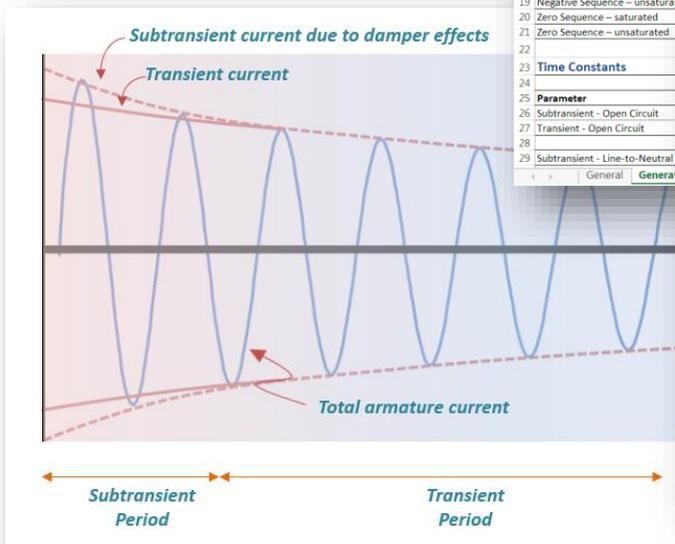
Generator Step-up Transformer

Excitation system data

Governor system data

Version 0.3.2

Generator Reactance and Time Constants					Notes - Round-rotor Generator		Notes - Salient-pole Generator	
Parameter	Direct Axis		Quadrature Axis		Units			
	Symbol	Value	Symbol	Value				
Synchronous - saturated	X_{dvs}		X_{qvs}		Per-unit Reactance	X_{dvs} should be slightly more than X_{qvs} X_{dli} should be slightly more than X_{qli}	$X'q = X_q$ with damper windings	
Synchronous - unsaturated	X_{dli}		X_{qli}					
Armature Leakage - saturated	X_{lmvs}							
Armature Leakage - unsaturated	X_{lmi}							
Subtransient - saturated	X''_{dvs}		X''_{qvs}		Per-unit Reactance	$X''_{dvs} = X''_{qvs}$ $X''_{dli} = X''_{qli}$	$X''_{d} = X''_{q}$ with damper windings and $X''_{q} = X_q$ without damper windings	
Subtransient - unsaturated	X''_{dli}		X''_{qli}					
Transient - saturated	X'_{dvs}		X'_{qvs}					
Transient - unsaturated	X'_{dli}		X'_{qli}					
Negative Sequence - saturated	X_{2vs}							
Negative Sequence - unsaturated								
Zero Sequence - saturated								
Zero Sequence - unsaturated								
Time Constants								
Parameter								
Subtransient - Open Circuit								
Transient - Open Circuit								
Subtransient - Line-to-Neutral S								



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Introduction

This document explains the generator specifications that the generator owner provides to the transmission planner for use in power flow, transient stability, and short-circuit studies. It accompanies the Generator Specifications workbook.

Audience

The audiences for this document include:

1. **Generator owners** who provide the information to the transmission owners.
2. **Transmission owners** and planners who use this information in their planning studies.
3. **Operating engineers** who also use this information in their operations planning and real-time operating studies, including state estimators and contingency analysis.
4. **Anyone looking for a simple explanation** of steady-state and transient generator specifications.

Section 1. Nameplate Information

This section comprises information about the generator's electro-mechanical specifications that's found on its nameplate, including its pole arrangement, nameplate ratings, and per-unit base values.

Prime mover. Generally, the generator's prime mover and rotor type (cylindrical versus salient-pole) are of little consequence in steady-state (power flow) analysis, but both play a major role in the generator's transient response.

Prime movers comprise **high-speed steam** and **combustion turbines, hydro turbines, diesel engines,** and **wind turbines.** Photovoltaic generators aren't considered as having a prime mover in the classical sense, and this document does not cover those resources.

The following table summarizes the prime movers' and rotor characteristics that are covered in this document.

Prime Mover	Typical Rotor Type	Rotor Speed	Inertia Constant	Comments
Steam Turbine	Cylindrical	High: 1800 or 3600 RPM	High	Stand-alone or back end of combined cycle generator
Combustion Turbine	Cylindrical	High: 1800 or 3600 RPM	Fairly high	
Hydro Turbine	Salient-pole	Low: 120 RPM ±	Highest	
Diesel Engine	???	Low	???	
Wind Turbine	???	Turbine: Low Generator: High (geared)	Lowest	

Rotor type. Generally, steam and combustion turbine generators are high-speed devices that use a **cylindrical rotor** (Figure 1) with either two poles (most common) or four poles (typical of nuclear generators). Hydro turbine generators are usually slow-speed devices that employ a **salient pole rotor** (Figure 2) with multiple poles.

Rotor speed, RPM. The rotor speed in revolutions per minute, RPM. The rotor speed is:

$$RPM = \frac{p}{2} (3600)$$

Where p = the number of poles.

Generator MVA rating. The rating in megavolt-amperes, MVA, stamped on the generator nameplate.

Generator voltage, kV. The nameplate voltage produced at the armature leads.

Power factor, %. The power factor for maximum continuous output at which the generator nameplate rating is calculated.

Cooling method. Generators typically employ air, hydrogen, or water cooling systems. Hydrogen-cooled generator are sealed to prevent hydrogen leaks, and can operate at various hydrogen pressures to increase the cooling capacity and, thus, allow the generator to increase its MVA rating.

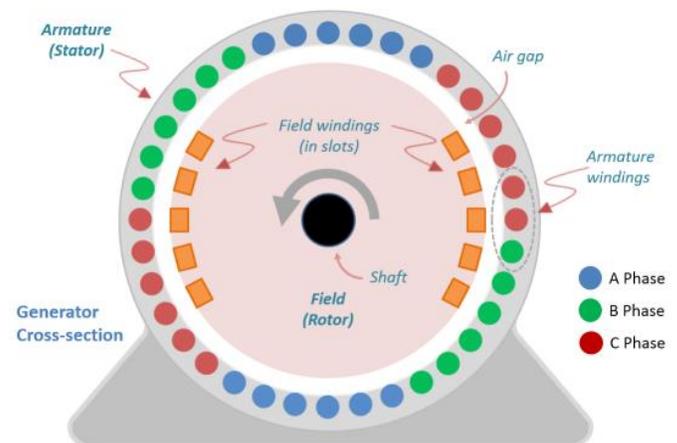


Figure 1 - Cylindrical, two-pole generator.

Turbine nameplate rating, MW_e. The megawatt rating stamped on the turbine nameplate that represents the maximum output of the turbine (expressed as electrical equivalent MW). The turbine is usually rated higher than the generator.

Short-circuit ratio. The ratio of the field current required for the rated voltage at open circuit to the field current required for the rated armature current at short circuit.

V-base and S-base. The per-unit voltage and power base values provided by the manufacturer.

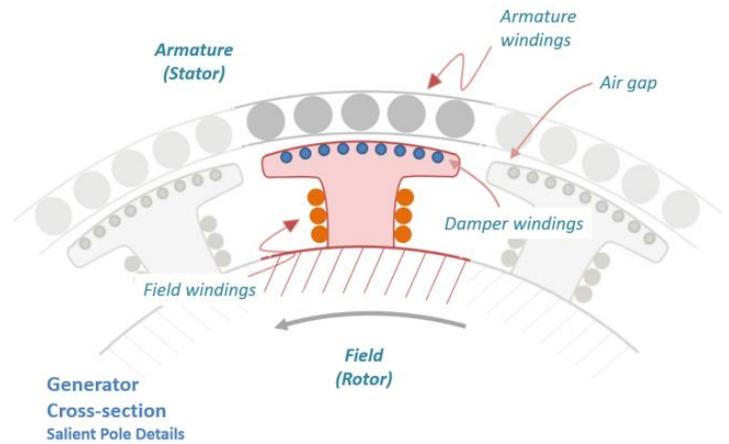


Figure 2 – Salient, multiple-pole generator.

Inertia

The inertia of the generator is the mechanical energy stored in its rotating parts—the turbine, generator, exciter¹, and shaft. The generator’s inertia affects how it responds mechanically (and, hence, electrically) to a disturbance on the transmission system. The total inertia of all on-line generators, and where the generators are located, determines the transient response of the entire transmission system.

Moment of inertia, J (Lb-ft²). The mechanical resistance of the generator to change its state of rotation. The moment of inertia is related to the total mass of the rotating components and their rotational speed, not the electrical rating of the generator.

Inertia constant, H (MW-seconds/MVA). The ratio of the total rotational energy stored in the rotating components divided by the generator’s nameplate MVA rating:

$$H = \frac{1/2 J \omega^2}{MVA}$$

The inertia constant is more a function of the prime mover than the generator, with wind generators having the lowest inertia relative to their electrical output, followed by combustion and steam turbines, with hydro turbines the highest.² (See Figure 3), The inertia constant normalizes the moment of inertia to the MVA base, which means the inertia constant should be similar among generators using the same type of prime mover regardless of size.

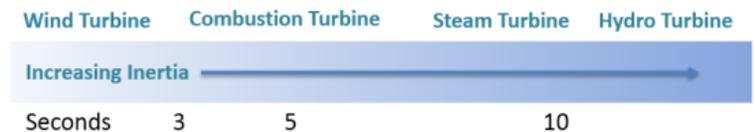


Figure 3 - Relative inertia constants for each prime mover type. (Values are only approximate.)

¹ Assuming the exciter is driven by the same prime mover as the generator. Exciters driven by a separate turbine do not contribute to the inertia of the turbine-generator connected to the transmission system.

² This should be fairly obvious given the size of the different kinds of prime movers.

Section 2. Generator Reactance and Time Constants

The Generator Model

Like transformers, generators consist of two electromagnetic fields that interact with each other; but unlike transformers, the fields are rotating with respect to each other and the circular shape of the rotor and armature allow the magnetic fields to spread out in multiple directions. This is especially true for round-rotor generators (See Figure 6), and less so for salient pole generators (See Figure 7) due to the shape of the poles, which tends to channel the flux. Salient pole rotors often have damper windings a well to minimize the shift in the air-gap flux path when a short circuit is applied to the generator leads.

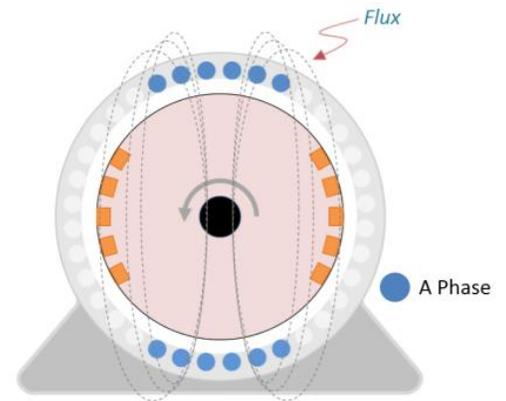


Figure 4 - Flux path on a round-rotor generator.

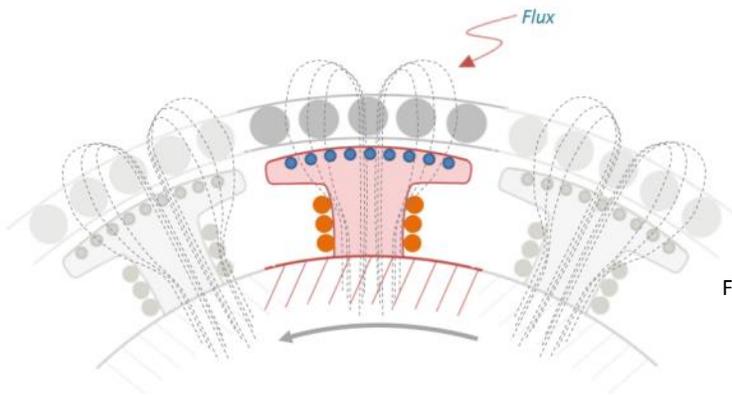


Figure 5 - Flux path on a salient-pole generator.

Generator Reactances

Flux patterns and saturation

The concepts of flux, flux saturation, and how the flux can be represented along the direct and quadrature axes of the armature and rotor are important key to understanding the generator reactances.

Flux saturation

Flux saturation refers to the degree to which the rotor field or armature “teeth” can accommodate additional magnetic flux, which, in turn affects the value of the machine’s transient and sub-transient reactances. When the generator’s flux paths are unsaturated, a sudden change in armature current (either due to a sudden load change or short circuit) is met with increased reactance due to the additional flux produced in the rotor or armature fields. Conversely, if the flux path is highly saturated, changes in the armature current cannot contribute to the flux build-up, which means the generator’s reactance is reduced.

Direct and Quadrature Axes

To accommodate the flux path patterns, we can represent the electro-mechanical equivalents of the generator reactances by assuming they lie in two directions: one along the **direct axis** of the rotor and armature windings and a second one along the **quadrature axis**, which is at right angles to the direct axis. (See Figure 8).

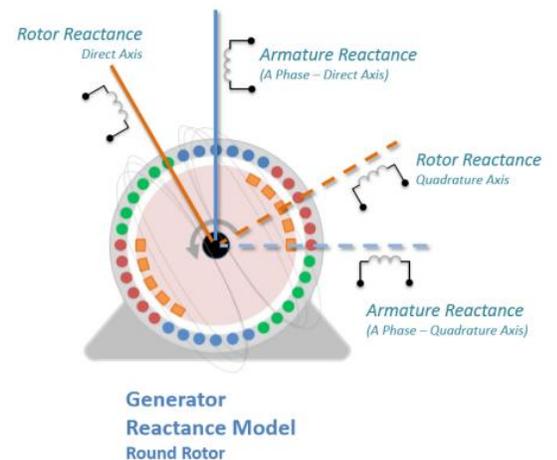


Figure 6 - Generator reactance can be depicted as having two components along the direct and quadrature axes of the windings. The coils shown in this diagram serve only to represent the model of the generator and do not have reactance values *per se*.

X_{dv} X_{qv}
 X_{di} X_{qi}

Synchronous Reactance

Synchronous reactance is the generator’s steady-state reactance caused by a combination of the **armature winding leakage reactance** plus the reactance used to represent the **armature reaction to a short circuit**. As shown in Figure 9, in the linear part of the open circuit voltage curve, the unsaturated synchronous reactance is constant. As the machine saturates, synchronous reactance falls. Synchronous reactance at a given field current (or excitation voltage) can be estimated from the gradient of the open circuit voltage and short circuit current curves.³

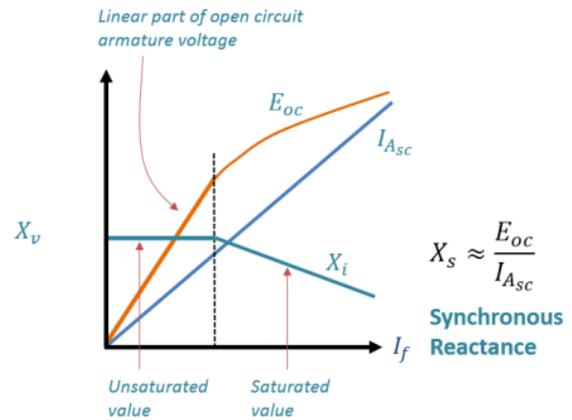


Figure 7 – The generator’s synchronous reactance is a function of the armature’s open-circuit voltage and short-circuit current.

X_{lm}

The **armature winding leakage reactance** is caused by the flux in the armature winding caused by the armature (load) current, and its magnetic path is normally not saturated.

Transient and Subtransient Reactance

The generator will exhibit **subtransient and transient reactances** when subjected to a short circuit (See Figure 10) that can be seen as increases in the armature current. Furthermore, the damper effects of the round-rotor or damper windings on the salient-pole rotor will cause an even higher armature current to flow *for the first few cycles* after the short circuit is applied (See Figure 11). These initial instantaneous current values are important for determining the interrupting ratings of associated devices, especially circuit breakers.

X''_{dv} X''_{qv}
 X''_{di} X''_{qi}

X'_{dv} X'_{qv}
 X'_{di} X'_{qi}

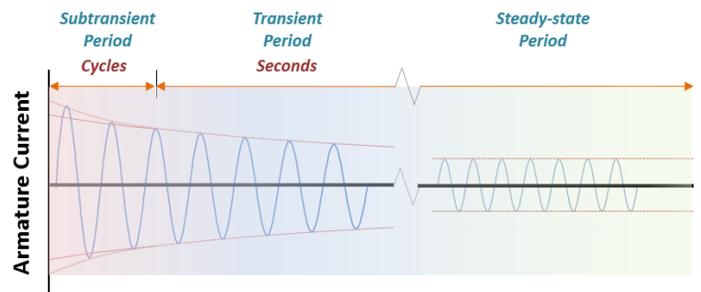


Figure 8 - Armature current immediately following a balanced, 3-phase short circuit.

Balanced short circuits

If the short circuit is balanced (3-phase), then the armature current will remain symmetrical around the zero axis, and the phasor diagram of the rotor current will comprise only positive sequence components.

Unbalanced short circuits

When subjected to an unbalanced short circuit, which includes one or two phases to ground or phase-to-phase contact, the armature currents become unbalanced, which is measured as a dc armature current offset during the transient period of the response. The magnitude of the dc offset depends on where in the ac cycle the short circuit occurs, and if the short occurs when the ac voltage is zero, the dc component can be almost twice the symmetrical current level. (See Figure 12.)

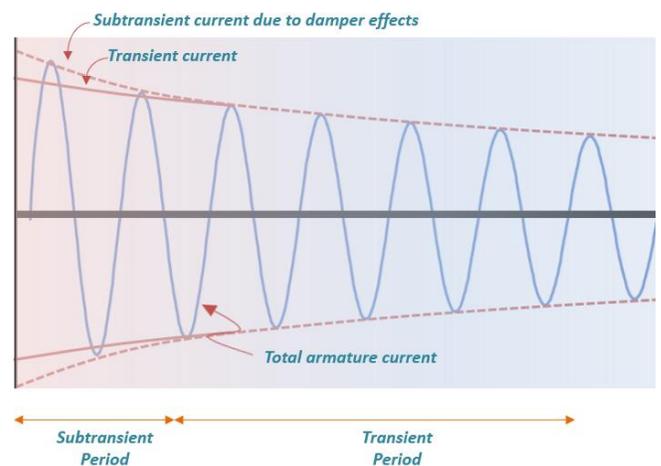


Figure 9 - Details of the effects of the transient and subtransient reactances on armature current following a balanced 3-phase short circuit.

³ Excerpt from course taught by Professor Andy Knight, Energy Systems Group, University of Alberta. Used with permission.

X2v
X2i

Negative sequence reactance results when there's an *unbalanced* short circuit applied to the generator terminals, the effect of which is to cause an armature field that rotates counter, or negative, to the field rotation direction. By using vector analysis, the resulting reactance can be decomposed into positive and negative sequence components.

The damper windings of a salient-pole rotor introduce considerable losses, which can be represented by negative sequence reactance, and tends to keep the generator more nearly loaded to its pre-fault values so that after the fault is removed, the machine will remain synchronized to the rest of the system.

X0v
X0i

Zero sequence reactance also results from an unbalanced short circuit, but only for line-to-ground faults and only when the generator has a grounded neutral. Thus, for generators without a grounded neutral, the zero sequence reactance may be neglected.

Typical Values – Round-rotor Generator

The following table shows typical values for a 230 MVA, air-cooled, round-rotor generator.

Reactances	Direct Axis		Quadrature Axis		Units
	Symbol	Value	Units	Value	
Synchronous – saturated	X _{dv}	2.0802	X _{qv}	2.0125	Per-unit Reactance
Synchronous – unsaturated	X _{di}	2.2767	X _{qi}	2.2026	
Armature Leakage - saturated	X _{lmv}	0.1339			
Armature Leakage - unsaturated	X _{lmi}	0.1410			
Subtransient – saturated	X'' _{dv}	0.1448	X'' _{qv}	0.1432	
Subtransient – unsaturated	X'' _{di}	0.1680	X'' _{qi}	0.1661	
Transient – saturated	X' _{dv}	0.1968	X' _{qv}	0.3726	
Transient – unsaturated	X' _{di}	0.2236	X' _{qi}	0.4234	
Negative Sequence – saturated	X _{2v}	0.1440			
Negative Sequence – unsaturated	X _{2i}	0.1670			
Zero Sequence – saturated	X _{0v}	0.0794			
Zero Sequence – unsaturated	X _{0i}	0.0835			

The synchronous reactance, X, for the direct axis is slightly more than for the quadrature axis for both the saturated and unsaturated conditions.

The subtransient reactance, X'', for the direct and quadrature axis are almost equal for both saturated and unsaturated conditions.

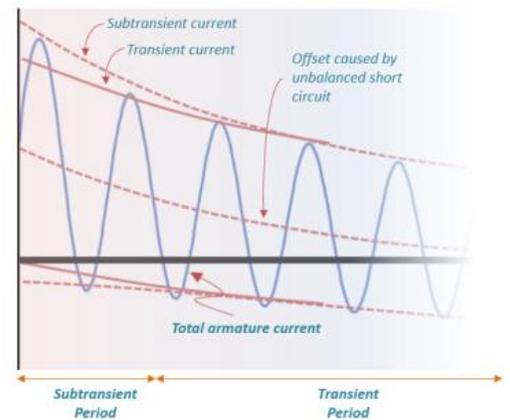


Figure 10 - Armature current immediately following an unbalanced, 3-phase short circuit. The unbalanced armature current produces a dc component during the subtransient period.

Typical Values – Salient-pole Generator

In general, the quadrature axis reactances of a salient-pole generator are much smaller than the direct axis reactances due to the physical structure of the rotor (See Figure 7). Furthermore:

- $X'_q = X_q$ and $X''_d = X''_q$ (approximately) with damper windings
- $X''_q = X'_q = X_q$ (approximately) without damper windings

Generator Time Constants

The generator’s time constants refer to the subtransient and transient time periods, specified in seconds, immediately following either a short circuit or open circuit applied to the armature terminals. (See Figure 13) The subtransient time periods, which are due to the decay of current due to the damper effect in round rotors or the damper windings in salient-pole rotors, are very short—lasting only cycles—compared to the transient time periods of several seconds. The times are usually calculated for four events—the

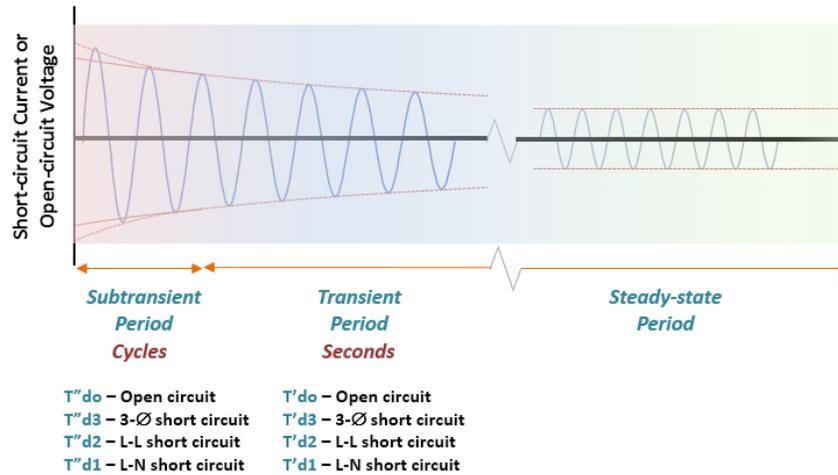


Figure 11 - Generator time constants for the subtransient and transient periods. This plot shows the short-circuit armature current or the open-circuit armature voltage.

opening of the generator’s terminals (open circuit), after which we follow the **armature voltage decay** to its steady-state condition, and three types of short circuits from which we follow the **armature current decay**. The three short circuits comprise a balanced, 3-phase fault, and two unbalanced line-to-line and line-to-neutral (ground) faults.

Typical Values

The following table shows typical values for a 230 MVA, air-cooled round rotor generator. Note that the subtransient time periods (T'') are on the order of cycles along both the direct and quadrature axes, while the transient time periods (T') are in seconds along the direct axis, and tenths of a second along the quadrature axis.

Time Constants	Direct Axis		Quadrature Axis		Units
	Symbol	Value	Symbol	Value	
Subtransient - Open Circuit	T''_{do}	0.048	T''_{qo}	0.910	Seconds
Transient - Open Circuit	T'_{do}	9.029	T'_{qo}	1.003	
Subtransient - Line-to-Neutral Short Circuit	T''_{d1}	0.042	T''_{q1}	0.056	
Transient - Line-to-Neutral Short Circuit	T'_{d1}	1.517	T'_{q1}	0.246	
Subtransient - Line-to-Line Short Circuit	T''_{d2}	0.040	T''_{q2}	0.051	
Transient - Line-to-Line Short Circuit	T'_{d2}	1.271	T'_{q2}	0.221	
Subtransient - Three-phase Short Circuit	T''_{d3}	0.035	T''_{q3}	0.035	
Transient - Three-phase Short Circuit	T'_{d3}	0.780	T'_{q3}	0.170	

Section 3. Rotor Characteristics

The rotor characteristics are fairly straightforward, and apply to both round and salient-pole rotors.

Field voltage. The dc voltage rating of the field winding, which is in the order of a few hundred volts.

Rotor short time thermal capacity, K. A number that represents the ability of the generator to withstand an unbalanced fault assuming negligible heat dissipation (hence, the “short time” rating. It’s calculated as the integrated product of the square of the *negative sequence* current, I_2 , at the generator’s rated output (MVA) and the duration of the fault in seconds. Even though the RSTTC appears to have the value of amp²-seconds, the value, which ranges from 5 to 30, isn’t given a unit. Generators subjected to faults of more than twice the specified value can suffer serious damage.

Field current. The rotor current measured at two points. One is at summer **P_{MAX}**, which means the summertime maximum continuous rating at the **rated power factor** and generator voltage. The other point is also at the summertime maximum continuous rating, but at **zero power factor**. (See Figure 14)

Field winding resistance at the specified temperature. The dc resistance at the temperature the generator owner specifies. The value is in the neighborhood of 0.1 to 0.2 ohms.

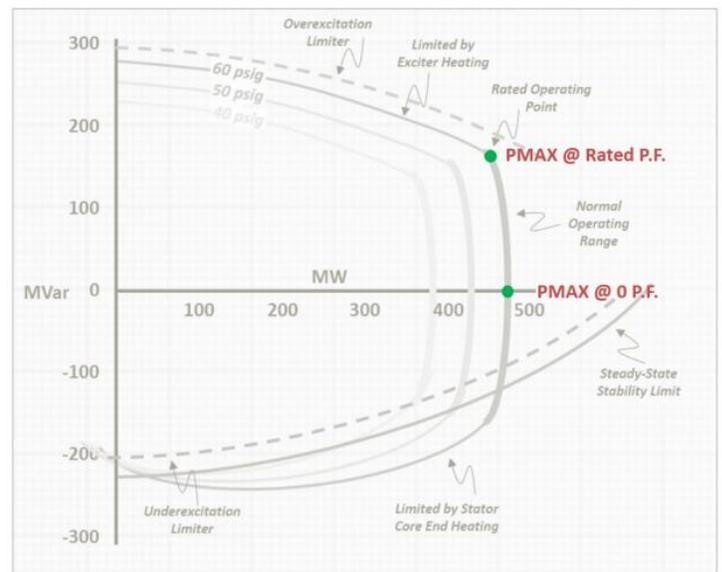


Figure 12 - The field current is measured at two operating points: 1. at the rated P.F. and 2. At 0 P.F.

Section 4. Armature Characteristics

General Information

Armature connection. How the armature phases are connected, which can be either a delta or wye configuration. The wye configuration allows the flow of negative sequence current into the armature during phase-to-ground short circuits if the center-point of the three phase windings is also grounded. (See Figure 15). The delta configuration does not have a neutral connection, which means a delta generator will not allow zero-sequence current to flow into the armature, and its zero-sequence reactance can be ignored. (See Figure 16)

Armature current. The armature current at **P_{MAX}** and rated power factor.

Three-phase armature winding capacitance. The capacitive reactance of the generator.

Armature Short-Circuit Time Constants

Ta3
Ta2
Ta1

The armature short circuit time constants refers to the time for the dc current component in the armature to decay following the application of a short circuit. The values are in tenths of a second, and are provided for a **three-phase, phase-to-phase,** and **phase-to-neutral** fault.

Armature Winding Resistance

R1
R2
R0

These values are the effective armature resistance as seen by **positive, negative,** and **zero sequence** currents, respectively.

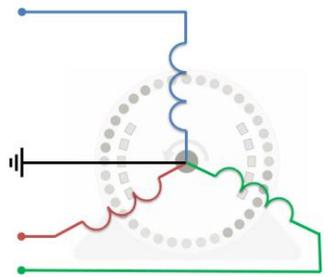


Figure 13 - Wye-connected armature allows negative sequence currents due to unbalanced short-circuits.

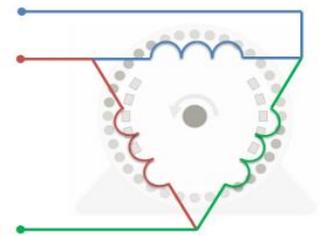


Figure 14 - Delta-connected armature.

Section 5. Continuous Gross Output Ratings

The continuous output ratings comprise the gross real and reactive power that is **continuously available** during the summer, winter, and spring-fall seasons **measured at the generator terminal bus**. (See Figure 5) The main differences in these ratings are due to the ambient (air) and water temperatures. The winter ratings for combustion turbine generators are considerably higher (10% to 20%) due to the lower air inlet temperatures, while ratings for steam generators are slightly higher (around 5%) due to increased efficiencies from the lower condenser water temperatures.

Provide the **design ratings** for **planned generators**, and **validated ratings** for **generators that are in service**.

Power flow representations of generator reactive capability generally start with what is commonly known as the 'D-curve' (see Figure 4). The models used, and the data requested in the worksheet, assume that the **reactive power output is a function of the real power output**. Reactive capability is, in reality, affected by other factors such as high-side transmission system voltages, hydrogen pressure, auxiliary bus voltages, protection schemes, and so on. All these factors affect the ability of a particular generator to supply or absorb reactive power. Today's commonly used power flow models presume a simplified generator model that ignores some, but not all, of these factors, forming a piece-wise linear representation. Although some models can accommodate many points to more accurately approximate the non-linear Q-P relationship, **modelers typically rely upon four key points** to define the reactive capability.

1. **QMAX** at rated **PMAX** should be specified at the **nameplate power factor**,
2. **QMIN** at **PMAX** is most often limited by protection schemes such as underexcitation limiters but can be limited by the field windings or end-core heating (or both), stability limits, etc.,
3. **QMAX** at **PMIN** is usually limited by armature windings or over-excitation or other protection schemes, etc.,
4. **QMIN** at **PMIN** is usually limited by field windings or underexcitation limiters, stability limits, etc.

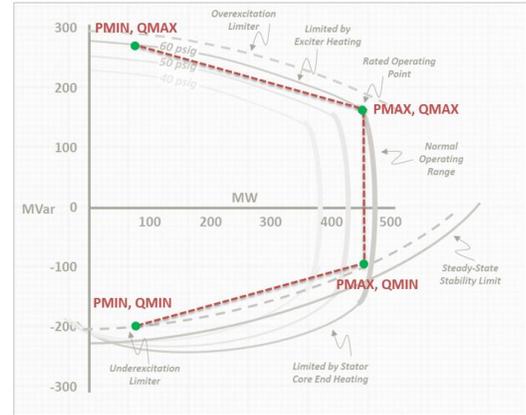


Figure 15 - The continuous output ratings are depicted on the "D-curve" of the generator.

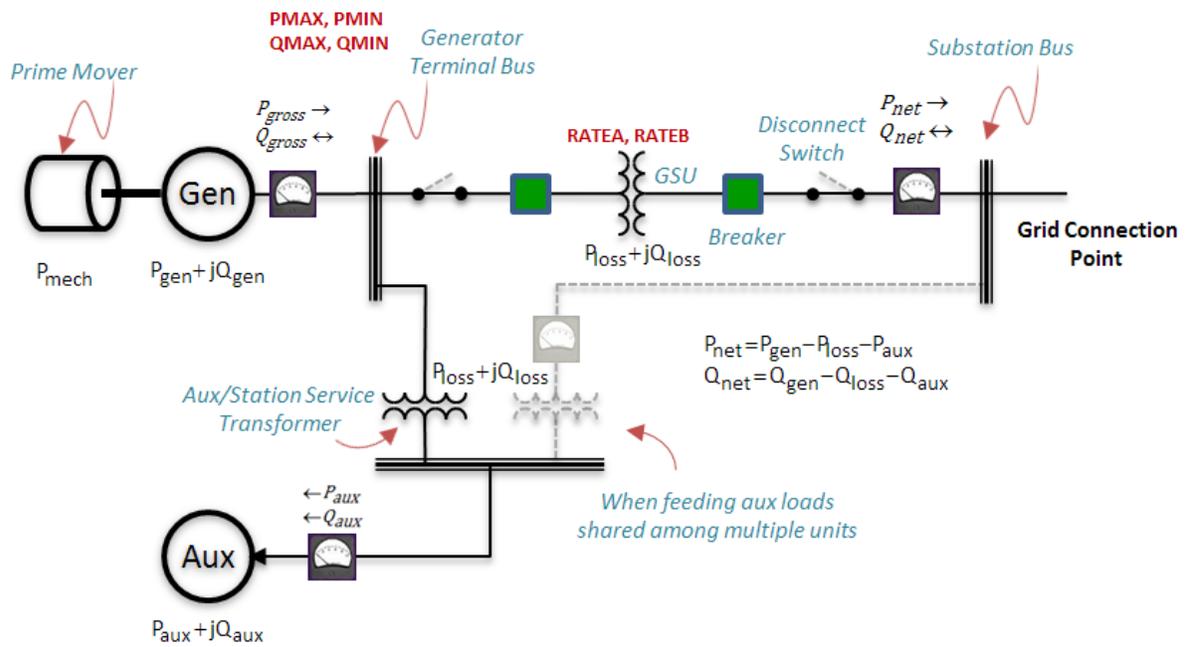


Figure 16 - The generator's continuous ratings are measured at the generator terminal bus.

Appendix 1 – Symmetrical Components

During normal steady-state operation, the current in all three phases of the generator armature are, for all practical purposes, balanced. However, when an unbalanced short-circuit (phase-to-phase or phase-to-ground) is applied to the generator (or synchronous condenser), the armature current loses its symmetry among the three phases.

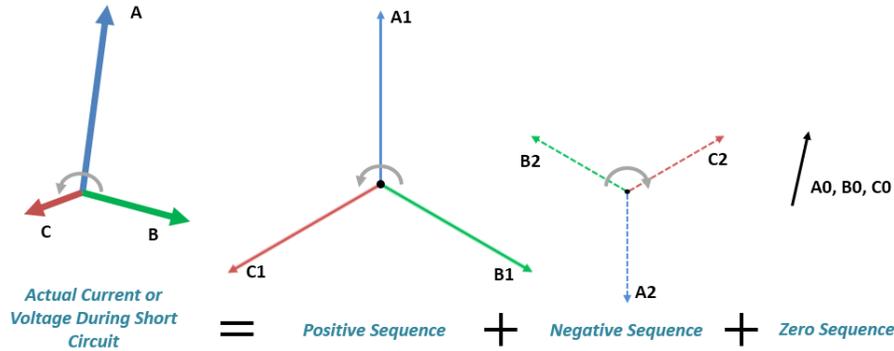


Figure 17 - An unbalanced line-to-ground short circuit causes positive, negative, and zero sequence currents to flow in the armature.

The following table lists four types of short circuits and the current (or voltage or impedance) component(s) that result.

Type of Short Circuit	Positive Sequence	Negative Sequence	Zero Sequence
Three-Phase	Yes	No	No
Line-to-Line	Yes	Yes	No
Line-to-Neutral	Yes	Yes	Yes
Double Line-to-Neutral	Yes	Yes	Yes

Appendix 2 – Transient Reactance Details

By Larry Anderson, AEP

For generator modeling, there are only synchronous, transient, and subtransient d and q-axis reactances. It is only the time constants that are designated as open-circuit or short-circuit with the short circuit time constants normally derived from the open circuit time constants and machine parameters. The significance of the time constants can best be explained with the following linearized Laplace transfer functions for the synchronous generator:

$$L_d(s) = L_d \frac{(1 + sT'_d)(1 + sT''_d)}{(1 + sT'_{d0})(1 + sT''_{d0})} \quad (1)$$

$$G(s) = G_0 \frac{(1 + sT_{kd})}{(1 + sT'_{d0})(1 + sT''_{d0})} \quad (2)$$

$$L_q(s) = L_q \frac{(1 + sT'_q)(1 + sT''_q)}{(1 + sT'_{q0})(1 + sT''_{q0})} \quad (3)$$

$$\Delta\Psi_d(s) = G(s)\Delta e_{fd}(s) - L_d(s)\Delta i_d(s) \quad (4)$$

$$\Delta\Psi_q(s) = -L_q(s)\Delta i_q(s) \quad (5)$$

From transfer functions (1) and (3), we see that the effective d and q-axis inductances of the generator looking into the stator terminals will vary with time as functions of the open-circuit and short-circuit time constants. For these time constants, the sub-transient quantities, denoted by "", are normally much smaller than the transient quantities, denoted by '. During steady state conditions, with $s = 0$, we see from transfer functions (1) and (3) that $L_d(0) = L_d$ and $L_q(0) = L_q$ which are the d and q-axis synchronous inductances of the generator. During a rapid transient, as s tends to infinity in transfer functions (1) and (3), the limiting values of $L_d(s)$ and $L_q(s)$ are given by the following:

$$L_d'' = L_d \frac{T'_d T''_d}{T'_{d0} T''_{d0}}$$

$$L_q'' = L_q \frac{T'_q T''_q}{T'_{q0} T''_{q0}}$$

These are just the d and q-axis subtransient inductances of the generator and represent the machine's effective inductances immediately following a sudden change. For the transient time period, as the machine is transitioning to a steady state from a sudden change, if we ignore the sub-transient time constants in (1) and (3) and let s tend to infinity, then the limiting values of $L_d(s)$ and $L_q(s)$ are given by:

$$L'_d = L_d \left(\frac{T'_d}{T'_{d0}} \right)$$

$$L'_q = L_q \left(\frac{T'_q}{T'_{q0}} \right)$$

These are just the d and q-axis transient inductances of the generator and represent the machine's effective inductances during the time period when it is transitioning to steady state following a sudden change.

Typically, the open-circuit time constants determine the rates of change of currents and voltages when the machine is open circuited at its stator terminals. The short-circuit time constants likewise determine the rates of change when the machine is short-

circuited at its terminals. The short-circuit time constants are always smaller than their associated open-circuit values.

Another interesting observation from transfer functions (4) and (5) during open-circuit conditions follows:

For open circuit conditions, Δi_d and $\Delta i_q = 0$. Therefore from transfer functions (4) and (5), we see that only the d-axis stator flux, Y_d , is nonzero for open circuit conditions. This means that the terminal voltage of the generator will only have a d-axis component and from transfer function (4), this component will respond to changes in field voltage, e_{fd} , with time constants T_{d0}' and T_{d0}'' . (Remember that voltage is just the time derivative of flux which is the same as multiplying transfer function (4) by the Laplace operator, s .)