Voltage Drop Calculations on Shipboard Power Systems

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Abstract. Voltage drop calculations determine whether the voltage at an end user load is within the minimum and maximum values specified by the appropriate interface standard. Within shipboard power systems, voltage drops between generator sets (or the output of power conversion equipment regulating the voltage) and loads are associated with cables and transformers. Long cables can operate below their ampacity limit and still result in voltages at loads being less than specified. Poor transformer selection can lead to over-voltages at loads under lightly loaded conditions and under-voltages under high loads. This paper presents three different methods for conducting voltage drop calculations depending on characteristics of the shipboard power system: quick-check; multi-level check; and over-voltage check. The quick check is most appropriate for power systems that generate, distribute, and use electrical power at the same voltage, or use regulated solid state power conversion to convert power from one voltage to another. The multi-level check is appropriate if the voltage drop between the generator or power electronic converter source and the load center is significant; often the result of transformer regulation. The over voltage check is appropriate if transformers are employed that have a rated secondary voltage above the upper bound of acceptable voltage. Smart Ship Systems Design (S3D) is a tool than can calculate voltage drops for dc and three-phase ac systems. This paper describes how to use S3D for conducting voltage drop calculations, provides system and component modelling guidance, recommends mitigation actions if needed, and demonstrates calculations through examples.

Keywords: voltage drop calculation, ship electrical power system, S3D, steady-state analysis

1. Introduction

In the design of shipboard power systems, voltage drop calculations are performed to determine if the voltage at the end user load is within the minimum and maximum values specified by appropriate interfaces standards. Specifically, voltage drop calculations determine:

a. Whether a cable or set of cables powering a load is large enough or enough cables are paralleled.
b. If the turns ratio and voltage regulation characteristics of a transformer are suitable.

Initially, power cables are usually chosen based on ampacity. As defined in MIL-HDBK-299 [1], ampacity is "the current, in amperes, a conductor can carry continuously under the conditions of use (conditions of the surrounding medium in which the cables are installed) without exceeding its temperature rating limit." Guidance for determining cable ampacity and cable derating for power cables bundled in raceways, cableways, etc., is provided by MIL-HDBK-299 [1] and MIL-STD-2003-4 [2]for naval applications; and by IEEE 45.8 [3] and ABS Rules for Building and Classing Marine Vessels [4] for commercial applications.

Within a power system, voltage drops between generator sets (or the output of power conversion equipment regulating the voltage) and loads are associated with cables and transformers. Cables, particularly long cables, can operate below their ampacity limit and still result in voltages at loads being less than specified in interface requirements. Calculations to determine whether the voltages at the loads adhere to the interface requirements are called "voltage drop calculations."

For naval ships with low voltage ac generators, power is typically produced with a nominal system voltage of 450 volts [5]. The power utilization voltage is 440 ± 5% volts (418 to 462 volts). This implies that the voltage drop from a generator to load should be no more than 32 volts.

For commercial ships with 450 Volt nominal system voltage, the allowed voltage tolerance is +6 % and -10% (405 to 477 volts) [6]. This implies the voltage drop from a generator to load should be no more than 45 volts. The voltage drop from the ship's service switchboard to any point of the system should not exceed 5% of nominal system voltage (22.5 volts in this case) per IEEE Std 45.1 [6]. ABS Rules for Building and Classing Marine

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Vessels [4] states the voltage drop below nominal voltage should not be greater than 6% at any point in the installation (423 volts for a 450 V nominal system voltage).

For naval ships with medium voltage ac generators, power is typically produced with a nominal system voltage of 4.16 kV, 6.6 kV, or 13.8 kV [5]. The allowed voltage tolerance is ±1 %.

For loads that operate at a different voltage than the generation voltage, the impact of transformer regulation should be incorporated into the analysis. As defined in [8], regulation of a transformer is the "change in secondary voltage, expressed in percent of rated secondary voltage, which occurs when … kVA output at a specified power factor is reduced from rated value to zero, with the primary impressed terminal voltage maintained constant" at its rated value.

This paper is motivated by the lack of guidance on how to perform voltage drop calculations onboard ship. An engineer new to shipboard power system design is often expected to perform these calculations without adequate preparation; voltage drop calculations are typically not part of an electrical engineering or naval architecture and marine engineering university curriculum.

The Smart Ship Systems Design (S3D) tool is capable of performing voltage drop calculations for dc and three phase ac systems. While S3D is used in this paper, the modeling approach presented here may be readily adapted to other simulation tools. The following sections describe three different types of voltage drop analyses, provides methods for performing component modeling, recommends mitigation actions if needed, and illustrates the approaches through examples.

The views expressed in this paper are those of the author and are not necessarily official policy of the U.S. Navy or any other organization. Engineers should consult and follow applicable contractual, regulatory, and technical warrant holder requirements.

2. S3D

S3D incorporates a framework for modeling energy networks composed of interconnected components. The identification of constituent components and their connections with each other is kept separate from the simulation models used to perform system simulations. In this way, the network definition, in the form of diagrams, may be re-used across different types of simulation. Currently S3D (version 4.5.0) only supports steady-state analysis; future plans include adding capability to perform quasi-steady-state and fully dynamic simulations based on the same network definition. Since voltage drop calculations are based on steady-state analysis, S3D is well suited for conducting the calculations.

S3D uses the Leading Edge Architecture for Prototyping Systems (LEAPS) as a common data repository with other ship design tools. [9] Data within LEAPS conforms to the ship ontology defined in the Formal Object Classification for Understanding Ships (FOCUS) product meta-model. By using LEAPS and conforming to FOCUS, S3D is designed to be interoperable with other ship design tools within the overall suite of design tools available to the ship designer. Figure 1 depicts the user interface for S3D's diagram designer application.

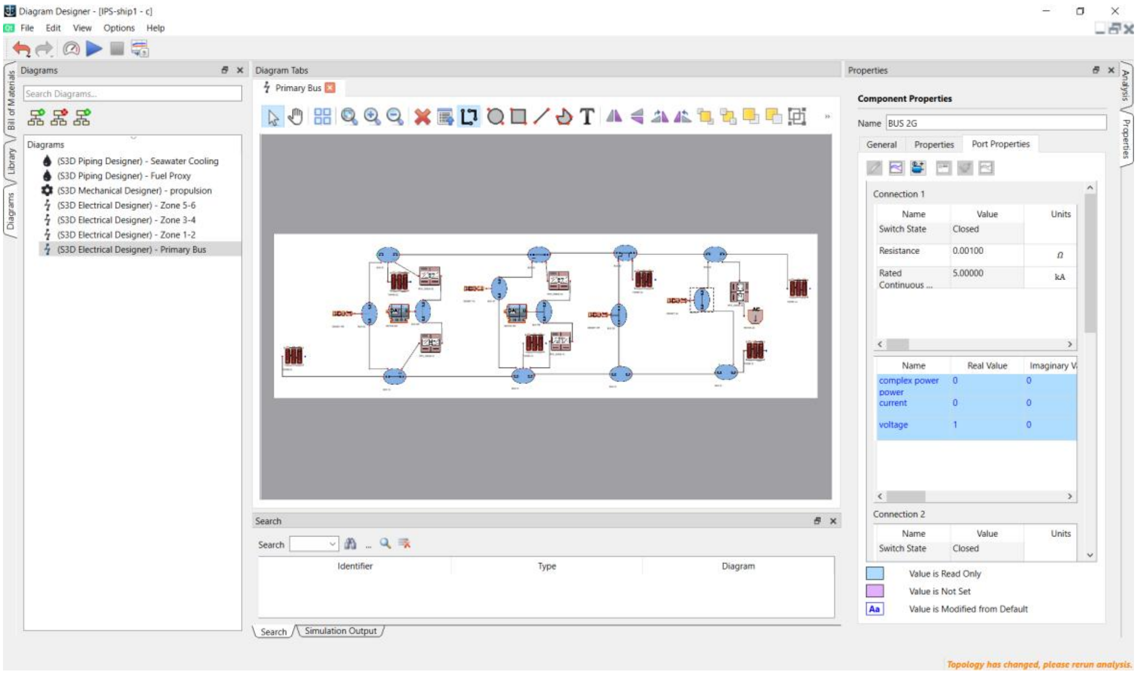

Figure 1. S3D Diagram Designer.

3. AC voltage drop analyses

This paper describes three different types of analyses: quick check, multi-level check, and over-voltage check. The quick check is most appropriate for power systems that generate, distribute, and use electrical power at the same voltage, or use regulated solid state power conversion to convert power from one voltage to another; the regulation of transformers is not an issue. This method assumes the voltage drop is very small between the generator or regulated power converter and the load center / switchboard feeding the load. The multi-level check is appropriate if the voltage drop between the generator or power electronic converter source and the load center is significant; often the result of transformer regulation. This method develops a reasonable estimate for the lowest voltage that will be experienced at the load center / switchboard. Most power systems are designed to preclude over-voltage at loads when generating power at the nominal system voltage. However, if transformers are used such that the no-load voltage exceeds the upper bound of the acceptable voltage range, then over-voltage conditions may exist at the load interface under lightly loaded conditions; the over-voltage check addresses this potential for an over-voltage.

3.1. Quick check

The quick check is the simplest check to model and perform. A quick check focuses on the voltage drop in the cable from the circuit breaker feeding the load, to the load's terminals. Normally, the circuit breaker is contained within a switchboard, load center or power panel. A quick check analysis assumes the voltage at the circuit breaker is equal to the nominal system voltage. The load's real power is set to its peak value and the associated reactive power.

To perform the quick check, model the system as a generator at the nominal system voltage connected via the cable to the load. Determine the steady-state solution and record the voltage magnitude at the load; flag it if the difference in magnitude with the nominal system voltage is greater than 5% of the nominal system voltage or if the voltage at the load is less than that allowed by the interface standard.

Figure 2 depicts an S3D Electrical System Diagram for performing a quick check. The properties of the _Cable and the _AC Static Load are established for each cable under study and recorded in a run matrix (Table 1). The _Gas Turbine Generator Set Liquid Cooled serves as a proxy for the rest of the electrical power system; it sets the voltage on the source end of the cable (operating voltage) to the nominal system voltage. Guidance for determining cable and load properties is provided in section 5.

The S3D Electrical System Diagram is analyzed within S3D for each run of the run matrix; the properties of the components are set to the values in the run matrix. The results of each simulation are recorded in a results table (Table 2). The mitigation activities in section 8 should be considered for any cable not meeting the criteria.

Appendix A provides an alternate iterative method for calculating the voltage at the constant power load.

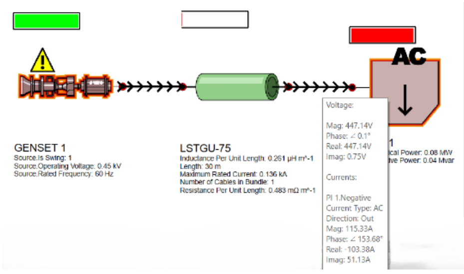

Figure 2. S3D implementation of quick check.

Table 1. Quick Check Run Matrix template

		Cable					Load	
Run	Cable ID	Inductance Per Unit Length (uH/m)	Length (m)	Maximum Rated Current (kA)	Number of Cables	Resistance per Unit Length (mOhm/m)	Actual Electrical Power (MW)	Actual Reactive Power (Mvar)
1								
2								
3								
4								
5								
6								
7								

Table 2. Quick Check Results Table template

Run	Cable ID	Voltage Magnitude at Load (V)	Voltage Limit (V)	Current Magnitude (A)	Maximum Rated Current (A)	Voltage Drop Acceptable	Load Current Acceptable
1			418			FALSE	TRUE
2			418			FALSE	TRUE
3			418			FALSE	TRUE
4			418			FALSE	TRUE
5			418			FALSE	TRUE
6			418			FALSE	TRUE
7			418			FALSE	TRUE

3.2. Multi-level check

A multi-level check incorporates a load-flow analysis to account for voltage drops between the generator and the circuit breaker serving the load. Once the lowest voltage at the circuit breaker is obtained, a modified form of the quick check method is used; the lowest voltage obtained is used instead of the nominal system voltage for the operating voltage of the _Gas Turbine Generator Set Liquid Cooled.

The load flow analysis models the entire ship power system to the load center level of detail. An Electric Power Load Analysis (EPLA) is required to determine the demand power at each load center for each combination of operating condition, ambient condition, power system line-up, electric propulsion minimum and maximum loads, and bus transfer position. Guidance for conducting an EPLA is provided by [10]. The Electrical Power System Concept of Operations (EPS-CONOPS) defines the power system configuration for each operating condition as a function of total electrical load. For ships with electric propulsion, both the minimum and maximum electric propulsion load appropriate for the operational condition should be investigated. The Propulsion System Concept of Operations (PS-CONOPS) describes the online propulsion motors (or prime movers for mechanical drive) for a given speed range for each operational condition.

Generator sets, electric propulsion, distribution equipment, all cables between the generator sets (or other sources of power) and the load centers, transformers or power conversion equipment between the generator sets and the load centers, bus transfers, and proxy loads should be modeled. Proxy loads are the “rolled” up electrical loads to model the demand power as calculated in the EPLA.

A run matrix is created to cover the full range of analysis required:

a. Generator sets and power converters: whether online, and load sharing method
b. Bus nodes / switchboards: whether specific switches / circuit breakers are open or closed

c. Bus transfers: position
d. Propulsion loads: set to the appropriate propulsion level
e. Loads: set actual (real) electrical power to the appropriate demand power for the operational condition and ambient condition. Set the actual reactive power to the appropriate value

Once the run matrix is executed in S3D, the lowest voltage magnitude is recorded for each load center. To determine the voltage at each load, the procedure used for the quick check method is used, except the magnitude of the Operating Voltage for the _Gas Turbine Generator Set Liquid Cooled is set equal to the recorded minimum voltage magnitude for the corresponding load center instead of the nominal system voltage.

3.3. Over-voltage check

If transformers are used such that the no-load voltage exceeds the upper bound of the acceptable voltage range, then over-voltage conditions may exist at the load interface under lightly loaded conditions. For over-voltage check systems modeling, the demand power at each load center for each combination of operating condition, ambient condition, power system line-up, electric propulsion minimum loads, and bus transfer position is required.

The demand power is normally obtained from an EPLA. The EPS-CONOPS defines the power system line-ups for each operating condition as a function of total electrical load. All cables between generator sets and load centers should be modeled. Cables between load centers and loads need not be modeled.

A run matrix is created to cover the full range of analysis required:

a. Generator sets and power converters: whether online, and load sharing method
b. Bus nodes / switchboards: whether specific switches / circuit breakers are open or closed
c. Bus transfers: position
d. Propulsion loads: set to the appropriate propulsion level
e. Loads: set actual (real) electrical power to the appropriate demand power for the operational condition and ambient condition. Set the actual reactive power to the appropriate value. Margins and service life allowances should not be included.

Once the run matrix is executed in S3D, the highest voltage magnitude is recorded for each load center. This voltage is compared to the maximum allowable voltage to determine if a potential over-voltage condition exists.

4. DC voltage drop analyses

The quick check is usually adequate for dc systems. DC power is typically produced from a regulated rectifier or converter; the voltage at this point is typically regulated to the nominal system voltage. In dc systems, the cable reactance does not contribute to voltage drop; the voltage drop is solely due to resistance. In ac systems, the reactance can rival the resistance for high ampacity cables typically found in the main distribution bus; voltage drops between the rectifier / power converter and the load center will likely be lower for dc systems as compared to ac systems. In many cases, the voltage drop between the rectifier / power converter and the load center / switchboard can be neglected; hence the quick check method should be adequate.

5. Component modeling

This section provides guidance for modeling components within S3D. This same guidance is generally applicable to other steady-state analysis tools.

5.1. Cable

In S3D, the following component properties for a _Cable component (Figure 3) should be specified:

- Inductance Per Unit Length (μH m^-1)
- Resistance Per Unit Length (mΩ m^-1)
- Maximum Rated Current (kA)
- Number of Cables in Bundle
- Length (m)

For the U.S. Navy, most low voltage power cables are of the LSTSGU type defined in [11]. Table 3 provides property data derived from [1] or estimated. Estimated quantities are in italic-bold-red font. The Maximum Rated

Current values (ampacity) are for a single conductor when the cable is physically or thermally isolated from other cables.

Individual datasheets should be consulted for medium voltage cables (rated above 1000 V) or for low voltage (rated no more than 1000 V) cable types other than LSTSGU. Where datasheets are unavailable, Appendix B provides techniques for estimating cable properties based on dimensional data and material composition.

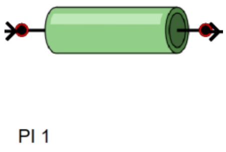

Figure 3. _Cable component

The resistance per unit length of a conductor is a function of temperature. If the resistance per unit length (ρ_0) is known at one temperature (T_0) in °C, then the resistance per unit length (ρ_1) can be calculated at another temperature (T_1) in °C using equation (1). [1]

$$\boldsymbol{\rho_1 = \rho_0\left(1 + 0.00393(T_1 - T_0)\right)} \quad (1)$$

For naval ships, an ambient temperature of 45 °C should be used for all cables except power cables; for power cables, an ambient temperature of 65 °C should be used. [1] Since only power cables are modeled in S3D, 65 °C should normally be used for naval ships.

The maximum rated current provided in Table 3 may require adjustment depending on how closely cables are packed in cable trays. As stated in [2], ampacities from [1] "may be used as the cable ampacity rating when the cable is physically or thermally isolated from other cables." For cases where derating guidance is not provided by [1] or [2], the ampacity is to be determined by test or analysis. Guidance on acceptable analysis methods is not provided. Ampacity guidance is only provided by [1] as a function of ambient temperature.

For commercial ships, [3] provides ampacity for cables at 45° C ambient mounted in single-bank installations with maintained spacing of less than one cable diameter between adjacent cables. These values are 0.85 times the "free air" values with at least one cable diameter spacing between adjacent cables. If cables are double banked, the single bank (close spacing) ampacities should be multiplied by 0.8

For early-stage design, applying the process define in [3] to the Maximum Rated Current values of Table 3 suggests using the following packing multipliers:

1.0	Single Banked, at least one cable diameter between adjacent cables
0.85	Single Banked, less than one cable diameter between adjacent cables
0.68	Double Banked (= 0.85 × 0.8), two layers of cables on the same cable tray.

Table 3. LSTSGU Cable Properties (bold-red-italic values are estimated)

Type and Size	Conductor size	Inductance per unit Length (uH/m)	Resistance per unit Length (50 °C) (mΩ/m)	Maximum Rated Current (50 °C) (kA)
LSTSGU-3	16 AWG (Class B)	0.374	15.49	0.010
LSTSGU-4	14 AWG (Class B)	0.348	9.657	0.017
LSTSGU-9	10 AWG (Class B)	0.313	3.891	0.036
LSTSGU-14	9 AWG (Class B)	0.357	3.095	0.047
LSTSGU-23	7 AWG (Class B)	0.339	1.957	0.064
LSTSGU-30	Navy Standard 30 (19)	***0.339***	1.29	***0.073***
LSTSGU-40	4 AWG (Class C)	***0.311***	1.045	***0.083***
LSTSGU-50	3 AWG (Class C)	0.261	0.757	0.101
LSTSGU-60	2 AWG (Class D)	***0.261***	0.685	***0.110***
LSTSGU-75	1 AWG (Class C)	0.261	0.483	0.136
LSTSGU-100	0 AWG (Class D)	0.252	0.382	0.160
LSTSGU-125	00 AWG (Class D)	***0.252***	0.32	***0.181***
LSTSGU-150	000 AWG (Class D)	0.252	0.243	0.216
LSTSGU-200	0000 AWG (Class D)	0.252	0.191	0.250
LSTSGU-250	250 MCM (Class C)	***0.252***	0.16	***0.282***
LSTSGU-300	300 MCM (Class D)	0.252	0.136	0.320
LSTSGU-350	350 MCM (Class D)	***0.252***	0.114	***0.361***
LSTSGU-400	Navy Standard 400 (127)	0.252	0.0984	0.400

For ship's that are volume constrained, the Double Banked factor should be used. For ship's that are weight constrained, the Single Banked – with at least one cable diameter between cables factor should be used. For designs that are both weight and volume constrained, the Single Banked, less than one cable diameter between adjacent cables factor should be used.

If multiple cables are paralleled into a bundle, the Maximum Rated Current should be set to the product of the Number of Cables in Bundle, the maximum rated current of a single cable, and the packing multiplier.

While the Maximum Rated Current does not have an impact on voltage drop calculations, providing a reasonable estimate for it enables S3D to identify cables that may be undersized based on ampacity and not voltage drop.

Cable length is usually estimated from the physical layout of equipment. If cable routing is known, then the length of the cable route should be used. If only the centers of equipment are known, then a reasonable estimate is to add the x, y, and z differences of the equipment center coordinates. If the equipment are only known to be located in two different spaces (zones), then adding the x, y, and z differences of the space (zone) center coordinates may be used. If the equipment are only known to be in the same space (zone), then using half the sum of the space's (zone's) length, width, and height may be used.

When using cable routing to estimate cable length, the estimate should account for the impact of cable bend radius and cable terminations. Table 4 provides cable diameter and bend radius data for LSTSGU cable (from [1] values in bold- red-italic are estimated). If data is not otherwise available, the minimum bend radius of a cable may be estimated as 8 times the cable overall diameter.

The additional length for cable terminations depends on:

- Details of where the cable route begins and ends with respect to where the final terminations on the equipment are located,
- The need to incorporate bends in the cable between the route and the final termination, and
- The minimum bend radius.

Table 4. LSTSGU Cable Diameter and Minimum Bend Radius
(bold-red-italic values are estimated)

Type and Size	Cable Diameter (mm)	Minimum Bend Radius (mm)
LSTSGU-3	10.4	76
LSTSGU-4	11.4	76
LSTSGU-9	14.6	102
LSTSGU-14	18.2	114
LSTSGU-23	20.6	127
LSTSGU-30	***21.3***	***136***
LSTSGU-40	***22.0***	***148***
LSTSGU-50	24.6	165
LSTSGU-60	**26.4**	**176**
LSTSGU-75	28.8	191
LSTSGU-100	32.2	203
LSTSGU-125	***35.5***	***224***
LSTSGU-150	38.5	241
LSTSGU-200	42.4	267
LSTSGU-250	***46.4***	***288***
LSTSGU-300	49.7	305
LSTSGU-350	***53.0***	***325***
LSTSGU-400	56.0	343

DC cables are generally either two conductor cable for low current values (about 100 amps or less) or four conductor cable for high current values (above 100 amps). At higher currents, the dc magnetic fields may become larger than desired if only two conductors are used; four conductor cables have improved magnetic field cancellation and thus lower dc magnetic fields.

If better data is not available, the ampacity of a dc cable may be estimated by using the ampacity of a three phase ac cable with a conductor cross sectional area 1.5 times that of the cross sectional area of the conductors for one phase for dc cable (one conductor for two-conductor cable, and two conductors for four-conductor cable). Roughly the same amount of heat should be generated per unit length for both cables; the insulation temperature will differ somewhat due to different geometries. Table 5 provides estimated ampacity for two-conductor and four-conductor 1000 volt dc cable. See [12] for estimates of cable properties for medium voltage four-conductor dc cable.

Table 5. Estimated ampacity for 1000 V dc cable (2 and 4 conductor) by conductor size

Conductor Size	2 Conductor Maximum Rated Current (50 °C) (kA)	4 Conductor Maximum Rated Current (50 °C) (kA)
3	0.016	0.028
4	0.023	0.044
9	0.052	0.087
14	0.061	0.081
23	0.076	0.109
30	0.082	0.133
40	0.110	0.176
50	0.130	0.206
60	0.148	0.233
75	0.176	0.274
100	0.207	0.334
125	0.239	0.389
150	0.274	
200	0.334	
250	0.390	

5.2. Transformers

The S3D _Transformer Air Cooled with Regulation model (Figure 4) should be used to model transformers for voltage drop calculations. The following properties are required:

- Rated Apparent Power (MVA)
- Rated Power Factor
- Rated Frequency (Hz)
- No Load Loss Factor (fraction of Rated Apparent Power)
- Full Load Total Loss Factor (fraction of Rated Apparent Power)
- Voltage Regulation
- Rated Voltage for Primary port (kV)
- Rated Voltage for Secondary port (kV)

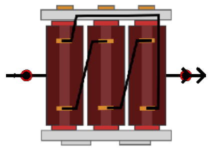

Figure 4. _Transformer Air Cooled with Regulation

Details on the calculations performed in the _Transformer Air Cooled with Regulation model are provided in Appendix C.

For medium voltage to low voltage transformers, datasheets should be consulted to determine the values for these properties. If datasheets are not available, Table 6 data may be employed; the voltage regulation values are estimated while the remainder of the data is from [13].

Table 6. Medium voltage – low voltage three phase transformer data (source [13])

Rated Apparent Power (MVA)	Power Rating at 0.8 PF	Efficiency category	No-load Losses (kW)	Losses due to Load (kW)	Rated Frequency (Hz)	no-load loss factor	Full Load Loss factor	Voltage Regulation	Rated Power Factor
1.0	0.8	B	0.94	9.0	60	0.000940	0.00994	0.0475	0.8
1.25	1.0	B	1.15	11.0	60	0.000920	0.00972	0.0475	0.8
1.6	1.3	B	1.45	14.0	60	0.000906	0.00966	0.0475	0.8
2.0	1.6	B	1.80	18.0	60	0.000900	0.00990	0.0475	0.8
2.5	2.0	B	2.15	22.0	60	0.000860	0.00966	0.0475	0.8
1.0	0.8	A	0.77	7.6	60	0.000770	0.00837	0.0400	0.8
1.25	1.0	A	0.95	9.5	60	0.000760	0.00836	0.0400	0.8
1.6	1.3	A	1.20	12.0	60	0.000750	0.00825	0.0400	0.8
2.0	1.6	A	1.45	15.0	60	0.000725	0.00823	0.0400	0.8
2.5	2.0	A	1.75	18.5	60	0.000700	0.00810	0.0400	0.8

For low voltage to low voltage transformers, data from [8] can be adjusted to three-phase applications from the single-phase data (see Table 7)

Table 7. Low voltage – low voltage three phase transformer data (source [8])

Rated Apparent Power (MVA)	Power Rating at 0.8 PF	Division	No-load Losses (kW)	Full Load losses (kW)	Rated Frequency (Hz)	No-Load Loss factor	Full Load Loss factor	Voltage Regulation	Rated Power Factor
0.003	0.0024	A	0.045	0.174	60	0.01500	0.05800	0.045	0.8
0.009	0.0072	A	0.090	0.315	60	0.01000	0.03500	0.026	0.8
0.015	0.0120	A	0.135	0.435	60	0.00900	0.02900	0.020	0.8
0.023	0.0180	A	0.165	0.540	60	0.00733	0.02400	0.020	0.8
0.030	0.0240	B	0.225	0.630	60	0.00750	0.02100	0.020	0.8
0.045	0.0360	B	0.300	0.960	60	0.00667	0.02133	0.020	0.8
0.075	0.0600	B	0.420	1.650	60	0.00560	0.02200	0.020	0.8
0.113	0.0900	C	0.540	2.250	60	0.00480	0.02000	0.020	0.8
0.150	0.1200	C	0.675	2.850	60	0.00450	0.01900	0.020	0.8
0.225	0.1800	C	0.975	3.720	60	0.00433	0.01653	0.020	0.8
0.300	0.2400	C	1.050	4.650	60	0.00350	0.01550	0.020	0.8

5.3. Loads

The _AC Static Load Air Cooled () and _DC Static Load Air Cooled () components should be used to model loads. The following properties are required:

- Actual electrical power (MW)
- Actual reactive power (MVA) (_AC Static Load Air Cooled only)

The values for the Actual electrical power (P) and (for ac) Actual reactive power (Q) should be as specified in the run matrix. If the power factor is known, the Actual reactive power can be calculated from the Actual electrical power using equation (2).

$$\boldsymbol{Q = \frac{P}{(PF)}\sqrt{1-(PF)^2} = P\sqrt{\frac{1}{(PF)^2}-1}} \quad (2)$$

If the reactive load Q and Power Factor are not known, estimate the reactive load by assuming a power factor (PF) of .90 lagging.

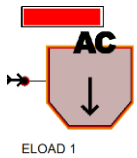

Figure 5. _AC Static Load Air Cooled

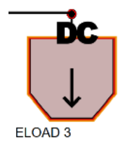

Figure 6. _DC Static Load Air Cooled

The loads for a given cable should reflect the peak average load over a two second period for the quick-check and the multi-level check. Disturbances less than two seconds are generally considered transient responses instead of steady-state responses. The minimum operating load should be used for the over-voltage check.

The loads for determining the voltages at the switchboards or load centers should be based on the demand power for the multi-level check and over-voltage check.

S3D models the loads as constant power loads. This means that the current magnitude will increase as the voltage at the load decreases. Some shipboard loads, such as electric heaters, are resistive where the current magnitude will decrease as the voltage decreases; S3D will over-predict the voltage drop for these loads.

Another consequence of constant power loads is that if the cable impedance is too large, the system will not be able to converge; there is a maximum level of power that can be provided to a constant power load for a given cable impedance.

5.4. Sources

Sources include generator sets, generators, energy storage and power converters that regulate their output voltage. The parameter of interest are the operating voltage and the method for sharing real and reactive power. The EPS CONOPS should provide guidance for determining how real and reactive power is intended to be shared. Currently, the method of implementing real and reactive power sharing with the _Gas Turbine Generator Set Liquid Cooled (Figure 7) is to:

a. For paralleled sources, designate one and only one source to have **is swing** set to TRUE; all other paralleled sources **is swing** should be set to FALSE.
b. Using the EPS CONOPS, PS CONOPS and the EPLA, estimate how much power each of the sources should provide for the given operational condition and ambient condition and set the **Actual Electrical Power** for each source appropriately.
c. Set the **Reactive Power Limit** for each source to 0.
d. Set the **Reactive Power Limit is Absolute** to TRUE for each source.
e. Analyze the system.
f. Add up the real power provided by all the paralleled sources and adjust the **Actual Electrical Power** as needed to share real power appropriately.
g. Add up the reactive power provided by all the paralleled sources (all but the generator with **is swing** set to TRUE should be 0). Adjust the **Reactive Power Limit** for each source to be the appropriate amount in accordance with the EPS CONOPS.
h. Analyze the system again.
i. Check to ensure power sharing of real and reactive power is appropriate, adjust as necessary.

GENSET 1

Figure 7. _Gas Turbine Generator Set Liquid Cooled

The component help and theory documents for the other components that can act as a source should be consulted to determine the equivalent component properties. These documents are available on the “General” tab of the Component Properties window within S3D’s diagram designer.

Normally, the EPS CONOPS would state that real (reactive) power as a fraction of rated electrical power would be the same for all paralleled sources.

For generator sets, it may be desirable to connect a tank with fuel and internal pressure to the fuel port on a piping diagram; this avoids a warning message that insufficient fuel is provided. Providing tanks for the cooling fluid inlet and cooling fluid outlet may also prove desirable. (see Figure 8)

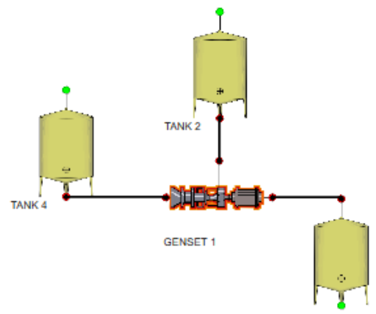

Figure 8. _Gas Turbine Generator Set Liquid Cooled piping diagram

5.5. Bus transfers

The _Bus Transfer component (Figure 9) should be used to model an Automatic Bus Transfer (ABT) or a Manual Bus Transfer (MBT). Bus transfers are used to switch the source of power for a load or group of loads. The Common port is connected to the load while the Position 1 and Position 2 ports are connected to the two sources of power. The component property **Switch Position** is used to determine which source of power is connected to its load.

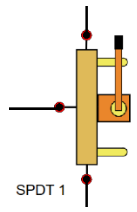

Figure 9. _Bus Transfer component

6. Single Phase AC Loads

While S3D does not currently have the capability of directly modeling single phase ac loads, reasonable results may be obtained using dc system modeling. For single phase ac loads less than 50 amps, cable similar to LSTSGA cable of size 23 (7 AWG) or less would typically be used. At 60 Hz the cable resistance dominates the cable impedance; the inductance can be ignored. Likewise, most single-phase loads have a high-power factor (above 0.90), hence modeling them as a dc load equal to the single-phase ac load's apparent power is reasonable.

S3D should not be used for analyzing cables for single phase ac loads significantly greater than 50 amps, or for low power factor loads (less than 0.9).

7. Concepts of Operation

7.1. EPS-CONOPS

For voltage drop calculations, the EPS-CONOPS establishes the electric plant line-up and approach to real and reactive power sharing as a function of total electrical load for each operating condition. The EPS-CONOPS is often represented as one or more tables describing these relationships. In Table 8, all of the generator sets are assumed to operate in parallel; at least two generators are online at all times; and except for the maximum load where all four generators are online, the generators are not loaded beyond 95% of rating (to prevent cycling loads and load additions from exceeding the rating). For several of the power ranges, two different generator set line-ups are allowed. Table 9 depicts an EPS-CONOPS representative of split-plant operation; generator sets 1A and 1B power the starboard bus and generator sets 2A and 2B power the port bus. Each bus operates independently of the other. Table 10 depicts an EPS-CONOPS for a system where energy storage provides sufficient rolling reserve power and energy to enable operation with only one generator set online (assuming this mode of operation is allowed by policy); and to allow generator sets to operate at 100% of their rating (energy storage provides momentary power to prevent generator set overloading due to load additions or cycling loads).

An EPS-CONOPS table should be provided for each operational condition.

Table 8. EPS-CONOPS for single bus operation

		Generator Set 1A	Generator Set 1B	Generator Set 2A	Generator Set 2B
	Rating (MW)	20	5	20	5
Total Load	up to 9.5 MW	offline	share	offline	share
	9.5 to 23.75 MW	share	offline	offline	share
		offline	share	share	offline
	23.75 to 28.5 MW	share	share	offline	share
		offline	share	share	share
	28.5 to 38 MW	share	offline	share	offline
	38 to 42.75 MW	share	share	share	offline
		share	offline	share	share
	42.75 to 50 MW	share	share	share	share

Table 9. EPS-CONOPS for split plant operation

		Generator Set 1A	Generator Set 1B	Generator Set 2A	Generator Set 2B
	Rating (MW)	20	5	20	5
Total Load	up to 4.75 MW on each bus	offline	swing	offline	swing
	4.75 MW to 19 MW on each bus	swing	offline	swing	swing
	19 MW to 25 MW on each bus	share	share	share	share

Table 10. EPS-CONOPS for single bus with energy storage operation

		Generator Set 1A	Generator Set 1B	Generator Set 2A	Generator Set 2B
	Rating (MW)	20	5	20	5
Total Load	up to 5 MW	offline	swing	offline	offline
		offline	offline	offline	swing
	5 MW to 10 MW	offline	share	offline	share
	10 MW to 20 MW	swing	offline	offline	offline
		offline	offline	swing	offline
	20 MW to 25 MW	share	offline	offline	share
		offline	share	share	offline
	25 MW to 30 MW	share	share	offline	share
		offline	share	share	share
	30 MW to 40 MW	share	offline	share	offline
	40 MW to 45 MW	share	share	share	offline
		share	offline	share	share
	45 MW to 50 MW	share	share	share	share

7.2. PS-CONOPS

The PS-CONOPS describes how propulsion motors / prime movers are configured for different levels of ship propulsion power requirements; the configuration can differ for different operating conditions. Table 11 depicts a typical PS-CONOPS for a twin shaft ship with two propulsion motors on each shaft.

Table 11. PS-CONOPS for two propulsion motors on each shaft of twin shaft ship

	Propulsion Motor 1	Propulsion Motor 2	Propulsion Motor 3	Propulsion Motor 4
Rating (MW)	15	15	15	15
0 < Total Propulsion <= 30 MW	1/2 Power	offline	offline	1/2 Power
	offline	1/2 Power	1/2 Power	offline
	1/2 Power	offline	1/2 Power	offline
	offline	1/2 Power	offline	1/2 Power
30 < Total Propulsion <= 60 MW	1/4 Power	1/4 Power	1/4 Power	1/4 Power

8. Mitigation

If the voltage drop calculations indicate a problem exists in that the voltage at a load may under certain circumstances be outside the acceptable range as defined by the applicable interface standards, then there are several approaches that can be taken. The following sections describe four common ways of addressing voltage drop issues. The designer should choose the mitigation strategy that best balances cost, risk, and ship integration impacts.

8.1. Increasing size of conductors

Perhaps the simplest way of addressing excessive voltage drop for a single cable is to increase the size of the conductors to the next standard value. This simple substitution can reduce the voltage drop 20-40%. However, a larger conductor weighs more, requires more area in cable ways, and costs more. Furthermore, if the cable is very long and traverses many spaces, changing the cable type could require significant rework of many drawings. While increasing the size of the conductors is a typical remedy for excessive voltage drop, in some cases, other mitigation methods may be more appropriate.

8.2. Power factor correction

If the power factor for the maximum load on a transformer is below 0.9, then one can consider adding a means for increasing the power factor to improve the voltage regulation of the transformer.

If the power factor is consistently lagging and low over the full range of operating conditions and ambient conditions, then the addition of line-to-line capacitance can bring the power factor closer to unity. The capacitance value should be selected to ensure the total power factor is always somewhat lagging (power factor no more than 0.98) to ensure the voltage regulator can share reactive power in a stable manner.

If the power factor is low for the limiting conditions, but not consistently low over the full range of operating conditions and ambient conditions, then a power conditioning device that provides power factor correction may be useful in reducing the reactive power provided by the transformer. Some power conditioners also reduce the harmonic content of currents provided by the transformer. This approach may be the most economical if the transformer is of high rating (greater than 250 kW) and has already been installed in the ship.

Induction motors directly connected to the power distribution system are often a source of reactive power. To raise the system power factor, one can provide these induction motors with variable frequency drives that have power factor correction circuitry and do not inject high amounts of harmonic and inter-harmonic currents into the power system.

8.3. Solid-state transformers and regulated power converters

Replacing a traditional transformer with a solid-state transformer or regulated power converter may eliminate some low voltage issues in a power system. The voltage drop due to the transformer regulation can be eliminated; the output of the power electronic converter would be regulated to the nominal system voltage. This method has the advantage of reducing overall system complexity by decoupling the voltage at the loads from the voltage on the primary distribution system. This approach could be very desirable if one expects considerable change in electrical loads over the ship’s service life.

8.4. Adjustment of transformer secondary voltage

Transformers are often available with taps at no load voltages above and below the nominal system voltage on the secondary. A tap with a no-load voltage above the nominal voltage but below the maximum voltage tolerance (462 volts for MIL-STD-1399-300-1 systems with a nominal system voltage of 450 volts) may enable operating all loads between their minimum and maximum voltages under all conditions.

Using a transformer with a no-load secondary voltage greater than the maximum voltage tolerance (for example 480 volts for a MIL-STD-1399-300-1 system with a nominal system voltage of 450 volts) is not advisable unless one can assure that the transformer will always have sufficient loading so its terminal voltage is below the maximum voltage tolerance.

This method of mitigation may be attractive if minimizing the number of drawing changes is of importance, or if ship construction has already commenced. If the cables have already been pulled, changing out the transformer (or merely changing the tap on a transformer) may be the most economical approach.

9. Examples

9.1. Quick check

Table 12 depicts an example run matrix for performing voltage drop calculations for nine different loads and their associated cables. This run matrix is used with the S3D electrical diagram depicted in Figure 10. The gas turbine generator set properties are set to:

_Gas Turbine Generator Set Liquid Cooled
Component Properties
Online = True
Port Properties: Source
Rated Voltage = 450 V (nominal system voltage)
Operating Voltage = 450 V
Rated Frequency = 60 Hz
Is Swing = True

Table 13 depicts the results transcribed from S3D for each of runs listed in the run matrix. Runs 1 through 7 show the cable is acceptable for both ampacity and voltage drop. Run 8 shows that both the ampacity of the cable and the voltage drop are not acceptable; a 15 kW load should use a cable larger than LSTSGU-4. Run 9 shows a case where the ampacity limit is not exceeded, but the cable impedance results in excessive voltage drop; a larger cable is needed.

Table 12. Example Run Matrix for Quick Check

		Cable					Load	
Run	Cable ID	Inductance Per Unit Length (uH/m)	Length (m)	Maximum Rated Current (kA)	Number of Cables	Resistance per Unit Length (mOhm/m)	Actual Electrical Power (MW)	Actual Reactive Power (Mvar)
1	10 kW Load - LSTSGU-4	0.348	100	0.017	1	9.657	0.01	0.0061974
2	20 kW Load - LSTSGU-9	0.313	100	0.036	1	3.891	0.02	0.0123949
3	40 kW Load - LSTSGU-23	0.339	100	0.064	1	1.957	0.04	0.0247898
4	60 kW Load - LSTSGU-50	0.261	100	0.101	1	0.757	0.06	0.0371847
5	100 kW Load - LSTSGU-100	0.252	100	0.160	1	0.382	0.1	0.0619744
6	250 kW Load - LSTSGU-400	0.252	100	0.400	1	0.0984	0.25	0.1549361
7	500 kW Load - LSTSGU-400	0.252	100	0.800	2	0.0984	0.5	0.3098722
8	15 kW Load - LSTSGU-4	0.348	100	0.017	1	9.657	0.015	0.0092962
9	10 kW Load - long - LSTSGU-4	0.348	200	0.017	1	9.657	0.01	0.0061974

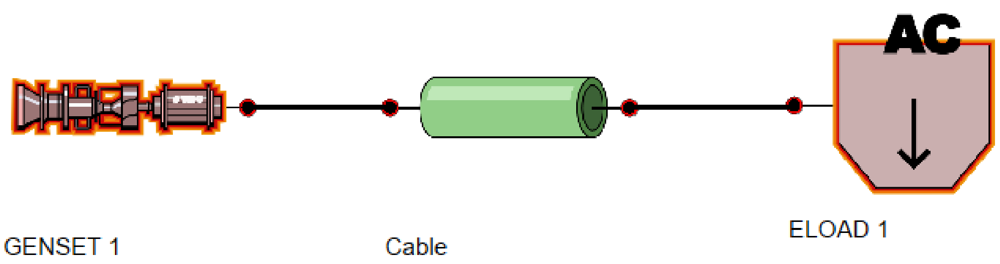

Figure 10. S3D Electrical Diagram for Quick Check

Table 13. Example Results Table for Quick Check

Run	Cable ID	Voltage Magnitude at Load (V)	Voltage Limit (V)	Current Magnitude (A)	Maximum Rated Current (A)	Voltage Drop Acceptable	Load Current Acceptable
1	10 kW Load - LSTSGU-4	427.0	418	15.9	17	TRUE	TRUE
2	20 kW Load - LSTSGU-9	431.5	418	31.5	36	TRUE	TRUE
3	40 kW Load - LSTSGU-23	431.0	418	63.0	64	TRUE	TRUE
4	60 kW Load - LSTSGU-50	438.8	418	92.9	101	TRUE	TRUE
5	100 kW Load - LSTSGU-100	440.0	418	154.4	160	TRUE	TRUE
6	250 kW Load - LSTSGU-400	441.1	418	385.0	400	TRUE	TRUE
7	500 kW Load - LSTSGU-400	441.1	418	770.0	800	TRUE	TRUE
8	15 kW Load - LSTSGU-4	414.2	418	24.6	17	FALSE	FALSE
9	10 kW Load - long - LSTSGU-4	400.4	418	17.0	17	FALSE	TRUE

9.2. Multi-level check

A multi-level check has two stages: Determine the lowest voltage at each load center; and determine the voltage at each load when the load center voltage is set to the lowest value determined in the first stage. Figure 11 and Figure 12 depict the medium voltage distribution and low voltage zonal distribution of a notional ship. Connection 2 of Bus MVZ6 is open; all other connections of bus nodes are closed. Tables 14-18 provide the configuration data for all of the other components. For this example, two operational conditions are defined: Operational Condition 1 and Operational Condition 2. Three cases are examined for each operational condition: All bus transfers in normal position; vital loads on odd load centers connected to alternate source while vital loads on even load centers connected to normal sources; and vital loads on even load centers connected alternate sources while vital loads on odd load centers connected to normal sources. The voltages on each of the low voltage bus nodes are recorded as depicted in Table 19. The minimum voltage for each node is used as the source voltage for checking cable voltage drops and cable currents. If we use the cables defined in the previous example as the non-vital loads connected to Bus Node LVZ2 and calculate the voltages at the loads using the Quick-Check method, the results depicted in Table 20 are obtained. The voltage drops for more cables are identified as excessive; more cables could possibly exceed their ampacity as well.

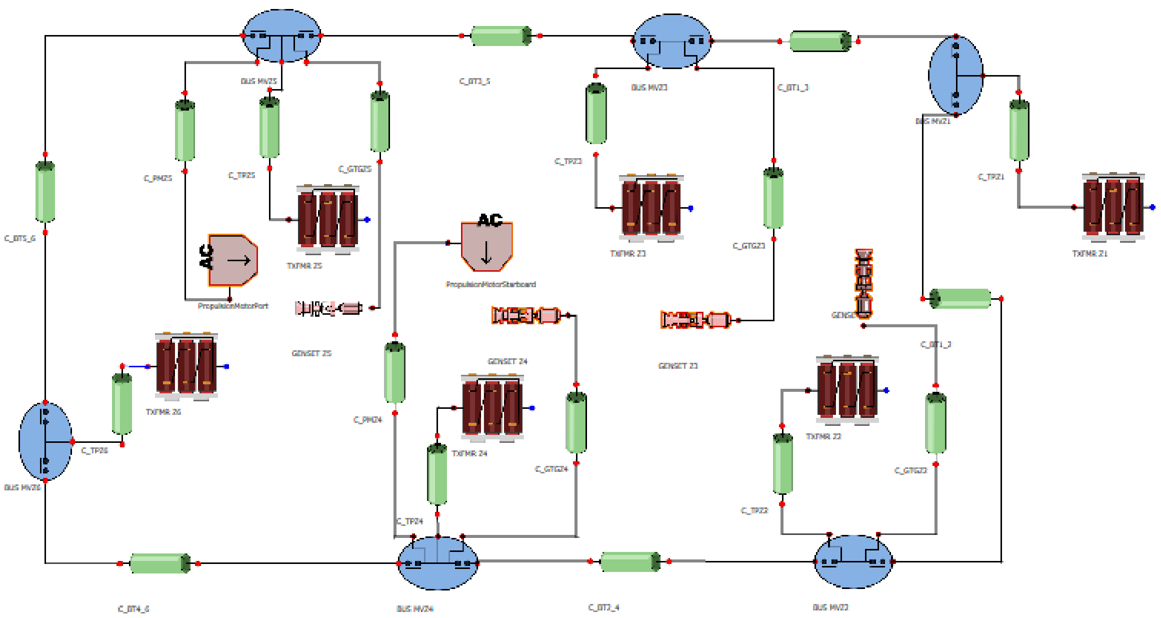

Figure 11. S3D Electrical Diagram for Medium Voltage Generation and Distribution for Multi-level check

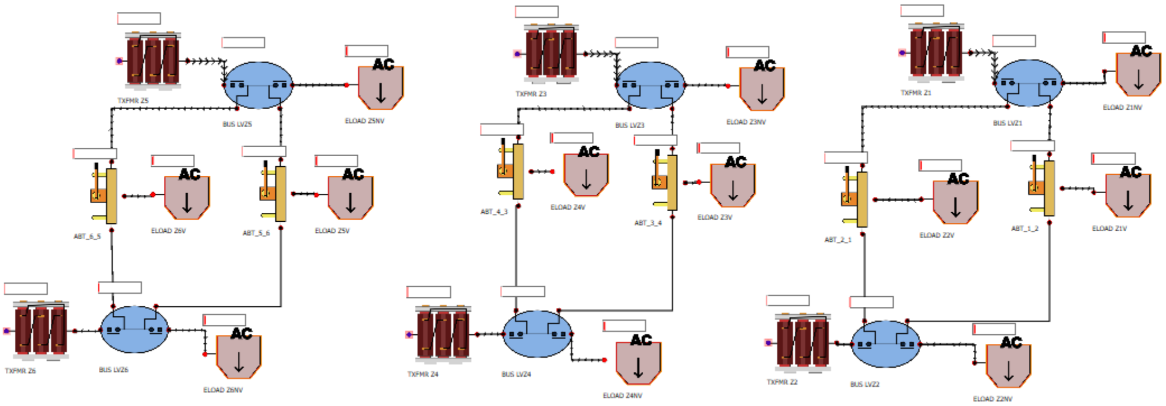

Figure 12. S3D Electrical Diagram for Low Distribution for Multi-level check

Table 14. Example _Cable Data for Multi-level check

Cable	Inductance per unit length (uH/m)	length (m)	Maximum Rated Current (kA)	Number of Cables in Bundle	Resistance per unit Length (mO/m)
C_BT1_2	0.252	50	1.2	3	0.114
C_BT1_3	0.252	50	1.2	3	0.114
C_BT2_4	0.252	50	1.2	3	0.114
C_BT3_5	0.252	50	1.2	3	0.114
C_BT4_6	0.252	50	1.2	3	0.114
C_BT5_6	0.252	50	1.2	3	0.114
C_GTGZ2	0.252	10	1.2	3	0.114
C_GTGZ3	0.252	10	1.2	3	0.114
C_GTGZ4	0.252	10	1.2	3	0.114
C_GTGZ5	0.252	10	1.2	3	0.114
C_PMZ4	0.252	10	1.2	3	0.114
C_PMZ5	0.252	10	1.2	3	0.114
C_TPZ1	0.261	10	0.1	1	0.757
C_TPZ2	0.261	10	0.1	1	0.757
C_TPZ3	0.261	10	0.1	1	0.757
C_TPZ4	0.261	10	0.1	1	0.757
C_TPZ5	0.261	10	0.1	1	0.757
C_TPZ6	0.261	10	0.1	1	0.757

Table 15. Example _Gas Turbine Generator Set Liquid Cooled Data for Multi-level check

Gas Turbine Generator Set	Online	Rated Electrical Power (MW)	Reactive Power Limit is Absolute	Reactive Power LImit (MVAR)	Rated Voltage (kV)	Rated Frequency (Hz)	Operating Voltage (kV)	Is Swing	Actual Electrical Power (MW)
GENSET Z2	TRUE	25	TRUE	0	13.8	60	13.8	TRUE	20
GENSET Z3	TRUE	25	TRUE	2.6	13.8	60	13.8	FALSE	22
GENSET Z4	TRUE	25	TRUE	2.6	13.8	60	13.8	FALSE	22
GENSET Z5	FALSE	25	TRUE	0	13.8	60	13.8	FALSE	0

Table 16. Transformer Data for Multi-level check

Full Load Loss Factor	0.0099	
No Load Loss Factor	0.0009	
Rated Apparent Power	1.875	MVA
Rated Frequency	60	Hz
Rater Power Factor	0.8	
Voltage Regulation	0.0475	
Winding Configuration	DeltaDelta	
Primary: Rated Voltage	13.8	kV
Secondary: Rated Voltage	0.45	kV

Table 17. Example _AC Static Loads for Multi-level check (Operational Condition 1)

AC Static Load	Actual Electrical Power (MW)	Actual Reactive Power (Mvar)	Online
ELOAD Z1NV	0.5	0.2	TRUE
ELOAD Z1V	0.5	0.2	TRUE
ELOAD Z2NV	0.5	0.2	TRUE
ELOAD Z2V	0.5	0.2	TRUE
ELOAD Z3NV	0.5	0.2	TRUE
ELOAD Z3V	0.5	0.2	TRUE
ELOAD Z4NV	0.5	0.2	TRUE
ELOAD Z4V	0.5	0.2	TRUE
ELOAD Z5NV	0.5	0.2	TRUE
ELOAD Z5V	0.5	0.2	TRUE
ELOAD Z6NV	0.5	0.2	TRUE
ELOAD Z6V	0.5	0.2	TRUE
PropulsionMotorPort	30	3	TRUE
PropulsionMotorStarboard	30	3	TRUE

Table 18. Example _AC Static Loads for Multi-level check (Operational Condition 2)

AC Static Load	Actual Electrical Power (MW)	Actual Reactive Power (Mvar)	Online
ELOAD Z1NV	0.4	0.2	TRUE
ELOAD Z1V	0.8	0.2	TRUE
ELOAD Z2NV	0.4	0.2	TRUE
ELOAD Z2V	0.8	0.2	TRUE
ELOAD Z3NV	0.4	0.2	TRUE
ELOAD Z3V	0.8	0.2	TRUE
ELOAD Z4NV	0.4	0.2	TRUE
ELOAD Z4V	0.8	0.2	TRUE
ELOAD Z5NV	0.4	0.2	TRUE
ELOAD Z5V	0.8	0.2	TRUE
ELOAD Z6NV	0.4	0.2	TRUE
ELOAD Z6V	0.8	0.2	TRUE
PropulsionMotorPort	30	3	TRUE
PropulsionMotorStarboard	30	3	TRUE

Table 19. Example results: voltages at bus nodes for different operating conditions and different bus transfer positions

	Bus Voltage Magnitude (V)						
	OC 1 - Normal	OC 1 - Even LC + Alt	OC 1 - Odd LC + Alt	OC 2 - Normal	OC 2 - Even LC + Alt	OC 2 - Odd LC + Alt	Minimum Voltage
BUS LVZ1	442	446	438	441	446	436	436
BUS LVZ2	438	432	444	437	430	444	430
BUS LVZ3	441	446	437	441	446	435	435
BUS LVZ4	438	432	443	437	430	444	430
BUS LVZ5	441	445	436	440	446	435	435
BUS LVZ6	438	432	443	437	430	444	430

Table 20. Example results: voltages at loads and cable currents using cables for Example 5.1 and connected to bus LVZ2 (Bus voltage = 430 V)

Run	Cable ID	Voltage Magnitude at Load (V)	Voltage Limit (V)	Current Magnitude (A)	Maximum Rated Current (A)	Voltage Drop Acceptable	Load Current Acceptable
1	10 kW Load - LSTSGU-4	406.0	418	16.7	17	FALSE	TRUE
2	20 kW Load - LSTSGU-9	411.0	418	33.1	36	FALSE	TRUE
3	40 kW Load - LSTSGU-23	410.0	418	66.3	64	FALSE	FALSE
4	60 kW Load - LSTSGU-50	418.0	418	97.4	101	TRUE	TRUE
5	100 kW Load - LSTSGU-100	419.0	418	162.0	160	TRUE	FALSE
6	250 kW Load - LSTSGU-400	421.0	418	404.0	400	TRUE	FALSE
7	500 kW Load - LSTSGU-400	421.0	418	807.0	800	TRUE	FALSE
8	15 kW Load - LSTSGU-4	392.0	418	26.0	17	FALSE	FALSE
9	10 kW Load - long - LSTSGU-4	377.0	418	18.0	17	FALSE	FALSE

9.3. Over-voltage check

To address the unacceptable voltage drop from the previous example, one could consider raising the rated voltage of the secondary winding. If the transformers in the previous example are replaced with ones with a secondary rating of 480 V (an industry standard), but are otherwise identical, then an over-voltage check is recommended to ensure the maximum voltage of 462 V is not exceeded at any of the zonal load centers.

For this example, the minimum load is calculated with the propulsion motors both off and the minimum loads (without margin and service-life allowance) for the two operating conditions as shown in Table 21 and Table 22. Repeating the analysis, the results as shown in Table 23 demonstrate that using transformers with a 480 V rated secondary is not a feasible solution; for all the load centers, the voltage under a minimal load is higher than allowed by the interface specification. An alternate method should be used to address voltage drop.

Table 21. Example _AC Static Loads for Over-voltage check (Operational Condition 1)

AC Static Load	Actual Electrical Power (MW)	Actual Reactive Power (Mvar)	Online
ELOAD Z1NV	0.35	0.16	TRUE
ELOAD Z1V	0.35	0.16	TRUE
ELOAD Z2NV	0.35	0.16	TRUE
ELOAD Z2V	0.35	0.16	TRUE
ELOAD Z3NV	0.35	0.16	TRUE
ELOAD Z3V	0.35	0.16	TRUE
ELOAD Z4NV	0.35	0.16	TRUE
ELOAD Z4V	0.35	0.16	TRUE
ELOAD Z5NV	0.35	0.16	TRUE
ELOAD Z5V	0.35	0.16	TRUE
ELOAD Z6NV	0.35	0.16	TRUE
ELOAD Z6V	0.35	0.16	TRUE
PropulsionMotorP	30	3	FALSE
PropulsionMotorS	30	3	FALSE

Table 22. Example _AC Static Loads for Over-voltage check (Operational Condition 2)

AC Static Load	Actual Electrical Power (MW)	Actual Reactive Power (Mvar)	Online
ELOAD Z1NV	0.3	0.16	TRUE
ELOAD Z1V	0.55	0.16	TRUE
ELOAD Z2NV	0.3	0.16	TRUE
ELOAD Z2V	0.55	0.16	TRUE
ELOAD Z3NV	0.3	0.16	TRUE
ELOAD Z3V	0.55	0.16	TRUE
ELOAD Z4NV	0.3	0.16	TRUE
ELOAD Z4V	0.55	0.16	TRUE
ELOAD Z5NV	0.3	0.16	TRUE
ELOAD Z5V	0.55	0.16	TRUE
ELOAD Z6NV	0.3	0.16	TRUE
ELOAD Z6V	0.55	0.16	TRUE
PropulsionMotorP	30	3	FALSE
PropulsionMotorS	30	3	FALSE

Table 23. Example _AC Static Loads for Over-voltage check Results

	Bus Voltage Magnitude (V)								
	OC 1 - Normal	OC 1 - Even LC + Alt	OC 1 - Odd LC + Alt	OC 2 - Normal	OC 2 - Even LC + Alt	OC 2 - Odd LC + Alt	Maximum Voltage	Maximum Limit	Voltage Acceptable
BUS LVZ1	474	477	471	474	477	470	477	462	FALSE
BUS LVZ2	471	467	475	470	465	476	476	462	FALSE
BUS LVZ3	474	477	470	473	477	469	477	462	FALSE
BUS LVZ4	471	467	475	471	465	476	476	462	FALSE
BUS LVZ5	474	477	470	473	477	469	477	462	FALSE
BUS LVZ6	471	467	475	471	465	476	476	462	FALSE

10. Summary

This paper presented three different methods for conducting voltage drop calculations depending on characteristics of the shipboard power system: quick-check; multi-level check; and over-voltage check. The quick check is most appropriate for power systems that generate, distribute, and use electrical power at the same voltage, or use regulated solid state power conversion to convert power from one voltage to another. The multi-level check is appropriate if the voltage drop between the generator or power electronic converter source and the load center is significant; often the result of transformer regulation. The over voltage check is appropriate if transformers are employed that have a rated secondary voltage above the upper bound of acceptable voltage. Smart Ship Systems Design (S3D) is a tool than can calculate voltage drops for dc and three-phase ac systems. This paper described how to use S3D for conducting voltage drop calculations, provided system and component modeling guidance, recommended mitigation actions if needed, and demonstrated calculations through examples.

Acknowledgments

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Appendix A. Iterative method for quick-check

The quick-check process can be solved iteratively using a spreadsheet or similar tool. The generalized circuit is depicted in Figure 13 where the circuit is understood to be a three-phase ac one-line diagram.

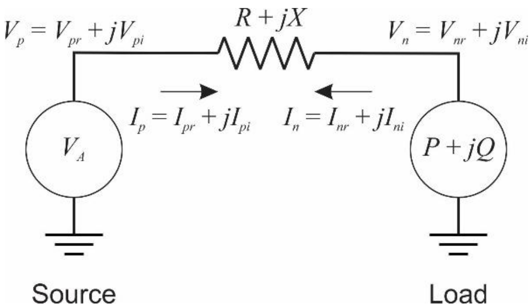

Figure 13. Quick Check circuit Diagram

The constitutive equations for the cable are defined as:

$$V_n - V_p = \sqrt{3} I_n (R + jX) \tag{a1}$$

$$I_p = -I_n \tag{a2}$$

The network equations are:

$$V_{pr} = V_A \tag{a3}$$

$$V_{pi} = 0 \tag{a4}$$

$$\sqrt{3} V_n I_n^* = -P - jQ \tag{a5}$$

Expressing in rectangular coordinates:

$$I_{pr} = -I_{nr} \tag{a6}$$

$$I_{pi} = -I_{ni} \tag{a7}$$

$$V_A - V_{nr} - jV_{ni} = \sqrt{3}(I_{pr} + jI_{pi})(R + jX) \tag{a8}$$

$$V_A - V_{nr} - jV_{ni} = \sqrt{3}(I_{pr}R - I_{pi}X) + j\sqrt{3}(I_{pr}X + I_{pi}R) \tag{a9}$$

$$V_{nr} = V_A - \sqrt{3}(I_{pr}R - I_{pi}X) \tag{a10}$$

$$V_{ni} = -\sqrt{3}(I_{pr}X + I_{pi}R) \tag{a11}$$

$$\sqrt{3}(V_{nr} + jV_{ni})(I_{nr} - jI_{ni}) = -P - jQ \tag{a12}$$

$$\sqrt{3}(V_{nr}I_{nr} + V_{ni}I_{ni}) + j\sqrt{3}(-V_{nr}I_{ni} + V_{ni}I_{nr}) = -P - jQ \tag{a13}$$

$$\sqrt{3}(V_{nr}I_{nr} + V_{ni}I_{ni}) = -P \tag{a14}$$

$$\sqrt{3}(-V_{nr}I_{ni} + V_{ni}I_{nr}) = -Q \tag{a15}$$

$$\sqrt{3}(V_{nr}I_{pr} + V_{ni}I_{pi}) = P \tag{a16}$$

$$\sqrt{3}(-V_{nr}I_{pi} + V_{ni}I_{pr}) = Q \tag{a17}$$

Substituting to eliminate the voltages

$$\left(V_A - \sqrt{3}(I_{pr}R - I_{pi}X)\right) I_{pr} + \left(-\sqrt{3}(I_{pr}X + I_{pi}R)\right) I_{pi} = \frac{P}{\sqrt{3}} \tag{a18}$$

$$-\left(V_A - \sqrt{3}(I_{pr}R - I_{pi}X)\right) I_{ni} + \left(-\sqrt{3}(I_{pr}X + I_{pi}R)\right) I_{pr} = \frac{Q}{\sqrt{3}} \tag{a19}$$

Put in the form of a recursion formula:

$$I_{pr} = \frac{\frac{P}{\sqrt{3}} + \left(\sqrt{3}(I_{pr}X + I_{pi}R)\right)I_{pi}}{\left(V_A - \sqrt{3}(I_{pr}R - I_{pi}X)\right)} \quad \text{(a20)}$$

$$I_{pi} = -\frac{\frac{Q}{\sqrt{3}} + \left(\sqrt{3}(I_{pr}X + I_{pi}R)\right)I_{pr}}{\left(V_A - \sqrt{3}(I_{pr}R - I_{pi}X)\right)} \quad \text{(a21)}$$

Once I_{pr} and I_{pi} have been solved for with the recursion formula, equations (a10) and (a11) may be used to calculate the real and imaginary voltage components (V_{nr} and V_{ni}) at the load. The voltage magnitude at the load ($|V_n|$) is given by equation (a22).

$$|V_n| = \sqrt{V_{nr}^2 + V_{ni}^2} \quad \text{(a22)}$$

Table 24 illustrates the use of the recursion formula to calculate the voltage and current at the load for the first case of the example in section 9.1

Table 24. Example Quick Check using spreadsheet

Cable		
Inductance per Unit Length	0.348	uH/m
Length	100	m
Number of Cables	1	
Resistance per Unit Length	9.657	mOhms/m
Load		
Actual Electrical Power	0.01	MW
Actual Reactive Power	0.006197	MVA
Source		
Operating Voltage	0.45	kV
Rated Frequency	60	Hz
R	0.9657	ohms
X	0.013119	ohms
VA	450	volts
P	10000	watts
Q	6197.4	VA
	Ipr	Ipi
Iteration 1	0	0
Iteration 2	12.83001	-7.951268
Iteration 3	13.71963	-7.963354
Iteration 4	13.76784	-7.964009
Iteration 5	13.77046	-7.964044
Iteration 6	13.7706	-7.964046
Iteration 7	13.77061	-7.964046
Iteration 8	13.77061	-7.964046
Iteration 9	13.77061	-7.964046
Iteration 10	13.77061	-7.964046
Vnr	426.7857	volts
Vni	13.00808	volts
Vn_mag	427.0	volts
Ip_mag	15.9	amps

Appendix B. Estimating cable inductance

This appendix provides guidance for estimating the inductance of a three phase cable as depicted in Figure 14. This approximation, given in equation (b8), assumes the cable is unarmored and that the impact of ferrous material near the cable on the inductance is negligible. The dimensions are defined as:

d	Distance between conductor centers (mm)
ρ	Radius of conductor (mm)
l	Length of the conductor (m)

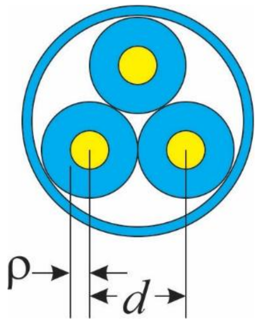

Figure 14. Three-Conductor cable dimensions

For balanced three phase operation, as assumed by S3D, La, the inductance per unit length (µH/m) is given by:

$$L_a = L_S - M \tag{b1}$$

Where:

L_s	Self inductance per unit length (µH/m)
M	Mutual inductance with other conductor per unit length (µH/m)

The self inductance and mutual inductance can be calculated with equations provided by [14]. The self inductance per unit length of a round wire is equal to:

$$L_S = 0.2\left[\ln\left(\frac{2000l}{\rho}\right) - \frac{3}{4}\right] \tag{b2}$$

The mutual inductance per unit length of two parallel conductors is equal to:

$$M = 0.2\left[\ln\left(\frac{1000l}{d\sqrt{2}} + \sqrt{1 + \frac{(1000l)^2}{2d^2}}\right) - \sqrt{1 + \frac{2d^2}{(1000l)^2}} + \frac{d\sqrt{2}}{1000l}\right] \tag{b3}$$

If we assume 1000 × l >> d, then:

$$M \approx 0.2\left[\ln\left(\frac{2000l}{d\sqrt{2}}\right) - 1\right] \tag{b4}$$

$$M \approx 0.2\left[\ln\left(\frac{2000}{\sqrt{2}}\right) + \ln(l) - \ln(d) - 1\right] \tag{b5}$$

The balanced inductance is therefore:

$$L_a \approx 0.2\left[\ln\left(\frac{2000l}{\rho}\right) - \frac{3}{4}\right] - 0.2\left[\ln\left(\frac{2000l}{\sqrt{2}}\right) - \ln(d) - 1\right] \tag{b6}$$

$$L_a \approx 0.2\left[\ln\left(\frac{d}{\rho}\right) + \frac{1}{4} - \ln\left(\frac{1}{\sqrt{2}}\right)\right] \tag{b7}$$

$$L_a \approx 0.2\left[\ln\left(\frac{d}{\rho}\right) + 0.5966\right] \tag{b8}$$

Appendix C. _Transformer Air Cooled with Regulation theory

This appendix details the equations that govern the behavior of the _Transformer Air Cooled with Regulation component in S3D. This component is equivalent to the assembly of components depicted in Figure 15.

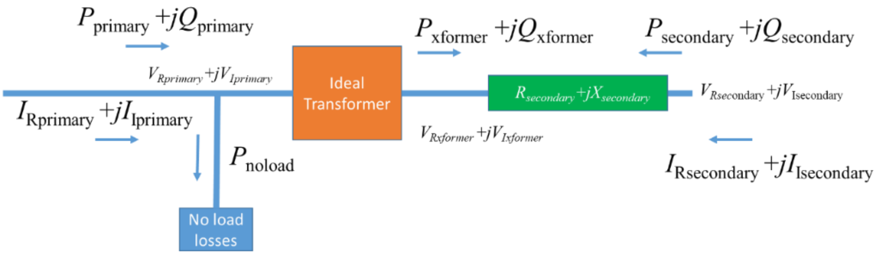

Figure 15. _Transformer Air Cooled with Regulation model

The properties describing the _Transformer Air Cooled with Regulation are defined as:

Rated Apparent Power (MVA): Used to calculate the **Rated Secondary Current** and is the basis for calculating losses at Full Load and No Load.

Rated Power Factor: Power factor for which **Voltage Regulation** is defined for

Rated Frequency (Hz): Frequency for which the other properties are defined for.

No Load Loss Factor: Power on the primary when the apparent power delivered on the secondary is zero. Percentage based on **Rated Apparent Power**.

Full Load Loss Factor: Total losses of the transformer when delivering **Rated Secondary Current**; Percentage based on **Rated Apparent Power**.

Voltage Regulation Factor: Reduction in the secondary voltage magnitude from the secondary rated voltage as a percentage of the secondary rated voltage when the transformer is supplying the **Rated Secondary Current** at **Rated Power Factor**.

Winding Configuration {Wye-Wye, Wye-Delta, Delta-Wye, Delta-Delta}: The winding configuration is used to determine the phase shift of the voltages between the primary and secondary windings.

Primary Rated Voltage (kV): The rated voltage at the primary port.

Secondary Rated Voltage (kV): The rated voltage at the secondary port.

These properties are used to calculate other properties needed to perform the simulation.

The turns ratio (n) is defined by:

$$n = \frac{Primary\ Rated\ Voltage}{Secondary\ Rated\ Voltage} \tag{c1}$$

The Rated Secondary Current is calculated from

$$Rated\ Secondary\ Current = \frac{Rated\ Apparent\ Power}{\sqrt{3} \times Secondary\ Rated\ Voltage} \tag{c2}$$

The losses at the Rated Secondary Current due to the I^2R losses are

$$P_{Loss\_R\_rated\_load} = \frac{(Full\ Load\ Loss\ Factor - No\ Load\ Loss\ Factor)}{100} \times Rated\ Apparent\ Power \tag{c3}$$

The resistance in the model is calculated from:

$$R_{secondary} = \frac{P_{Loss\_R\_rated\_load}}{3\left(\frac{Rated\ Secondary\ Current}{1 - \frac{Voltage\ Regulation\ Factor}{100}}\right)^2} \tag{c4}$$

Converting to polar coordinates as shown in Figure 16:

V_{sec} = voltage Magnitude at the secondary of the ideal transformer at rated power factor (PF)
θ_{Vsec} = voltage Angle at the secondary of the ideal transformer at rated PF

V_{fld} = voltage Magnitude at the secondary port at full load at rated PF
θ_{Vfld} = voltage Angle at the secondary port at full load at rated PF
I_{fld} = current magnitude out of the secondary port at full load at rated PF
ϕ_{Ifld} = current angle out of the secondary port at full load at rated PF
$X_{secondary}$ = Reactance of the secondary

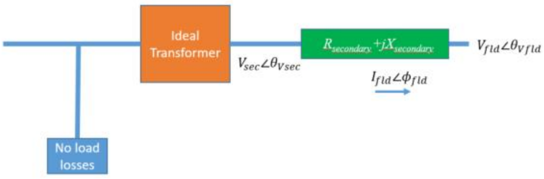

Figure 16. _Transformer Air Cooled variables for calculating $X_{secondary}$

Then

$$I_{fld} = \frac{Rated\ Secondary\ Current}{\left(1 - \frac{Voltage\ Regulation\ Factor}{100}\right)} \quad \text{(c5)}$$

$$V_{fld} = \left(1 - \frac{Voltage\ Regulation\ Factor}{100}\right) \times Secondary\ Rated\ Voltage \quad \text{(c6)}$$

$$V_{sec} = Secondary\ Rated\ Voltage \quad \text{(c7)}$$

If we assume

$$\theta_{Vfld} = 0 \quad \text{(c8)}$$

Then

$$\phi_{Ifld} = -acos(Rated\ Power\ Factor) \quad \text{(c9)}$$

$$V_{sec}cos(\theta_{Vsec}) - V_{fld} = \sqrt{3}\left(R_{secondary}I_{fld}cos(\phi_{Ifld}) - X_{secondary}I_{fld}sin(\phi_{Ifld})\right) \quad \text{(c10)}$$

$$V_{sec}sin(\theta_{Vsec}) = \sqrt{3}\left(R_{secondary}I_{fld}sin(\phi_{Ifld}) + X_{secondary}I_{fld}cos(\phi_{Ifld})\right) \quad \text{(c11)}$$

The equations (c12) and (c13) can be solved iteratively to determine $X_{secondary}$ and θ_{Vsec}.

$$\theta_{Vsec} = asin\left(\frac{\sqrt{3}}{V_{sec}}\left(R_{secondary}I_{fld}sin(\phi_{Ifld}) + X_{secondary}I_{fld}cos(\phi_{Ifld})\right)\right) \quad \text{(c12)}$$

$$X_{secondary} = \frac{\sqrt{3}R_{secondary}I_{fld}cos(\phi_{Ifld}) - V_{sec}cos(\theta_{Vsec}) + V_{fld}}{\sqrt{3}I_{fld}sin(\phi_{Ifld})} \quad \text{(c13)}$$

If ϕ_{Ifld} is zero (power factor = 1.0), then the above equations will not work. Instead use equations (c14) and (c15) if the Rated Power Factor = 1.0 (or very, very close to 1.0)

$$\theta_{Vsec} = acos\left(\frac{\sqrt{3}(R_{secondary}I_{fld}) + V_{fld}}{V_{sec}}\right) \quad \text{(c14)}$$

$$X_{secondary} = \frac{V_{sec}sin(\theta_{Vsec})}{\sqrt{3}I_{fld}} \quad \text{(c15)}$$

The reactance $X_{secondary}$ is calculated at the **Rated Frequency**. The reactance should be corrected for the actual Frequency at the primary port:

$$X_{Secondary} = X_{secondary} \times \frac{Frequency}{Rated\ Frequency} \quad \text{(c16)}$$

The **Winding Configuration** impacts the shift in phase between primary and secondary voltages and currents. The following corrections $\theta_{winding}$ are made to the primary voltage and current angles:

Wye-wye 0

Wye-delta	$\frac{\pi}{6}$ rad
Delta-wye	$-\frac{\pi}{6}$ rad
Delta-delta	0

The constitutive equations for Figure 16 are given by:

$$V_{Rprimary} + jV_{Iprimary} = V_{primary}\angle\theta_{primary} \quad (c17)$$

$$I_{Rprimary} + jI_{Iprimary} = I_{primary}\angle\phi_{primary} \quad (c18)$$

$$V_{Rxformer} + jV_{Ixformer} = V_{xformer}\angle\theta_{xformer} \quad (c19)$$

$$V_{Rsecondary} + jV_{Isecondary} = V_{secondary}\angle\theta_{secondary} \quad (c20)$$

$$I_{Rsecondary} + jI_{Isecondary} = I_{secondary}\angle\phi_{secondary} \quad (c21)$$

$$\theta_{primary} = \theta_{xformer} + \theta_{winding} \quad (c22)$$

$$V_{primary} = nV_{xformer} \quad (c23)$$

$$P_{primary} = P_{xformer} + P_{noload} \quad (c24)$$

$$Q_{primary} = Q_{xformer} \quad (c25)$$

$$P_{primary} + jQ_{primary} = \sqrt{3}V_{primary}I_{primary}\angle(\theta_{primary} - \phi_{primary}) \quad (c26)$$

$$P_{secondary} + jQ_{secondary} = \sqrt{3}V_{secondary}I_{secondary}\angle(\theta_{secondary} - \phi_{secondary}) \quad (c27)$$

$$P_{xformer} + jQ_{xformer} = \sqrt{3}V_{xformer}I_{secondary}\angle(\theta_{xformer} - \phi_{secondary} + \pi) \quad (c28)$$

$$V_{Rsecondary} + jV_{Isecondary} - V_{Rxformer} - jV_{Ixformer} = \sqrt{3}(R_{secondary} + jX_{Secondary})(I_{Rsecondary} + jI_{Isecondary}) \quad (c29)$$

The property **Full Load Power** is given by equation (c32)

$$\theta_T = asin\left(\frac{\sqrt{3}\times Rated\ Secondary\ Current \times X_{Secondary}}{Secondary\ Rated\ Voltage}\right) \quad (c30)$$

$$V_S = Secondary\ Rated\ Voltage\ \times cos(\theta_T) - \sqrt{3} \times Rated\ Secondary\ Current \times R_{Secondary} \quad (c31)$$

$$\boldsymbol{Full\ Load\ Power} = \sqrt{3} \times Rated\ Secondary\ Current \times V_S \quad (c32)$$