Shipboard power system limiting load flow and load flow analysis

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***Abstract*—Load flow analysis is conducted for shipboard power systems to determine the required current rating for cables and switchboards. Because shipboard power systems differ from terrestrial systems, the processes used to conduct load flow analysis also differ. This paper describes how to use limiting load flow analysis for sizing cables and switch boards during the earliest stages of design, as well as load flow analysis to refine the sizing requirements in later stages of design.**

***Index Terms*—load flow analysis, marine vehicles, power distribution, power system analysis.**

I. Introduction

Load flow analysis determines the voltage, power, and current at each node of a power system network for a given operational condition and environmental condition. Load flow analysis is a steady-state analysis and for three-phase systems, generally assumes balanced operation. In balanced operation, the magnitudes of the voltages of each phase are assumed equal and the magnitudes of the currents of each phase are assumed equal. The phase angles of the three phases are assumed to be 120° apart.

In terrestrial power systems, load flow analysis is used to

- Check for the potential to overload transmission lines or other distribution equipment.
- Ensure voltages remain within allowable limits.
- Estimate energy losses within the distribution system and explore ways to minimize them; determine the economical way to generate and distribute electrical power.
- Evaluate resilience of the system due to losses of one or more transmission line or other distribution equipment.

In the design of shipboard power systems, load flow analysis is usually conducted to determine the potential for overloading cables and other distribution equipment in both normal operation and contingency operation. Load flow analysis can also support voltage drop calculations; Voltage drop calculations are used to ensure voltages remain within allowable limits under a variety of system configurations and operational conditions. In shipboard systems, load flow analysis has not been routinely used to determine methods of reducing distribution system losses.

Ship design is traditionally conducted in a series of stages that each add additional levels of detail. The earliest stages of design comprise concept design, followed by preliminary and contract design, and concluding with detail design. Ship construction follows detail design. Contract design may in some documents be called baseline design and detail design may be called product design. [1] [2] [3] The choice of level of limiting load flow analysis or load flow analysis depends on the level of detail of the ship design that is available during a particular stage of design.

Limiting load flow analysis does not calculate the load flow directly, but instead calculates current and power bounds for the load flow analysis. [4] [5] Limiting load flow analysis is useful in concept design when the details necessary to conduct a rigorous load flow analysis are not available. Many times, the more rigorous load flow analysis conducted in later stages of design enable reducing the required rating of the cables or distribution equipment.

This paper focuses on how to use limiting load flow and load flow analysis to determine the required current / power rating of shipboard power system cables and distribution equipment to avoid overloading across various operational conditions. Load flow analysis to support voltage drop calculations will be addressed in a future paper.

II. Differences Between Terrestrial and Shipboard Power Systems.

Terrestrial and shipboard power systems differ in significant ways; these differences impact the manner in which the load flow should be conducted. Differences include: [6]

- Larger frequency deviations.
- Lack of time-scale separation.
- Load sharing instead of power scheduling.
- Short electrical distances.
- Significant load dynamics.
- Greater centralized control.

- Ungrounded or high-impedance grounded systems.
- Differing physical environment.

Of these differences, the factors that impact load flow analysis the most are

- Load sharing instead of power scheduling. Commercial systems usually assign real power levels and voltage magnitude to most online generators; the mismatch between generation and total load is handled by a generator acting as a swing generator (sometimes called a slack bus). Onboard ship, real and reactive power is generally shared among paralleled generator sets.
- Short electrical distances. The lengths of cables onboard ship are typically less than 350m which is orders of magnitude less than the lengths of cables in terrestrial power systems. Cable impedance cannot be used to limit reactive power flow in shipboard systems.
- Greater centralized control. The limited size of shipboard power systems enables centralized control; centralized control is generally not feasible in terrestrial power systems.

III. Limiting Load Flow During Concept Design

In the earliest stages of design, limiting load flow analysis may be used to determine an upper bound for the required ampacity of main distribution cabling and switchboards. Cables and switchboards should be able to safely carry the maximum current experienced during their service life. Determining this maximum current is a goal of both limiting load flow analysis and load flow analysis.

The maximum current through a cable or switchboard depends on which power generation sources are online, the configuration of the network, and which loads are online. These are all dependent on the operational condition and the ambient condition (Temperature and humidity). For a given operational condition, the Electrical Power System Concept of Operations (EPS-CONOPS) identifies which configurations of power generation sources apply and which network configurations apply [3]. Other distributed system concepts of operation (such as propulsion) detail allowable configurations of those systems. As one adds in emergency conditions, the number of permutations of online generation, switchboard configuration, and load configurations becomes extremely large (potentially in the hundreds or thousands) for each operational condition – ambient condition combination. Identifying the worst case becomes challenging.

Limiting load flow analysis determines an upper bound for the maximum current through a cable or switchboard without performing a detailed accounting of all the source and load configurations. Limiting load flow analysis is appropriate in concept design because much of the data necessary to conduct a load flow analysis will not have been developed yet. There are three levels of limiting load flow analysis: most conservative, less conservative, and least conservative.

The simplest limiting load flow estimate for the maximum current through cables and switchboards is the sum of the rated currents of all sources. While this is the most conservative estimate, in the earliest stages of design when loads have only been estimated at the total ship level, this approach may be sufficient.

A less conservative upper limit for cables is to consider the topology of the power system. For cables, some sources may be only able to supply current to one end of the cable across all power system configurations. For each end of the cable, the sum of the rated currents for all sources that can connect to that end are summed. The larger of the two sums is used as the less conservative limiting load flow.

For switchboards, the less conservative limiting load flow is the sum of the sources that could topologically connect to it. Usually, but not always, this is the same as the rated currents of all sources.

Once loads have been estimated and assigned to switchboards or load centers (possibly via automatic bus transfers) as part of an Electric Plant Load Analysis (EPLA) [7] [8], then the least conservative limiting load flow approach may be used. This method recognizes that for each direction of current flow through a cable, the maximum current will be either limited by source capacity or the load. The maximum operating load across all operating conditions on one end of the cable is compared to the sum of rated current from all sources on the other end; the smaller of the two is the current limit for that direction. Loads that could be present on either end of the cable should be incorporated in load summations on both ends. The limiting load flow is the larger of the current limits in either direction. When calculating the maximum operating load, margin and service life allowance should be included.

In cases where the cable is part of a multi-path network topology, such as a ring bus, where one end of the cable is topologically connected to the other end, then a refinement of the process should be used. The limiting load flow should be calculated multiple times for a cable; where in each case, one (or possibly more) of the other cables in the path between the two ends are removed such that the two ends of the cable are no longer topologically connected. The highest limiting load flow for all of the cases should be used.

For switchboards, the least conservative limiting load flow compares the sum of the maximum load currents to the sum of the source currents and uses the smaller of the two. Because the layout of the switchboard is not typically known, the method assumes all of the sources are on one end of the switchboard bus bars and all the loads are on the other end of the bus bars. For bidirectional connections such as bus-ties or energy storage, the calculations are performed for both the case where the connection only considers load currents, and the case where the connection only considers sources. The largest limiting load flow for all the cases is then used to determine the required rating of the switchboard.

IV. Load Flow During Preliminary and Contract Design

Once the EPS-CONOPS and the concepts of operation of other distributed systems are developed during preliminary design, a load flow analysis can be conducted. For a load flow analysis, a generator set scheduling table as well as a propulsion motor scheduling table (if the ship employs an integrated power system) should be incorporated in the EPS-CONOPS and Propulsion CONOPS. [9] Scheduling tables for other systems should be developed if multiple configurations of large loads are possible. Additionally, the EPS-CONOPS should provide guidance for the configuration of the shipboard power system for each operational condition.

If a power system configuration incorporates multiple paths between sources and loads, then the details of the cables comprising the bus-ties are required in order to estimate their resistance and reactance; the cable impedance determines how much power flows along each path. Alternately, if cable data is not available, methods to approximate these systems with purely radial systems may be employed as described in [10] or with using the method of breaking the redundant paths as described in the previous section for the limiting load flow method.

The worst-case load flow through a cable or switchboard may not occur when the total ship electric load is a maximum. The maximum load flow typically occurs in cases where there is large amounts of asymmetry of loads and sources. For ships with electric propulsion, the propulsion power can often be adjusted to maximize asymmetry within the constraints of the Propulsion CONOPS.

Picking the operational conditions, propulsion motor loading, and generator set configuration that yields the largest load flow for a given cable or switchboard can either be done manually based on applying logic, or can be comprehensively explored using automated tools.

For configurations without multiple paths between sources and loads, simple spreadsheets or similar tools may prove adequate. Voltage drops are usually assumed to be negligible; the voltage at every point in the system is assumed to be near the nominal system voltage.

For configurations featuring multiple paths between sources and loads, voltages and cable impedances determine how much power and current flow through each path; the use of steady-state modeling tools such as S3D may be desirable. [9] [11] Cable inductances and resistances should be estimated based on estimated cable lengths and cable resistances and inductances per unit length. Cable resistances and inductances may be estimated from data provided in [12] [13] [14]. The sensitivity of the results to cable data, such as cable length, should be evaluated to reflect design and construction tolerances.

V. Load Flow During Detail Design

During detail design, a load flow analysis should be conducted as was previously done in preliminary and contract design, except that in cases of multiple paths between sources and loads, methods that approximate the system with radial systems should not be used. This requires knowing resistance and inductance characteristics of the cable comprising the multiple paths. During detail design, the EPLA is expected to mature, better knowledge of cable selection, routing, and lengths should support better estimates of resistances and inductances, and refinements in CONOPS should be reflected in updated generator and propulsion motor scheduling tables. Additionally, non-traditional lineups used in casualty conditions should be explored.

Once switchboard specifications have been developed and procurements initiated, load flow analysis may identify situations where the switchboard bus bars may be overloaded. In these cases, load flow analysis may be employed to identify operational restrictions to avoid overloading. If these restrictions are too onerous and not acceptable to the customer, the switchboard design should be altered to accommodate the increased current requirements.

VI. Limiting Load Flow Example

To illustrate the limiting load flow process, Figure 1 will be used to estimate the upper bound for the maximum current through Bus Tie BT-12 and in Medium Voltage Alternating Current (MVAC) switchboards M1 and M2. This analysis is based on the parameters depicted in Tables I-II. For Table II, loads that could be present on either the L1 or L2 connection, but not both, are indicated with '+'. An example of this type of load would be conditions where 2 of 5 fire pumps are online, but the specific fire pumps that are online can be arbitrary. Another example would be a vital load that normally is connected to one switchboard, but could connect to the other switchboard via a bus transfer device. This example is for illustrative purposes only; the values depicted are notional and any correlation of the values to those of real ships is purely accidental.

In the earliest stages of design before the data in Table II is known and the exact topology has not been determined, but the total generation has been estimated as depicted in Table I, the maximum current I_{max1} for BT-12, M1, and M2 can be bounded by the maximum rated current of all the generator sets (DG1, DG2, DG3, and DG4) as shown in (1).

$$I_{max1} = \frac{4 \times 10\ MW}{\sqrt{3} \times 6.6\ kV} = 3.5\ kA \tag{1}$$

The less conservative approach considers the topology. Because the loads on each switchboard sum to over 20 MW and the generator ratings for each switchboard sum to only 20 MW, the limiting load flow I_{max2bt} for the bus tie is 20 MW. No more than 20 MW can possibly flow through the bus tie. The limiting load flow is given by (2).

$$I_{max2bt} = \frac{2 \times 10\ MW}{\sqrt{3} \times 6.6\ kV} = 1.75\ kA \tag{2}$$

The less conservative approach for the switchboards M1 and M2 yields the same result as the simplest approach (1) since all four sources can topologically connect to the switchboards.

The least conservative approach to calculating the limiting load flow for bus-tie BT12 is shown in

Table III. For the Low Voltage Alternating Current (LVAC) loads, one accounts for loads that could connect to either switchboard by including them in the load sums on both ends of the cable. The maximum operational load on each end of the cable could correspond to different operational conditions. Also, the maximum propulsion load is assumed to be zero for the inport operational conditions. This approach again results in a limiting load flow of 20 MW which corresponds to 1.75 kA.

The least conservative approach is depicted in Table IV for switchboard M1 and Table V for switchboard M2. For switchboard MI, the limiting load flow is 20.4 MW which corresponds to 1.78 kA. For switchboard M2, the limiting load flow is 20MW which corresponds to 1.75 kA.

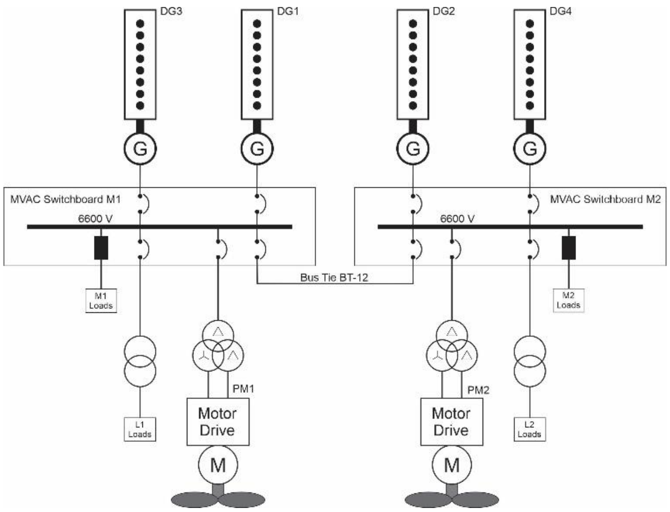

Figure 1. Example ship power system

TABLE I: EQUIPMENT POWER RATING

Equipment	Power Rating (MW)
DG1, DG2, DG3, and DG4	10
PM1 and PM2	15

TABLE II: LOAD POWER RATINGS

Operational Condition	**M1 Loads (MW)**	**M2 Loads (MW)**	**L1 Loads (MW)**	**L2 Loads (MW)**
Inport Summer	2.0	2.3	1.8 + 0.3	1.6 + 0.3
Inport Winter	1.9	2.3	2.5+ 0.3	2.8 + 0.3
Cruise Summer	1.1	1.1	2.1 + 0.2	1.9 + 0.2
Cruise Winter	1.0	1.1	3.5 + 0.2	3.3 + 0.2
Functional Summer	1.5	1.2	2.1 + 0.4	1.9 + 0.4
Functional Winter	1.5	1.0	3.5 + 0.4	3.0 + 0.4

TABLE III: LIMITEING LOAD FLOW BUS TIE BT-12 CALCULATIONS

	M1 to M2 (MW)	M2 to M1 (MW)
Sources	10 + 10 = 20	10 + 10 = 20
Propulsion	15	15
Worst Case Loads Operational Condition	Cruise Winter	Functional Winter
MVAC Loads	1.1	1.5
LVAC Loads	3.3 + 0.2 =3.5	3.5 + 0.4 = 3.9
Total Loads	15 + 1.1 + 3.5 = 19.6	15 + 1.5 + 3.9 = 20.4
Smaller of Sources and Total Loads	19.6	20
Limiting Load Flow		20

TABLE IV: LIMITING LOAD FLOW SWITCHBOARD M1 CALCULATIONS

	BT-12 Load (MW)	BT-12 Source (MW)
Sources	10 × 2 = 20	10 × 2 + 10 × 2 = 40
Propulsion	15	15
Worst Case Loads Operational Condition	Functional Winter	Functional Winter
MVAC Loads	1.5 + 1.0 = 2.5	1.5
LVAC Loads	3.5 + 3.0 + 0.4 = 6.9	3.5 + 0.4 = 3.9
Total Loads	15 + 2.5 + 6.9 = 24.4	15 + 1.5 + 3.9 = 20.4
Smaller of Sources and Total Loads	20	20.4
Limiting Load Flow		20.4

TABLE V: LIMITING LOAD FLOW SWITCHBOARD M2 CALCULATIONS

	BT-12 Load (MW)	BT-12 Source (MW)
Sources	10 × 2 = 20	10 × 2 + 10 × 2 = 40
Propulsion	15	15
Worst Case Loads Operational Condition	Functional Winter	Functional Winter
MVAC Loads	1.5 + 1.0 = 2.5	1.0
LVAC Loads	3.5 + 3.0 + 0.4 = 6.9	3.0 + 0.4 = 3.4
Total Loads	15 + 2.5 + 6.9 = 24.4	15 + 1.0 + 3.4 = 19.4
Smaller of Sources and Total Loads	20	19.4
Limiting Load Flow		20.0

VII. LOAD FLOW EXAMPLE

Since Figure 1 does not include multiple paths between sources and loads, only the addition of generator and propulsion scheduling tables are needed to conduct a load flow analysis. For this example, the EPS-CONOPS is assumed to require bus-tie BT-12 be closed under normal operational conditions; generators are normally paralleled. Additionally, the EPS-CONOPS is assumed to require at least two generator sets be online at any one time to enhance Quality of Service. Table VI lists the unique configurations possible for this system; note that for configurations where only one generator set is connected to the switchboard, DG1 and DG3 are interchangeable as are DG2 and DG4. The EPS-CONOPS is assumed to require paralleled generators share power equally.

The propulsion CONOPS is assumed to set propulsion power to 0 for the inport conditions. For the cruise conditions, the propulsion CONOPS is assumed to require the propulsion power on each shaft be equal. For the functional conditions, the propulsion CONOPS is assumed to account for the ship maneuvering; the propulsion power on each shaft may be any value up to its rated value such that the total load power does not violate the upper bound of the generator scheduling table.

The maximum load flow through BT-12 occurs when there is a maximum difference between the source power on one switchboard and the load power on the other switchboard. For this reason, configuration 2A is not likely to result in the maximum load flow.

For the inport conditions, the maximum flow through BT-12 can logically (based on asymmetry) be determined to occur in either configuration 2B or 2C for the inport winter condition. For configuration 2B, the load flow through BT-12 for inport winter is 5.4 MW. For configuration 2C, the load flow through BT-12 for inport winter is 4.7 MW.

Tables VII-X depict the calculations for determining the BT-12, M1 Switchboard and M2 Switchboard worst case load flows for the cruise and functional conditions. For the functional conditions, multiple cases are shown to vary the total amount of propulsion power and in the case of configuration 4A, to which switchboard the switchable loads are connected.

The results of the load flow analysis show that for the functional summer condition, the bus-tie BT-12 requires a rating of 16 MW or 1.4 kA. The maximum load flow for the switchboards occurs for the functional winter condition; switchboard M1 requires 20.4 MW or 1.8 kA and switchboard M2 requires 19.7 MW or 1.7 kA. During detail design when the connections to the switchboard bus bars are designed, it may be possible to select connection points for each circuit breaker such that a lower amperage bus bar is sufficient.

The 16 MW calculated as the maximum load flow for BT-12 compares to the 20.4 MW calculated using the limiting load flow method. As expected, the limiting load flow method is more conservative, but reasonably close. For switchboard M1, the limiting load flow method and the load flow method both resulted in the same value: 20.4 MW. For switchboard M2, the load flow calculations resulted in a requirement for 19.7 MW as compared to the limiting load flow calculations of 20 MW.

TABLE VI: GENERATOR SCHEDULING TABLE

Config	Power Range (MW)	DG3	DG1	DG2	DG4
2A	0 – 19	Off	Share	Share	Off
2B	0 – 19	Share	Share	Off	Off
2C	0 – 19	Off	Off	Share	Share
3A	19 – 28.5	Off	Share	Share	Share
3B	19 – 28.5	Share	Share	Share	Off
4A	28.5 – 40	Share	Share	Share	Share

TABLE VII: LOAD FLOW CALCULATIONS – CRUISE SUMMER

	Configuration (MW)				
	2B	2C	3A	3B	4A
M1 LVAC Load	2.1	2.3	2.3	2.1	2.3
M1 MVAC Load	1.1	1.1	1.1	1.1	1.1
M1 Motor Load	6.3	6.3	11.05	11.05	15
M1 Total Load	9.5	9.6	14.45	14.25	18.4
M1 Source	19	0	9.5	19	18.2
M2 LVAC Load	2.1	1.9	1.9	2.1	1.9
M2 MVAC Load	1.1	1.1	1.1	1.1	1.1
M2 Motor Load	6.3	6.3	11.05	11.05	15
M2 Total Load	9.5	9.4	14.05	14.25	18
M2 Source	0	19	19	9.5	18.2
BT-12 Load Flow	9.5	**9.6**	4.95	4.75	0.2
Switchboard M1 Load Flow	**19**	9.6	14.45	**19**	18.4
Switchboard M2 Load Flow	9.5	**19**	**19**	14.25	18.2

TABLE VIII: LOAD FLOW CALCULATIONS – CRUISE WINTER

	Configuration (MW)				
	2B	2C	3A	3B	4A
M1 LVAC Load	3.5	3.7	3.7	3.5	3.7
M1 MVAC Load	1.0	1.0	1.0	1.0	1.0
M1 Motor Load	4.95	4.95	9.7	9.7	15
M1 Total Load	9.45	9.65	14.4	14.2	19.7
M1 Source	19	0	9.5	19	19.55
M2 LVAC Load	3.5	3.3	3.3	3.5	3.3
M2 MVAC Load	1.1	1.1	1.1	1.1	1.1
M2 Motor Load	4.95	4.95	9.7	9.7	15
M2 Total Load	9.55	9.35	14.1	14.3	19.4
M2 Source	0	19	19	9.5	19.55
BT-12 Load Flow	9.55	**9.65**	4.9	4.8	0.15
Switchboard M1 Load Flow	19	9.65	14.4	19	**19.7**
Switchboard M2 Load Flow	9.55	19	19	14.3	**19.55**

TABLE IX: LOAD FLOW CALCULATIONS – FUNCTIONAL SUMMER

	Configuration (MW)				
	2B	2C	3A	3B	4A
M1 LVAC Load	2.1	2.5	2.5	2.1	2.5 2.5 2.1
M1 MVAC Load	1.5	1.5	1.5	1.5	1.5
M1 Motor Load	0	12	15	0 6.5	15
M1 Total Load	3.6	16	19	3.6 10.1	19 19 18.6
M1 Source	19	0	7.33 9.5	14.67 19	11 18.5 18.5
M2 LVAC Load	2.3	1.9	1.9	2.3	1.9 1.9 2.3
M2 MVAC Load	1.1	1.1	1.1	1.1	1.1
M2 Motor Load	12	0	0 6.5	15	0 15 15
M2 Total Load	15.4	3	3 9.5	18.4	3 18 18.4
M2 Source	0	19	14.67 19.0	7.33 9.5	11 18.5 18.5
BT-12 Load Flow	15.4	**16**	11.67 9.5	11.07 8.9	8 0.5 0.1
Switchboard M1 Load Flow	**19**	16	**19** **19**	14.67 **19**	**19** **19** 18.6
Switchboard M2 Load Flow	15.4	**19**	14.67 **19**	18.4 18.4	11 18.5 18.5

TABLE X: LOAD FLOW CALCULATIONS – FUNCTIONAL WINTER

	Configuration (MW)				
	2B	2C	3A	3B	4A
M1 LVAC Load	3.5	3.9	3.9	3.5	3.9 3.9 3.5
M1 MVAC Load	1.5	1.5	1.5	1.5	1.5
M1 Motor Load	0	9.6	15	0 4.1	15
M1 Total Load	5.0	15	20.4	5.0 9.1	20.4 20.4 20
M1 Source	19	0	8.13 9.5	16.27 19	12.2 19.7 19.7
M2 LVAC Load	3.4	3.0	3.0	3.4	3.0 3.0 3.4
M2 MVAC Load	1	1	1	1	1
M2 Motor Load	9.6	0	0 4.1	15	0 15 15
M2 Total Load	14.0	4.0	4 8.1	19.4	4 19 19.4
M2 Source	0	19	16.27 19	8.13 9.5	12.2 19.7 19.7
BT-12 Load Flow	14	**15**	12.27 10.9	11.27 9.9	8.2 0.7 0.3
Switchboard M1 Load Flow	19	15	20.4	16.27 19	**20.4** **20.4** 20
Switchboard M2 Load Flow	14	19	16.27 19	19.4	12.2 **19.7** **19.7**

VIII. CONCLUSIONS

The limiting load flow method is computationally simple and able to develop bounding limits for the required current rating for bus-tie cables and switchboards. The limiting load flow method is appropriate for concept design. The worked example demonstrates the simplicity of the calculations.

As more information is known during preliminary and contract design, load flow methods are more appropriate and may result in lower required current ratings. As demonstrated in the examples, the complexity of the load flow calculations is much greater than for the limiting load flow method.

Power systems, such as ring buses, where there are multiple paths between sources and loads greatly increase the magnitude of calculations for load flow analysis. For load flow analysis, these systems require estimation of cable inductances and impedances and system modeling within a power flow modeling environment (such as S3D) to determine the fraction of power that flows in each path.

Power systems without multiple paths between source and loads, such as the example problem, may be solved with spreadsheets. However, as the number of operational conditions, switchboards, loads, and sources increase, the permutations of configurations that should be analyzed grows geometrically; these systems call for automated approaches to defining the permutations and conducting the analyses.

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