Risk Mitigation of Design Requirements Using a Probabilistic Analysis

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Abstract

The definition of requirements for complex systems requires a balance between system over-design and associated risk. A severely over-designed system poses minimal risk of failing to meet the user's operational requirements, however the over-designed system poses increased risk of high costs, usability and reliability due to system complexity, and many other issues. The method proposed in this paper creates a more accurate representation of a complex system in order to determine requirements, and quantifies the risk associated with the defined requirements. The sizing of naval power transformers in electrical distribution systems requires an updated approach to quantify the risk inherent in the system requirements definition process. The proposed methodology uses a systems engineering approach, performing a probabilistic (Monte Carlo) analysis of the electrical loads powered by each, individual transformer. Transformer size can then be determined based on the electrical requirements and the amount of risk the program manager is willing to assume.

1. Introduction

Risk mitigation is an important step in the design of new systems that is rarely quantified. Risk can be defined as the uncertainty of meeting a specific program goal or objective. The systems engineering process dictates using a risk management strategy to identify and mitigate potential risks. Risk analysis is an important tool that should be applied during the system's requirements definition stage to quantify the probability of occurrence and effects of the requirements to the system's technical performance measures. Risk analysis could be used to predict if the project will stay within budget, be delivered on time and be capable of performing its specified mission.

In software requirements engineering, the definition of risk is the potential the design requirements will not meet the user's technical performance, cost and usability objectives. Risk within the design requirements must be quantified early in the design process in order to evaluate potential consequences. Early quantification of the risk will allow engineers to evaluate alternatives by performing a cost benefit analysis or weighing the expected cost versus the encumbered risk.

In dealing with complex systems, the potential for risk increases drastically with increasing system complexity. Risk mitigation is crucial for program managers in order to conserve resources by avoiding potential pitfalls. Identification and quantification of potential project risks is key to risk mitigation. This paper will describe how a probabilistic analysis was used to quantify risk and redefine the system design requirements used to size naval power transformers.

2. Identification of Transformer Sizing Issue

2.1 Transformer Requirement Definition Process

Power transformers are used to raise and lower the voltage of alternating current as needed to transfer electrical power from one circuit to another. Transformers are an essential part of an electrical distribution system to ensure the correct voltage is distributed to fulfill the electrical needs of the system's electrical loads. However, transformers are capacity limited devices, although they are able to support a limited amount of overloading for short periods of time. The electrical demands cannot exceed the specific transformer's capacity or the electrical loads will not be fulfilled. It is necessary to determine the electrical requirements of the system's electrical loads and use this information to determine the required capacity of a transformer. It is not possible to determine the electrical requirements of a concept ship design through onboard data collection since a physical ship does not exist to

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collect the actual electrical loading data. The US Navy uses an analysis method based on an accumulation of electrical requirements of the individual loads, which will be described in this section.

The US Navy has used a radial electrical distribution system architecture design for nearly a hundred years. However, with continually increasing electrical loads, both from new mission applications and the evolution from steam, air, and hydraulic auxiliaries to electric auxiliaries, a new electrical architecture was needed to distribute power throughout the ship. The US Navy has chosen a zonal electrical distribution system architecture to meet these requirements in addition to providing increased reliability and survivability.

The zonal electrical architecture has several characteristics that are different from a radial electrical architecture. Only one of these characteristics will affect the sizing of the switchboard and its supplying transformer. Loads that support distributive systems, such as fire pumps, or air conditioning plants need to be reflected in the sizing of the transformer feeding the load. For example, previous sizing methods have averaged the fire pumps' electrical loads over all of the transformers. A distributed design must match the load with the transformer it is supplied by. The radial system doesn't have this concern, as its loads would be fed from a ship level distribution, instead of the zone basis. However, the empirical demand curves and deterministic processes that have worked on radial architectures, fail to address the uniqueness of high voltage zonal architectures using a limited number of large transformers.

The level of conservatism in the traditional guidance affects the definition of transformer capacity requirements in a radial electrical system. The US Navy General Specification for Ships Section 314 [1] requires capacities of not less than 100% of the potential connected load in addition to reserve capacity loading requirements. While a requirement of 100% capacity of potential connected load will ensure 100% confidence of meeting the demand, the transformer requirements derived from this method lead to maximum transformer cost and weight. Although this method ensures zero risk of the transformer not being able to support its actual loading requirements, the transformer requirements definition process needs to account for and quantify the risk associated with a specific sized transformer. Once the risk is quantified, a cost benefit analysis can be performed to decide if the additional cost and weight are justified for the additional capacity requirements.

New guidance for sizing load center switchboards and their transformers is being drafted in the American Bureau of Shipping - Naval Vessel Rules (NVR) [2]. The NVR represent the culmination of experience of the Navy and the American Shipbuilding Industry. This method accounts for the electrical power factor and energy conservation by using the true and apparent electrical power of each load. The true power required by the connected electrical loads is the power drawn by the electrical resistance of a system and is measured in kilowatts (kW). The apparent power value, measured in volt-amperes (kVA) is the voltage on an AC system multiplied by all current flowing in. The apparent power is the vector sum of the true power and reactive power, which is the power stored in and discharged from the electrical loads. Since the transformer must be able to generate and distribute the actual electrical need, it is necessary to determine the relationship between the true and apparent powers for each load. The power factor is this ratio and is measured in a percentage (kW/kVA x 100%). The NVR [2] uses the power factor to determine loading requirements in their new guidance.

Abbreviated for this paper, the NVR [2] states that the load center transformers are to be sized based on the connected load power requirements multiplied by a demand factor (percent time that the load is expected to be energized; varies with operational scenario), then multiplied by a non-fixed service life margin (varies by load type; allows for future system growth). The second option is to use the total connected load multiplied by the non-fixed service life margin, multiplied by a demand factor from MS-18299 [3]. Since this option is used when the individual electrical loading requirements are not known, an eighty percent power factor, or worst-case scenario is assumed when calculating the kVA value.

The second option of the NVR [2], as described above, is only to be used when specific electrical parameters of the individual loads is unknown, thus does not allow an accurate demand factor to be determined. The empirical data used to compile the power factor curves can be found in MS-18299 [3]. The empirical data is based on ships with steam propulsion along with steam auxiliary or diesel ships with auxiliary boilers to create steam for auxiliaries such as heating. Air conditioning and cooling were also lower on these ships owing to a lack of ship-wide air conditioning and fewer electronics systems than the Navy ships of today. The overall effect was an electrical plant with much lower electrical power demands. These differences, when combined with the magnitude of scalability that is required (loads today are much larger), makes it doubtful that MS-18299 [3] is any longer applicable.

2.2 Methodology

The current method of sizing US Navy power transformers lacks a way to quantify the risk associated with implementing the design requirements on a specific platform. A probabilistic, Monte Carlo approach was chosen for this analysis in order to more realistically depict the electrical loading as seen by each transformer. This approach allows the designer to determine the requirements for each transformer individually versus the current method, based on the radial architecture designs that averaged the total electrical load across each transformer.

The previous transformer sizing method involved establishing the electrical requirements of the individual electrical loads as defined by the Electrical Load Analysis (ELA). Next, all loads were summed and used to define electrical loading requirements for the total ship. Next, the total ship requirements were averaged and evenly distributed between the transformers. The ELA did not distinguish the different electrical loads connected at the transformer level. Instead, transformer requirements were allocated down from the total electrical load of the ship. This method is shown in Figure 1 below.

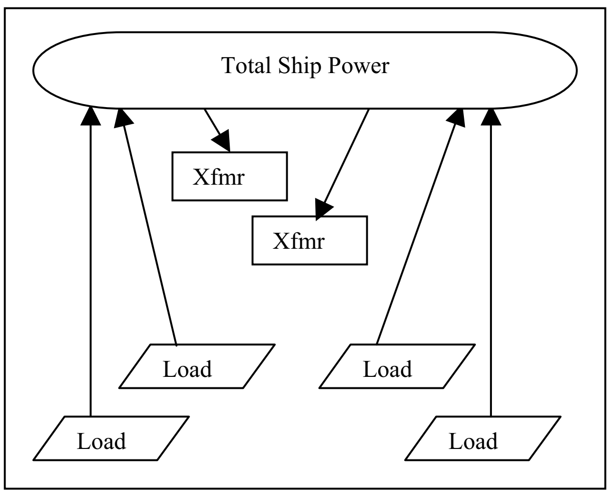

Figure 1: Traditional method of averaging total ship power across transformers.

As seen in Figure 2, the transformer sizing method using the Monte Carlo analysis also begins with the electrical requirements of the individual electrical loads as defined by the ELA. However, this data is allocated up to determine the probabilistic loading requirements of each transformer. Next, the total ship electrical requirements are determined using a sum of the electrical loading requirements for each transformer.

The new approach correlates each electrical load to the transformer that supplies its power. A Monte Carlo analysis is performed on the loads at the transformer level to determine a representation of expected loading requirements during each operating scenario. The calculated loading requirements at each transformer are summed to determine the loading requirements for the total ship. Although calculating the total ship electrical load requirements is important to size the power generation plants, the focus of this analysis was to determine the sizing requirements of the transformers.

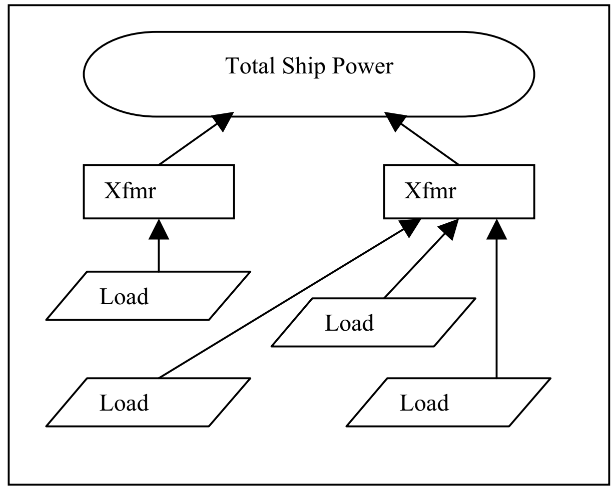

Figure 2: Proposed method of determining probabilistic load profiles at each transformer.

Performing a probabilistic analysis would allow the system designer to quantify the risk associated with the requirements definition. Risk, in this paper, is defined as the percentage of time during the mission in which the transformer is undersized, thus unable to support the actual electrical loading requirements due to the capacity limits of the prescribed transformer.

2.3 Definition of Monte Carlo Analysis

Probabilistic models are tools with which it is possible to model complex systems. These models are based on assigning a probability that a specific outcome will occur for many different scenarios occurring within the complex system. Each scenario could record the outcome of system, subsystem, components, etc. or a combination of the parts within the system. Probabilistic analysis can predict how interaction between the parts of the system based on their behavior during specified scenarios affects the system as a whole. Each scenario can be independent or dependent of the other scenarios, although the outcome for each individual scenario will cumulatively affect the total system. Monte Carlo is a sampling method for probabilistic models based on random occurrences.

The Monte Carlo method was named after the gambling city in the south of France since each game was based on chance. For example, when a standard die is thrown there is a 16.7% chance or probability the die will land on 1 during any particular roll. Since rolls or scenarios of the die are independent, a roll of 1 during the first roll does not affect the outcome of the second roll. The probability the second roll of the die will yield 1 is still 16.7%. Performing a Monte Carlo analysis on this example would involve rolling the die, recording the outcome and repeating the process. Computer based tools automate this process and allow for performing multiple iterations very quickly. Using computer-based tools also allows for rapid compilation of the data, which can be displayed in graphical form to easily distinguish results from the analysis. Graphs usually consist of bar charts containing the number of occurrences versus outcome, for example, the number of times the dice landed on 1 versus the outcome of 1. For the die example, the bar chart would have 6 outcomes and each outcome would have a specific number of occurrences, in this simple example, around 16.7% of the total number of iterations or occurrences. The accuracy of the simulation is based on the total number of iterations and can be calculated by the following formula:

$$N=(z_{(\alpha/2)}*(\sigma/e))^2$$

Where: N = Number of Iterations Required
α = 1 - Confidence Percentage
σ = Largest Standard Deviation of a Sample Run
e = Allowable Error in Outcome

2.4 Application of a Probabilistic Approach to Size Naval Power Transformers

To determine the representative electrical load profile at each transformer, a Monte Carlo analysis was performed on the individual electrical loads and their respective probability of occurrence. The loading and probability data was based off the ELA data for electrical loads and load factor, respectively. The current ELA is formatted to reflect the guidance of NAVSEA Design and Practice Criteria Manual Chapter 300 [4]. The guidance requires four operational missions be reviewed at two environmental conditions for a total of eight scenarios. The operational profiles are Anchor, Cruise, Mission, and Shore. The two different environmental conditions are at 10˚F and 90˚F air temperatures. The output of the ELA is the maximum operating load under the worst-case environmental conditions. The largest total ship electrical load of the eight scenarios is then used as a basis to size the electrical generation plant. Safety factors of design and service life margins are added to the calculated total shipload and this value is used to size the electrical generation plant.

The Monte Carlo analysis was performed on each transformer for each of the four operating missions in both summer (90° F) and winter (10° F) temperatures to ensure the transformer was sized to meet the operating profile with the highest electrical demand. To minimize design requirements risk, the US Navy sets the electrical system size requirements based on the worst case operating condition, even though the ship may never experience the extreme temperature scenario. Since the combination of energized equipment varied significantly between the transformers, it was crucial to allocate each equipment load to its primary feeding transformer and perform the analysis on the transformer level.

Industry methods have, in the past, used the transformer sizing criteria of 170% peak load in Winter or 130% of peak load in Summer, as noted in IEEE [5]. The definition of peak load in the commercial power industry is the load used to define the transformer sizing criteria. Determination of the industry peak loads in these examples had been through load profile data available by historic electrical demand data. The US Navy does not have historical load profile data, especially for the electric machinery recently converted from steam, air or hydraulic. However, IEEE [6] provides a method for average or mean load, like the ELA load values, to be used for estimating the peak load or value. IEEE [6] noted that the probabilistic transformer load profile for the power industry could assume a normal distribution. This would allow using a load determination method that accounted for the dynamic load condition that the ELA averages out.

The ELA contains the power requirement for each electrical load and a load factor, which typically can be used as the probability percentage that the load would be on and drawing power during a 24 hour time period. For example, a fire pump might have a load of 101 kW and a load factor of 0.9. Table 1 gives an example of data used from the ELA including: shipboard loads, their kW power requirements and their respective load factors.

Next, the ELA data was sorted per transformer and a Monte Carlo analysis was performed on each transformer data set. The Monte Carlo analysis used the ELA probability to determine if a specific load was on or off. For example, the fire pump from Table 1 would randomly be on in 90% of the simulations and off in 10% of the simulations. If the load was on-line, the power requirement for that load was added to the other "on-line" loads within the transformer data set. If the load was off-line, the power requirement for the load was zero and thus it was not added into the total power required for the transformer.

Performing the probabilistic analysis resulted in a bar graph histogram of the electrical load versus the number of occurrences. Advances in computational power allow probabilistic simulations to be performed

Table 1: Example of loads with associated power requirements and probability of the load being energized (on a 10^0 F day)

Electrical Load (Equipment)	Power Requirement (kW)	Probability of Occurrence (Load Factor)
AIR COND CHW PUMP	104.74	0
AIR COND PLANT	267.94	0
PWR BOX 1	0.89	0.1
PWR BOX 2	2.36	0.1
REFR UNIT COOLERS	8.40	0.15
FIRE PUMP	101.70	0.9

in a fraction of the time previously required, thus this analysis was performed to achieving a 99% confidence level that the overall load would be within 3 kW. This analysis was performed 2440 times per transformer and the total power requirement for each transformer was plotted versus the number of occurrences based on the 2440 runs performed.

2.5 Modifications to the Electrical Load Analysis

To use the ELA for transformer sizing, four minor modifications were applied to use the electrical loads in a probabilistic analysis. The first modification involved changing the load factors for air heaters from 0.9 to 1.0 on 10˚F scenarios. The second change was the addition of a power factor for each load. The third change was to ensure that intra-zonal system loads were correlated to reflect the systems and component interdependencies. Finally, the fourth change ensured inter-zonal distributive system loads were correlated.

The first modification was altering the load factor for electric air heaters to reflect 1.0 instead of 0.9. This modification is related to the industrial requirement in National Electric Code [7] where electrical air heaters are given a demand factor of 1.0. The ELA load factor requirements in NAVSEA Design Data Sheet 310 [8] only allow limited values from 0.0 to 0.9. So the ELA only reflects 90% of the connected heater load. However, a review by the Heating, Ventilation, and Air Conditioning (HVAC) Integrated Product Team (IPT) concluded that the heaters are sized appropriately 10% high and most heaters have solid-state controls. Since the heaters have the solid-state controls the actual connected load was decreased by 10%. Therefore, the use of solid-state heat controls and the change of probability should negate each other when summed.

The second modification is to estimate the power factor for each load scenario the transformer will realize. Originally, the conservative approach is to use an eighty percent power factor. However, as mentioned in NVR [2], since the loads are known, the actual power factor should be calculated. Currently, the NAVSEA Chapter 300 [4] does not require the power factor to be listed with each piece of equipment. This modification should take into account the hundred percent power factor that the electric air heaters use and bring the overall power factor up to around ninety percent. Power factors were assigned to each load as follows: 1.0 for resistive loads; 0.925 for electronic equipment in 400 SWBS; 0.9 for all other electronic equipment; 0.65 for lighting; 0.8 for motor loads; and 0.5 for welding equipment. This will decrease the required capacity of the transformers.

The third modification is to correlate loads together. NAVSEA Chapter 300 [4] provides guidance that lists individual pieces of equipment instead of systems. Therefore, application of a probabilistic analysis to an ELA may allow two of three generator auxiliaries to be running, but the third (equally important auxiliary) to be off. This does not reflect actual operating conditions. Moreover, the generator's keep-warm heaters would not be activated when the generator is running. These system loads need to be correlated together.

The fourth modification is correlating of zonal loads. As noted above, NAVSEA Chapter 300 [4] provides guidance that lists individual pieces of equipment instead of systems. The desired outcome is the worst case loading condition based on the load factors, environmental conditions and operational scenarios. This allows the distributed systems to have representative loads on, if the entire system is not required. For instance, normally only one chill water plant is required on a 10˚F Cruise scenario. The ELA doesn't care if the first or last chill water plant is reflecting this demand, as long as only one of the five plants is listed as active. This does not reflect actual operating conditions. For the sizing of the transformer within a zone, the chiller plant that is active could very well be the chiller plant in its zone. Therefore, the distributed system loads need to be correlated to allow each transformer to have the probability of powering the one chill water plant that the ship needs. This modification should increase the transformer loading in most zones, and decrease the loading in the zones that were representing the system.

3. Results

Implied, but not discussed earlier, is the risk that early design, transformer sizing requirements will not meet the actual, onboard ship requirements. The program manager must assume this risk until the ship actually experiences all the conditions for which it was designed. When defining the transformer requirements, the program manager faces a difficult decision and must balance minimizing transformer cost, weight, size, and at the same time minimize the risk that the transformer is under-sized. By choosing to select a conservative requirements definition approach to minimize the risk of an under-sized design (since this leads to power outages of critical equipment), the requirements dictate a larger capacity transformer, which equates to higher cost, weight, and size. Quantifying the risk inherent to the requirements definition analysis would allow the program manager to make a more informed decision as to how much over design should be allowed and still be cost effective. This is even truer when dealing with systems of fixed thresholds of capacities and costs. For example, Table 2 is a chart of capacity, weight, and volume of various capacity transformers. There are discrete thresholds associated with the capacities, which must be considered when deciding which transformers to use.

Table 2: Comparative transformer capacities and sizes

Capacity (MVA)	Maximum Weight (lbs)	Volume (ft^3)
3.75	22,000	517
5.0	31,000	660
7.5	40,000	765

If the transformers' electrical requirements were defined/sized too low they would run the risk of not providing enough power. If they are defined too high, it may force selection of the next higher capacity with associated cost, and size penalties. The Monte Carlo analysis allows you to quantify this risk since, using Figure 3 as example, if the transformer sizing requirements were made at 2000kW (the right end of the dark shading), the analysis shows, in that operating scenario, approximately 70% of the time the transformer capacity could not support the electrical load. This risk is shown in the bar chart by the light shaded area. Although the risk quantification method was used in this analysis to calculate the risk at a specific operating scenario, the same methodology can be used to calculate the risk inherent to the transformer requirements over a typical lifecycle of a US Naval ship. Future research could focus on quantifying this risk.

Considering the consequences, it has been assumed that a very low risk should be adopted. This strategy is reflected in the methodologies that both the US Navy and Industry used to employ. However, cost, size and time are driving Industry and the US Navy to size the transformers with more risk.

Reviewing the data from a ship level, we found that the operational conditions (mission scenarios) and temperature used to size the generator was not necessarily the highest load condition for the individual transformers. The results showed that while six of the eight transformers were loaded the highest in Cruise, two transformers had the highest load in Mission. This observation suggests that using the worst-case operating condition load output of the ELA, as a method for sizing transformers is not necessarily an accurate methodology in Concept and Preliminary Design. Instead, individual transformer loading in all operational conditions and temperatures should to be reviewed, and the highest load for each transformer used as the worst-case condition for sizing criteria.

The probabilistic analysis of the load profile is displayed in histogram format. Figures 3, 4, and 5 provide examples of the load profile from three transformers. These graphs provide us with two obvious observations. The first is the different shading of the histograms, and the second is the different shapes of the histogram.

The shading of the histograms provides two additional observations once the shading is defined. The shading is meant to differentiate between the load scenarios that would be accounted for by the ELA (left) and the higher value load scenarios that are not accounted for with the ELA (right). Two observations are now apparent, first the shading changes in different locations and second the amount of load scenarios that are accounted for by using the ELA.

The first observation is how the different shading levels of each figure reflect the different equipment loading and demand factor application to the loads for each transformer. Figure 3's transformer is located near the bow. Most of the loads connected to this transformer are transient in nature and earn load and demand factors of less then 0.3 on average. Figure 4's transformer is located in the Machinery Space. Most of the loads connected are not transient during the operational profile simulated and earn load and demand factors on average of greater than 0.8. Figure 5's transformer is also located in a Machinery Space, but it has a large number of hotel loads, such as HVAC heaters and galley loads. The result for Figure 5 is an ELA value that falls almost at the mean of the load distribution curve.

The second observation is the shape of each load distribution. The Monte Carlo analysis proved the electrical load of each transformer did not follow a normal distribution. Figure 5 has the most unique shape. As discussed above, the reason for this two hump distribution is the odd pairing of transient hotel loads and the near steady state load of propulsion equipment. Figure 3 has a more normal distribution curve, and Figure 4 has a more logonomial distribution curve. These two curves allow a higher degree of confidence in applying the standard deviation calculation to determine the peak loading of the transformer. However, while Figure 5's shape is not traditional, mathematically the standard deviation calculations can still be applied.

3.1 Comparison of Methods

The probabilistic analysis provides insight into the operation of the transformer. Using the ELA as a comparison, different load scenarios developed. When most of the loads connected to a transformer are transient in nature and earn load and demand factors of less then 0.3 on average, the ELA value is less than the mean of the load distribution curve. When most of the loads connected are not transient during the operational profile simulated and earn load and demand factors on average of greater than 0.8, the ELA is greater than the mean of the load distribution curve.

Finally, when a transformer has a large number of hotel loads, such as HVAC heaters and galley loads, the result is an ELA value that falls almost at the mean of the load distribution curve.

Comparing the probabilistic method to the old methodology, that averages connected load times Service Life Margin multiplied by the appropriate Demand Factors (typically 0.50), the comparison transformer would have been sized based on a probability value that accounts for only 50% of all normal load scenarios. Table 3 compares the various transformer sizing methodologies. Shown are the associated percent of load scenarios that are accounted for with each method, and the inherent risk that the equipment will be inadequately sized.

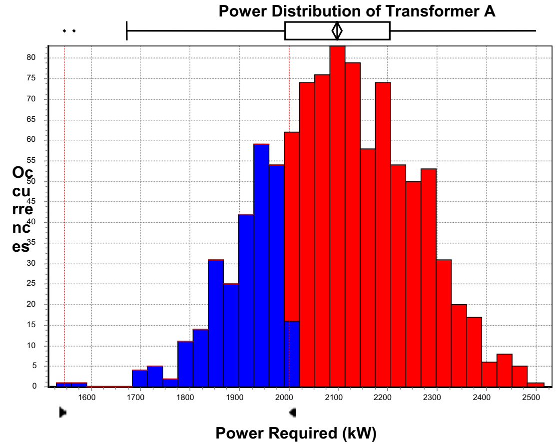

Figure 3: Fairly Normal Distribution of Loads

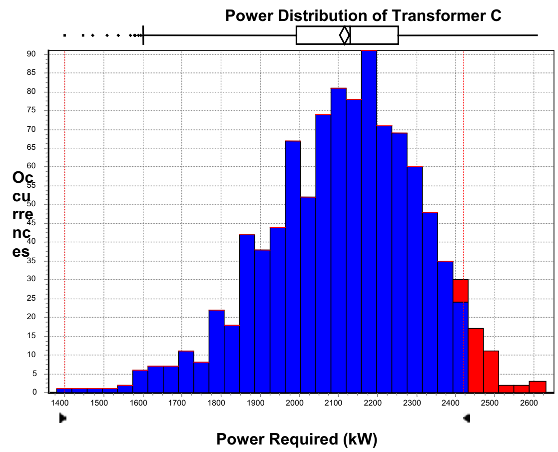

Figure 4: Skewed Distribution

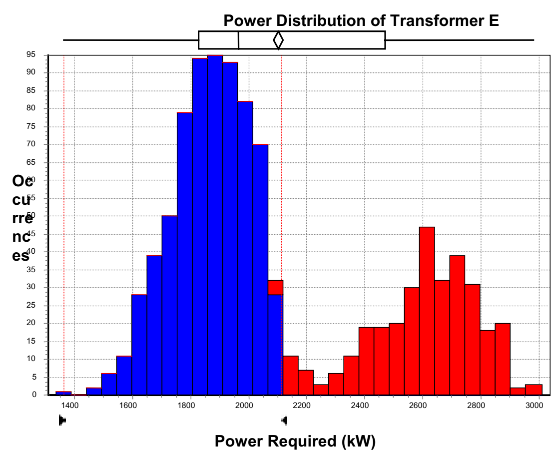

Figure 5: Irregular Distribution

Table 3: Comparison of Transformer Sizing Methods

Transformer Sizing Method	Load Scenarios Accounted For (%)	Inherit Risk of Under-design (%)
LHD 8 Load Balance	30	70
ABS NVR Method	50	50
LHD 8 ELA Probabilistic	**95**	**5**
Six-Sigma	99.9997	0.0003
Past Industrial Method	>100	0

4. Conclusions

Existing methods for determining primary transformer size requirements do not adequately address the new electric power distribution architectures that are being utilized in new construction US Navy ships. A new method including a probabilistic based analysis approach for determining electrical loading requirements for primary transformer sizing is proposed. Using a probabilistic approach will allow the program manager to incorporate risk mitigation during the design stages by giving a more accurate representation of potential shipboard load requirements. The results of this analysis demonstrate that using current US Navy methods for transformer sizing requirements on "mostly-electric" and "all-electric" ships using a zonal electric distribution architecture could result in significant risk that the transformers will experience overload conditions far exceeding what is considered acceptable in terms of total load and duration. This could result in compromised mission capability, increased ship vulnerability, and significantly reduced component life with associated unexpected replacement costs. Conversely, using standard industry methods for transformer sizing would require a very detailed load profile and would most likely result in transformers that were oversized, resulting in excessive weight, volume, and costs. The analysis results of this work showed that, even when taking the conservative approach represented by existing design criteria doctrine, significant risk of inadequate design exists for the new electrical system architectures. Modifications to the analysis setup can provide an even more representative depiction of actual shipboard equipment operating requirements. The proposed analysis method can further be expanded to include potential fault and failure modes, damage control modes, and survivability modes. Utilizing a probabilistic analysis could result in significant cost savings in the acquisition phases and total life cycle, but most importantly could yield a more robust and survivable system design since the potential for system failure has been quantified.

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