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Electrical Systems Analysis

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Electrical System Analysis

***What the various studies are and what answers you can expect from them*.**

Introduction

As the power requirements of DP vessels increase so does the need to provide redundancy in the electrical system design. More loads, more generators, and more redundancy mean more buses and, to predict the performance of the electrical system for all the possible configurations, more studies. The efforts required to evaluate the performance of the systems increase with their size and complexity. Among the specialized studies used to analyze electrical power systems those most frequently conducted for DP vessels fall into six broad categories:

Short Circuit Calculations,
Load Flow (Power Flow) Calculations,
Motor Starting Calculations,
Harmonics Analysis,
Transient/Dynamic (Stability) Analysis,
Coordination (Discrimination) Studies.

The results of each of these studies serve specific purposes in the planning, design, and operation of electrical power systems. All enhance the reliability of the vessel.

Relays and circuit breakers are tested and calibrated according to the coordination study. Spectrum analyzers measure the harmonics present in the power system. Power flows, voltage drops, continuous and starting currents can be measured and compared to the load flow and motor starting calculations, though for many configurations this will never actually be done. The transient performance of the system can be measured for many operating configurations to verify the calculation models, but again these tests seldom are done in a quantitative fashion. Short circuit tests are destructive, thus are not conducted in the field (at least, not on purpose).

While it is not exclusively a problem of the electrical discipline, that results of some the calculations will never be tested conclusively is reason enough for the calculations to be performed as accurately as possible.

Genesis of Electrical System Studies

Before there is an electrical system, there are mechanical loads. First the mechanical systems are defined, then the electrical loads are estimated from the individual mechanical loads. These mechanical and electrical loads are tabulated for various operating cases and totaled, providing an estimate of the overall power requirements.

Once the loads have been defined, they are grouped into “load centers” according to their physical location on the vessel. For a particular vessel classification, the requirements of the certifying agency essentially define the degree of redundancy in generation and in the supply to the load centers. Together with the load lists, these requirements form the basis of the power system design, and a rudimentary single-line diagram evolves to graphically describe the overall electrical system.

At this point in the design process, operating voltages must be selected for generation and utilization equipment. Along with the practical and economic factors, and preferences of the vessel owner or operator, equipment ratings are major considerations in the selection of voltage levels. Most non-interrupting electrical apparatus, such as transformers, motors, and generators carry a voltage rating and either a current or a power rating and are built specifically for the frequency at which they will operate. Voltage and current limitations apply to power cables, but these normally do not have frequency ratings. Devices that are used to open a circuit carry additional ratings. Starters, contactors, and some switches are rated to interrupt load current, but none are rated to interrupt faults. Circuit breakers and fuses, however, are designed to interrupt fault currents, and each carries an explicit rating which defines the current magnitude that it is capable of interrupting.

While compiling and maintaining accurate “load lists” and single line diagrams are very important throughout the development of the electrical system design, performing short circuit calculations is essential to the safe operation of the electrical system.

Short Circuit Calculations

What is a short circuit? A short circuit, or fault, is the *unconstrained* flow of electrical current. It is caused by the failure of electrical insulation or by accidentally damaging or coming into contact with electrical conductors. The extremely large currents flowing into a fault create immense amounts of heat and enormous mechanical forces, either of which can cause tremendous damage. Electrical equipment must be mechanically braced and interrupting devices must be adequately rated to safely withstand and isolate the high currents of faults; and to guarantee these results, a great deal of effort is spent on the calculations that provide the magnitudes of potential faults. During the commissioning and startup of equipment, a large part of the testing efforts are devoted to eliminating all possibilities of short circuits occurring.

Short circuit calculations are performed to determine the actual fault levels at every point in the system where an interrupting device is applied. The computed short circuit levels are compared with equipment ratings to ensure that every device in the system is applied within its fault interrupting rating.

What are the interrupting ratings? The answer depends on the standards employed. Most electrical equipment used on DP vessels is built either to ANSI/IEEE standards or to IEC standards. There are numerous differences between the design, testing, and installation requirements for the equipment built in accordance the two standards. Not only does the term “interrupting rating” have different meanings in the two different sets of standards, it also has different meanings for different voltage levels within the same set of standards. Consequently, the only way to have a valid short circuit magnitude for comparing to the equipment interrupting ratings, one must use the methods of the specific standard for the equipment being furnished.

What kinds of faults are there? Three-phase faults involve the most energy and are used to determine equipment interrupting ratings. There are phase-to-phase faults, two-phase-to-ground faults, and single-phase-to-ground faults. Single-phase-to-ground faults can occur only if the neutral of a wye connected transformer or generator provides a path for the ground fault current to flow.

What are the sources of fault current? Rotating machines: generators and motors that are directly connect to the ac system are sources of fault current. Motors connected via ac or dc drives are not considered fault current sources. What limits the fault current? System impedances: internal impedances of the sources plus the external impedances of power transformers and cables limit the fault current.

The first step in computing three-phase faults is to make an impedance diagram for all the elements in the electrical system, including all sources and system impedances. Next, an equivalent impedance is computed to represent the parallel combination of the internal impedances of generators and/or motors on a common bus. A point in the system is identified for placing a fault. Then the impedances of all the parallel between the sources and the fault are reduced to a single equivalent impedance. Finally, this single impedance is used to compute the short circuit magnitude of the three-phase fault.

The method just described for computing three-phase short circuit magnitudes is valid and correct. Unfortunately, this simple method does not account for the fact that the short circuit contributions of the sources are not constant, they decay in time from an initially high value. Fortunately, the method of computing the initial short circuit magnitude is an issue on which the many standards writing bodies around the world basically agree. Unfortunately, the rates at which the currents decay are not constant, nor are the rates the same for all sources; and the standards bodies do not agree on the analytical methods for approximating these facts.

The ANSI/IEEE methods modify the impedances of the sources before computing the "interrupting currents." IEC methods modify the individual current contributions to derive the effective "interrupting currents." Calculated by either method, the "interrupting currents" are conservative estimates for evaluating the interrupting duties of equipment built to the standards of the calculation method.

The short circuit calculations used for equipment ratings usually are not the only calculations required by the electrical system studies. For appraising equipment interrupting duties the number of on-line sources and system configurations are chosen to produce the "worst case" three-phase fault magnitudes. Even though the worst case circumstance may be physically possible to arrange, it frequently does not represent a realistic operating condition. The multiplying factors that ensure conservative calculations in the worst case may force unrealistic approximations in other cases. For example, short circuit calculations, usually without the multiplying factors, are used in coordination studies while examining the responses of protective devices when the system is lightly loaded and only one or two generators are on-line.

No matter how many conventional short circuit calculations are performed, the results do not show clearly how a particular fault varies with time or how the various currents from the contributing sources, decaying at their distinct rates, combine to form the total fault. While the conventional calculations may yield results satisfactory for most purposes, obtaining a representation of the fault currents as a function of time requires a "transient study."

Because most power systems on DP vessels are ungrounded, three-phase fault calculations are the only type necessary for system analysis. Single-phase-to-ground faults have no path for ground currents to flow, and the magnitudes of the other fault types typically are less than the three-phase values. Marine grounding practices are well beyond the scope of the present discussion, but it is important to note that as the size of the DP vessels increase so do the voltage levels, particularly for the main generation systems. At the higher voltage levels system grounding practices must be reconsidered. The practice of operating electrical systems ungrounded, which is suitable at voltages below 1000 V and marginally suitable at voltages to about 5000 V, should not be followed at higher voltage levels. These systems must be grounded in some fashion. High resistance grounding is the method most commonly employed. Magnitudes of ground fault currents must be determined for systems that are grounded in any fashion.

Load Flow Calculations

Load flow calculations are the analytical extensions of the "load lists." These calculations examine the power flow throughout the whole electrical system for both "normal" and "alternate" configurations. Voltage drops are computed from the generation bus to the load centers. Power flow through each cable and transformer is computed. The system losses are included with the loads to establish the generation levels necessary to keep the overall system in equilibrium.

System impedances are modeled the same as for the short circuit studies, but similarities between the calculations end there. Only rotating loads are used for the short circuit studies but all loads, heaters, lighting, hotel, propulsion, drilling, etc., are considered in the load flow calculations. For on-line motors, the real (kW) and reactive (kVAR) power levels at their operating loads are used instead of their impedances. Generators are represented in load flow calculations either as sources with fixed outputs or as “infinite” sources capable of supplying whatever power is necessary to maintain the voltage at the generation bus.

The results of these calculations may be used to schedule generators for various operating cases. Overloaded cables and transformers and excessive voltage drops are identified easily, advancing the formulation of remedial strategies.

Motor starting calculations, harmonics analysis, and transient analysis all begin with a load flow calculation, in one form or another.

Motor Starting Calculations

On DP vessels, motor starting calculations occasionally are performed for motors applied at the voltage levels of the emergency and auxiliary systems, but seldom are necessary for motors applied at the voltage level the main generation system. Motor starting studies are performed in cases where a motor is relatively large with respect to the available generation or where it is relatively large with respect to the kVA rating of a transformer. In both cases, the critical relative size occurs where the nominal motor hp is 20% or more of the nominal kVA of the source, either generator or transformer.

Three different types of studies are included in the category of “motor starting calculations.” Measured by the amount of additional data required to perform the studies, the simplest type of calculation is determining the initial voltage drops throughout the system at the instant a motor is started. This calculation is a minor variation of the load flow calculations. The only additional information required to perform this calculation is motor nameplate data. The next simplest type of calculation examines motor and system voltages during the interval of starting and accelerating a motor. Performing this type of study requires additional information about both the motor and load, and about the voltage regulators and exciters of the generators, if these are to be included. The third type of calculation is performed with “transient analysis” methods and requires extensive data, not only about the motor and load, but also about the generators, their prime movers and governors, and other large motors in the system. Results of this study show both the voltage and frequency profiles at selected locations in the system while the motor is being started and accelerated.

Harmonics Analysis

Electrical systems of DP vessels are rich in harmonics.

What are harmonics? These are the voltages and currents in the electrical system which have frequencies other than the rated frequency of either 50 Hz or 60 Hz . Harmonics are expressed as multiples of the fundamental frequency. For a 60 Hz system, the 5th harmonic is 300 Hz, the 7th is 420 Hz, ...

What causes harmonics? Switching the solid state devices in ac and dc drives are the main causes of harmonics. On DP vessels, the chief sources of harmonics are the thruster drives, ac or dc. Where drilling is involved, the predominantly dc drives of the drilling loads also are major contributors to the harmonic spectrum.

What harm do power system harmonics do? Harmonics distort the sinusoidal character of the ac waveform. They cause overvoltages on the power system. They increase the losses of the power system. Harmonics cause heating in motors, generators, and transformers which result in reduced capacity, loss of service life, and sometimes total failure of the equipment. They cause protective devices to fail and affect the performance of electronic equipment.

What are the limits for harmonics? Most standards, rules, and guidelines limit the total harmonic distortion of the voltage waveform to 10% on buses that serve only power conversion equipment and to 5% on buses serving conventional loads. Total harmonic distortion, THD, is the rms value of all harmonics present in the waveform expressed in percent of the fundamental frequency.

What can be done about harmonic problems? Filters can be designed to minimize the effects of the harmonics. These are arrangements of inductors, capacitors, and sometimes resistors that are tuned for the troublesome harmonics. The filters provide low impedance paths for the flow of the harmonic currents, diverting these currents from other equipment.

Harmonics analysis is a specialized type of load flow calculation. Models for the internal impedances of the generators are added to the network of system impedances. Drives are modeled as sources of harmonic currents. Revising system reactances for the different frequencies, load flow calculations are run for the frequencies of interest, beginning with the fundamental. The results of the load flow computations for all frequencies are combined into a family of outputs that define the harmonic spectrums of the voltages and/or currents at the points of interest.

Harmonics are not constant in the power system, they vary with the loading of individual drives, the configuration of the system, and the number of on-line generators. Harmonic analysis is used to quantify the harmonic voltages and currents on the system for various configurations and operating conditions and to evaluate the affects of filters on the system harmonics.

It is common practice to apply filters to the generation buses. Difficulties in determining the optimum sizes for the filters increase with the number of tie breakers used in the generation bus. Filters are sized and tuned for worst case harmonics conditions, but their affects on the system line also must be examined for light load conditions when few generators are on-line. In these cases, to prevent possible overvoltages due to the capacitors, the filters may have to be disconnected from the system.

Transient/Dynamic (Stability) Analysis

Depending on the facet of the system being examined, the analysis method is called by different names. The studies are called “transient” because they investigate abnormal incidences that occur for a short time interval. They are called “dynamic” because they investigate the balance between mechanical and electrical energy and the forces that act to keep the energy systems in equilibrium, or to drive them apart. They are called “stability” when the investigation is whether or not synchronous machines will remain in synchronism with one another.

By whichever name the study is called, it refers to the voltage and frequency responses with respect to time of system elements following a disturbance. The disturbance may be the incidence of a short circuit, clearing the fault, the sudden application of a load, the sudden loss of load or generator, opening a tie breaker, etc.

A substantial amount of data is necessary to adequately model the mechanical and electrical systems and sub-systems. But once the data is compiled and the model parameters determined, significant information about the performance of a system can be determined with the studies. The studies compute how the power, voltage, and frequency of major machines oscillate with respect to each other, through what extremes the oscillations travel, and the duration of the oscillations.

Transient studies are a series of load flow calculations performed sequentially. First, a steady-state solution is obtained for the conditions of the system prior to the disturbance. The disturbance will add or remove either mechanical or electrical power. When this change is incorporated into the model, the initial responses of the system parameters are calculated. The process is repeated, time is advanced by a small increment, then small changes in the mechanical and electrical systems also are computed, and a new solution is obtained for the power flow, until system equilibrium is reached (or until it goes unstable).

These studies are particularly useful for DP vessels to analyze the “what ifs” for likely configurations and operating conditions. Remedial decisions can be made in advance of a potential problem to avoid compromising the reliability of the electrical system. The calculations and decisions based on them can be used as inputs to power management systems.

Coordination (Discrimination) Studies

Of all the studies performed on electrical systems, coordination studies are the most subjective. The various standards bodies have requirements that define the extent of protection for major equipment, generators, motors, cables, and transformers. Although the degree of protection differs slightly among the standards, the intent of the various standards are similar enough that good engineering practices and common sense usually will satisfy the requirements.

A coordination study includes examining the settings for voltage, frequency and power relays, but the bulk of the coordination efforts are devoted to the settings of overcurrent devices. The objective of a coordination study is to specify settings for protective devices that (1) provide overload protection for the circuit to which it is applied and (2) ensure that faults are cleared as rapidly as possible by the nearest device upstream from the fault. Settings are determined for every overcurrent device in the system, beginning with the devices that serve the loads and stepping sequentially to the next upstream devices until the protective devices of the generators are reached. Time margins are specified between each step to give a downstream device time to open the circuit before an upstream device operates.

Protective devices are set to be selective at the maximum short circuit levels that each breaker must interrupt, that is when all generators and motors are on-line. These settings also must be examined for cases where the available short circuit currents are less than maximum.

Selectivity between overcurrent devices is demonstrated graphically. To show the coordination among a family of devices simultaneously, the time-current characteristic of each device in series is plotted on a common log-log graph. Then the settings of the protective devices are manipulated so that circuit protection is maximized, clearing times are minimized, and suitable time margins between characteristics are preserved. How these objectives are best satisfied is subjective, there may be no “best solution.” For some combinations of protective devices, where dissimilar characteristics of the curve family prevent achieving complete selectivity, or where complete selectivity would require excessively long clearing times, coordination compromises always favor personnel and equipment protection.

A situation for which obtaining selectivity is very difficult, and one that sometimes can not be avoided, is where a several devices in series are applied to circuits having nearly the same kVA ratings. Another situation where a breach of coordination can occur is for alternate system configurations where the desired settings for a protective device are in conflict with the settings required by the normal configuration.

Coordination and selectivity between overcurrent devices usually are possible in the normal configurations of a well designed system. Even the most difficult of the coordination problems can be avoided at the design stage by judicious choice of equipment ratings and/or protective devices.

Summary

Single line diagrams and load lists provided the baseline references for electrical system studies. These are the two most important documents (followed by cable schedules and equipment lists) for describing the configuration and the loads of an electrical system. They should be kept up to date and as accurate as possible.

Short circuit calculations are *essential* to safe operation of the electrical system. The results of these calculations are used to ensure that interrupting devices and equipment ratings are correct for their applications.

Load flow studies compute the operating voltages of all buses and the flow of real and reactive power throughout the system. They are used for determining generation requirements of various load conditions, for determining or verifying ratings of circuit components, and are particularly useful for analyzing alternate configurations.

Motor starting studies ensure the successful starting of large motors without causing excessively low voltages elsewhere in the system.

Harmonics analysis is used to evaluate the potential of a system to produce harmful voltage and current harmonics. These studies are used to design and locate filters that prevent equipment damage due to harmonics.

Transient analysis methods are used to examine system performance when the variations with time are required for power, voltage, and frequency parameters; and when the conventional short circuit, load flow, or motor starting calculations can not provide information in sufficient detail. These studies require the most data and, because of the many types of mechanical and electrical sub-systems involved, are the most difficult to model. But these studies provide the most information about the manner in which the system recovers from a disturbance.

Coordination studies are done to limit the time that equipment can be overloaded, to minimize the time required to isolate and remove a fault, and to minimize the portion of the system disrupted by removing an overcurrent condition. Although it is the most subjective of the electrical system studies, when done correctly the coordination study greatly enhances system safety and reliability.

Conclusion

From the conception of an electrical system through protective device settings, electrical system studies are necessary to ensure proper equipment ratings, personnel safety, and equipment protection. Each type of study contributes valuable information to improve the design, operation, and reliability of the electrical system. All the types may be needed to analyze a complex system thoroughly.