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Power System Analysis

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Power System Analysis

Lecture Notes

Chapter 1 –Introduction

Power system analysis software programs make possible the study of proposed and actual systems under many operating conditions. Answers to many questions regarding impact of expansion on the system, short circuit capacity, stability, load distribution, etc., can be intelligently and economically obtained.

The studies most likely needed are load flow studies, cable ampacity studies, short-circuit studies, coordination studies, and motor starting studies. The responsible engineer for system design must decide which studies are needed to ensure that the system will operate safely, economically, and efficiently over the expected life of the system.

A basic understanding of power engineering is essential to correctly interpret the results of computer calculations. It is important to emphasize that the need for a thorough foundation and base of experience in power system engineering in addition to modern, effective computer software. Power system analysis engineering software is an excellent tool for studying power systems, but it cannot be used as a substitute for knowledge and experience. The design engineer needs to be able to interpret and explain the results of computer calculations and be confident that the results correctly determine the electrical distributions system's characteristics and performance.

In dealing with power systems of any complexity, one of the first essentials is a single-line diagram, in which a single line represents each of the polyphase circuits. This diagram is a symbolic representation of the principal connections, showing the equipment in its correct electrical relationship and usually having indicated on it, or in supplementary tabulations, data essential to the determination of the impedance diagram. A typical single-line diagram for a large industrial power system is shown in Figure 1-1 page 4 of Chapter 1.

Chapter 2 –Applications of power system analysis

Studies, properly conceived and conducted, are a cost effective way to prevent surprises and to optimize equipment selection. In the conceptual phase and design phase for new electrical systems the studies identify and avoid potential deficiencies during system development. In existing systems, the studies help locate the cause of equipment failure and misoperation, and determine the corrective measures for improving system performance.

Load flow analysis:

Load flow studies determine the voltage, current, real, and reactive power and power factor in a power system. Load flow studies should begin as early as possible for new large industrial systems. These studies are an excellent tool for system planning. These studies should be used to confirm selected switchgear, transformer, and cable sizing. These studies should also be used to confirm adequate voltage profiles during different operating conditions, such as heavily loaded and lightly loaded system conditions. Load flow studies can be used to determine the optimum size and location of capacitors for power factor correction. The results of load flow studies are also starting points for other system studies.

Short-circuit analysis:

Short circuit studies are as necessary for any power system as other fundamental system studies such as load flow studies, motor starting studies, cable ampacity studies, etc. Short circuit studies can be performed at the planning stage in order to help finalize the system layout, determine voltage levels, and size cables, transformers, and conductors. For existing systems, fault studies are necessary in the cases of added generation, installation of extra rotating loads, system layout modifications, re-arrangement of protective equipment, verification of adequacy of existing breakers, re-location of already acquired switchgear in order to avoid unnecessary capital expenditures. “Post mortem” analysis can involve short circuit studies to determine the reason and the conditions that led to a system’s failure.

Stability analysis:

The ability of a power system, containing two or more synchronous machines, to continue to operate after a change occurs on the system is a measure of its stability. In industrial power system, stability may involve the power company system, and one or more in-plant synchronous machines. Several contingencies can impact system stability and need to be evaluated and or studied. Load shedding schemes and critical fault clearing times can be determine to select proper setting for protective relays. These types of studies are the single most complex studies done on a power system.

Motor starting analysis:

The ability of a power system to provide power to its largest electrical load is vital to the overall performance of the system. For typical industrial systems this load is an electric motor. By using motor starting study techniques, the best method of starting can be selected, the proper motor design can be determined, and the required power system design features can be determined.

Harmonic analysis:

A harmonic-producing load can affect other loads if significant voltage distortion is caused. Analysis is commonly done to predict distortion levels for addition of a new harmonic producing load or capacitor bank. Analysis is also commonly done to evaluate alternatives for correcting problems found by measurement.

Switching transient analysis:

Transients severe enough to cause problems in industrial power systems are most often associated with inadequate or malfunctioning breakers or switches and the switching of capacitor banks and other frequently switched loads. The arc furnace is most frequently studied because of its high frequency of switching and the related use of capacitor banks. These types of studies are performed to analyze other system anomalies, such as ferroresonance, transient recovery voltage, etc.

Reliability analysis:

When comparing various power system design alternatives there are two factors, (1) acceptable system performance quality factors (including reliability) and (2) cost are essential in selecting an optimum design. Using probability and statistics analyses, the reliability of a power system can be studied in depth. With these results, economics and reliability can be considered to select the optimum power system design.

Cable ampacity analysis:

Cable ampacity studies calculate the current-carrying capacity of power cables in underground or above ground installations.

Ground mat analysis:

The purpose of a ground mat study is to calculate the worse-case potential differences that can exist in an industrial facility during a severe fault and to insure that these values do not exceed the limits that can be tolerated by the human body.

Protective device coordination analysis:

The objective of a protection scheme in a power system is to minimize hazards to personnel and equipment while allowing the least disruption of power service. Short circuit calculations are a prerequisite for a coordination study. The results establish the minimum and maximum current levels for which coordination must be evaluated and which aid in setting or selective the devices for adequate protection. Typically the coordination study has been performed graphically by manually plotting time-current operating characteristics of various devices, along with conductor and transformer damage curves to illustrate the quality of protection and coordination possible. Computer programs that provide a graphical representation of the device coordination as it is developed are replacing the manual curves.

DC auxiliary power system analysis:

DC power is used for circuit breaker control, protective relaying, instrumentation, uninterruptible power systems, emergency lighting, communications, etc. The introduction of computer techniques to dc power systems analysis has allowed a more rapid and rigorous analysis of these systems compared to earlier manual techniques.

Chapter 3- Analytical procedures

The most common causes of errors in circuit analysis are the following:

a) Failure to use a valid analytical procedure because the analyst is unaware of its existence or applicability.
b) Careless or improper of "cookbook" methods that have neither a factual basis, nor support in the technical literature, nor a valid place in the electrical engineering discipline.
c) Improper use of a valid solution method due to application beyond limiting boundary restraints or in combination with an inaccurate simplifying assumption.

Many situations occur in industrial and commercial power systems that illustrate some or all of these common causes of error, as well as the resulting evils. For example, it is common that low voltage motor feeder cables be sized to limit the voltage drop to less than three per cent when the motor is operating continuously at rated conditions. Let's assume the voltage is 480 volts, three phase; and then the voltage drop is calculated by multiplying the rated motor current times the cable impedance of the motor feeder cable. To determine the percent voltage drop is it necessary to divide the voltage drop (in volts) by the system rated voltage of 480 volts? Or is it the rated line to neutral voltage of 277 volts? Or, should the motor rated voltage of 460 volts be used instead? Each of these issues can affect the result and ultimately the size of the cable selected.

In order to be confident in the analytical methods used it is necessary to thoroughly understand the fundamentals. The more important analytical solution methods are:

a) Linearity
b) Superposition
c) Thevenin and Norton equivalent circuits
d) Sinusoidal forcing function
e) Phasor representation
f) Fourier representation
g) Laplace transform
h) Single-phase equivalent circuit
i) Symmetrical component analysis
j) Per unit method

Probably the simplest concept of all, linearity is also one of the most important because of its influence on the other principles. An important limitation of linearity is that it applies only to responses that are linear for the circuit conditions described (that is, a constant impedance circuit will yield a current that is linear with voltage).

Superposition is then a direct consequence of linearity; in any linear network containing several dc or fixed frequency ac excitation sources (voltages), the total response (current) can be calculated by algebraically adding all the individual responses caused by each of the independent sources acting alone, i.e., all other sources inactivated (voltage sources shorted by their internal impedances, current sources opened).

The Thevenin equivalent circuit is a powerful tool that states that any active linear network can be represented by a single voltage source, equal to the open circuit voltage across any two terminals of interest, in series with the equivalent impedance of the network viewed from the same two terminals with all sources in the network inactivated. This method is typically used to model a Utility electrical connection to an industrial or commercial power system for load flow studies, short-circuit studies, motor starting studies, etc. The determination of the equivalent circuit is usually accomplished by modeling the source as equivalent impedance in series with an appropriate voltage source that would yield the fault current if the terminals were shorted.

The most common error made by practicing power engineers is not taking into account the phase relationships between various quantities when calculating current, voltage, impedance, or power. It is common that an engineer will add voltages or currents together and treat the values as having the same phase angle to simplify the problem.

The per unit method of calculation (or the percentage method) is a short hand method of calculating circuit elements in a common kVA and kV base. It is essential that the power system engineer be familiar with calculation methods because electrical distribution equipment's electrical characteristics are described using this method. For example, a transformer's impedance is provided in percent impedance, which requires the rated transformer's kVA and kV in order to determine the value of impedance in ohms.

In addition some equipment may be rated at one voltage rating and be applied on another voltage rating; for example a power transformer could be rated at 67 kV on its primary and connected to a 69 kV network. In this case the transformer impedance needs to be converted to a common base voltage of 69 kV to be utilized in system studies with the other elements in the 69 kV network.

Chapter 4- System modeling

It is important to understand that for expressing power flow that the convention for real power (*P)* is that it has a positive sign for a load that consumes energy or a source that generates energy. By convention also, the positive sign of reactive power (*Q*) is used for inductive loads; that is, the current lags the voltage applied (consumes vars) and a negative sign for capacitor loads; that is, the current lead the voltage applied ("generate" vars).

When a generator is supplying power (real and reactive) to inductive loads both the sign of *P* and the sign of *Q* are positive and the generator is operating with a lagging power factor. In other words the generator is supplying the vars to the inductive loads. Conversely if a generator is supplying power to a capacitive load then the sign of *Q* at the generator is negative and the generator is operating with a leading power factor; and the generator is referred to as consuming vars.

Impedance diagrams show a single phase equivalent of a three phase balanced power system. These diagrams are working tools to keep track of the masses of data for even small system studies. It is also possible to use a simplified one-line diagram sometimes referred to as a single line diagram as the tool to keep track of the resistances, inductances, and capacitances without rigorously drawing the graphic symbol for each element.

There are no rigid rules on how much of a power system should be modeled for a given study. The responsible engineer will need to exercise judgment and experience when modeling a power system.

For a cable the effective resistance of the conductors should be used. The effective resistance takes into account material, size, shape, temperature, frequency, and environment. For cables and their conductor temperatures there is a choice of either estimating the conductor temperature or assuming the worst case.

For calculating the inductive reactance for a cable the GMD (geometric mean distance) must be known. This factor can be difficult to determine when the installation of cable is not geometrically symmetrical (parallel single conductor cables in horizontal configuration).

For calculating the parameters for the equivalent circuit for transformers transformer test data can be utilized, or for existing transformers (when transformer test data is not available) nameplate data can also be used. When the responsible engineer is designing the power system and needs to specify the transformer impedance then typical values for transformer ratings (including impedance) can be found in the ANSI C57 Series power transformer standards.

The model for induction motors to be used in short circuit studies to account for their contributions to the short circuit current is a voltage source in series with impedance. The voltage source is justified by the fact that at the instant of a short circuit, the flux that exists at the air gap cannot change instantly. The energy the flux represents has to dissipate in the form of current through resistance. The flux will decay rapidly for an induction motor because there is no source of current to maintain it. Thus, the time constant will be in the order of a few cycles.

The synchronous machine model varies tremendously with the type of study. For steady state conditions the generator can be modeled as a constant voltage source and a scheduled amount of kW. It is not recommended that this type of model be used for motor starting studies or load impact studies.

Chapter 5- Computer solutions and systems

Computers and power system analysis programs have become more readily available and easier to use. Unfortunately, it is still easy to get erroneous results from computer programs. Data used in a study must be carefully assembled and checked for input errors. In general, it is important to exercise engineering judgment when reviewing computer results and avoid the tendency to blindly accept numbers on a printout.

Familiarity with the possible solution techniques is helpful when selecting the program, or interpreting the results from computer studies. Solution methods such as Cramer's rule, Laplace expansion, Gauss elimination method, Gauss-Siedel, and Newton-Raphson are widely used in computer programs.

One common issue concerning computer systems is the selection of the correct software for the intended application. This chapter provides information that can be used to develop selection criteria when purchasing a software package. In addition user groups can be contacted and other professionals that are currently using the software for engineering purposes can be contacted for reference to determine how well the package works, is it user friendly, and how well the manufacturer supports their product (questions and problems).

A trial use period for the complete program under evaluation is preferred over use of a limited demonstration package.

Chapter 6- Load flow studies

One of the most common studies used in power system analysis is the load flow calculation. This study is instrumental in the planning, design, and operation of distribution systems for industrial facilities. This study can be used to evaluate the effects of various equipment configurations, additions or modifications to generators, motors, or other electrical loads. Modern systems are complex and have many paths or branches over which power can flow. Electric power flow will divide among these branches until a balance is reached in accordance with Kirchoff's laws. The computer programs to solve load flows are divided into two types; static and dynamic. This discussion is concerned with only static network models and their analysis.

As the load distribution, and possibly the network, will vary considerably during different time periods, it is necessary to obtain solutions representing the major different system conditions such as peak load, normal load, light or no load. These solutions will be used to determine either optimum operating modes for normal conditions, such as the proper setting of voltage control devices, or how the system will respond to abnormal conditions, such as outages of lines or transformers. It also serves as the basis for other types of studies such as short-circuit, stability, motor starting, and harmonic studies. It provides the network data and an initial condition for these studies.

Figure 6.1 is a single line diagram of a sample industrial system that will be used to illustrate some aspects of load flow studies. Notice how the figure shows the operating configuration in terms of which breaker is open and which is closed.

The input data file is the foundation of all load flow analysis, which lists each power system component, defines its mathematical model, and how the components are connected together. Typically the input data is divided into:

a. Bus data
b. Branch data
c. Generator data
d. Transformer data
e. Load data

This data is included (or should be) with every load flow output file in order to document the system and load configuration that the solution applies for. The load flow study should have a predefined set of criteria that the system evaluated must meet. These criteria include:

a. Voltage criteria
b. Power flows on cables and transformers must be within equipment ratings.
c. Generator reactive outputs must be within the limits defined by the generator capability curves.

The load flow analysis is used to design a system that has a good voltage profile during normal operation and that will continue to operate acceptably when one or more lines become inoperative due to line damage, lightning strokes, failure of transformers, etc. In addition, the size and placement of power factor correction capacitors and the setting of generator scheduled voltages and transformer tap positions can be studied with load flows.

An informative method of presenting load flow results is to display them graphically on the system single-line diagram. These power flows can be directly related to configuration, operating conditions, and equipment parameters.

Chapter 7- Short-circuit studies

Whether it is an existing system that is being expanded, or a new system is installed, available short-circuit currents should be determined for proper application and specification of electrical components. The main reasons for performing short-circuit studies are:

(1) Verification of the adequacy of existing interrupting equipment.
(2) Determination of the system protective device settings.
(3) Determination of the fault currents that the electrical components are required to withstand during fault conditions for proper application.
(4) Determination of voltage profiles during fault condition of different kinds and different severity.
(5) Conceptual design, system layout, neutral grounding, and substation grounding.

Three-phase short circuits often turn out to be the most severe fault condition. It is thus customary to perform only three phase-fault simulations when determining maximum possible magnitudes of fault currents. However, important exceptions do exist. For instance, a single line-to-ground short-circuit currents can exceed three-phase short-circuit current levels when they occur in the vicinity of, (1) a solidly grounded synchronous machine, (2) the solidly grounded wye side of a delta-wye transformer of the three-phase core (three-leg) design, (3) the grounded wye side of a delta-wye autotransformer, and (4) the grounded-wye, grounded-wye, delta-tertiary, three-winding transformer.

System configuration consists of the following:

(a) The location of all potential sources of fault current,

(b) How these fault current sources are connected through transformers, lines, cables, busways, and reactors.

It is conceivable that more than one single-line diagram should be considered for a given study, depending on the system operating modes and on the nature of the study. If the study is done to access switchgear adequacy and/or selection, maximum fault currents should be calculated. This entails that fault currents must be calculated under maximum conditions for the facility, and closed bus ties, while any utility interconnections should be assumed to attain their highest fault levels. If the study is done to assess protection sensitivity requirements, some of these conditions may need to be relaxed. Different system service conditions may force the study of more than one system topology alternative, particularly in protective relaying studies.

A very important aspect in short circuit studies is data preparation, which can be computationally demanding. Especially if the software utilized only accepts input data on a per-unit basis. Data necessary for conducting a short circuit study is typically:

(a) Utility interconnection point and associated fault MVA levels (both three phase and line to ground
(b) Generation data
(c) Motor Data
(d) Transformer data
(e) Feeder data
(f) Other Load data (other than motor loads)

It is essential for the program to assist the analyst prepare the data for the study and provides the means of identifying and correcting obvious and common errors. Therefore when selecting computer software for short-circuit analysis it is advisable to compare the features of the various available programs to select the package that will provide the optimum features for the analyst. Table 7.4 in "IEEE Recommended Practice for Industrial and Commercial Power System Analysis", IEEE Std. 399-1997 provides a list of features as a guide to such an evaluation.

Chapter 8- Stability studies

The problem of system stability had its beginning when synchronous machines first operated in parallel or in synchronism. It was recognized early that the amount of power that can be transferred from one synchronous machine to another is limited. This amount of load is known as the stability limit, and when it is exceeded, the machine acting as a generator "over speeds" and the machine acting as a motor "stalls".

As power systems developed, it was found with certain machines, particularly with certain systems connected through high-reactance tie lines, that it was difficult to maintain synchronism under normal conditions and that the systems had to be separated in the event of faults or loss of excitation. Various emergency conditions occasionally made it necessary to operate machines and lines at the highest practical load; under these conditions stability limits were found by experience. Subsequently it became apparent that many of the interruptions to service were the result of disturbances that caused loss of synchronism between various machines and that, by modifying the system design, layout, or operation; it was possible to provide a better standard of service.

The early analytical work on system stability was directed to the determination of the power limits of synchronous machines under two conditions: first, the pull-out of a synchronous motor or generator from an infinite bus; and second, the pull-out or stability limit for two identical machines, one acting as a generator and the other acting as a motor. However, the principal developments in system stability did not come about as an extension of synchronous machine theory, but as a result of the study of long distance transmission systems.

Section 8.2 “Stability fundamentals” is a good introduction to the concepts of stability study. However, for a more rigorous explanation of the concepts of stability the student is directed to reference B2 in the bibliography *Electrical Transmission and Distribution Reference Book,* Westinghouse Electric Corporation, East Pittsburgh, PA, 1964, Chapter 13.

The discussion of the transient behavior of a single synchronous machine is based on a single machine connected to a good approximation of an infinite bus. An example is the typical industrial situation where a synchronous motor of at most a few thousand horsepower is connected to a utility company system with a capacity of thousands of megawatts. Under these conditions, we can safely neglect the effect of the machine on the power system. However, when there are two machines of finite inertia, it is frequently convenient to replace the system of two machines by another system consisting of one machine with an equivalent inertia and a second machine with infinite inertia. By this means the problem is reduced to that of a single machine system. If the stored energies of the machines are (H_a kva_a) and (H_b kva_b), then the equivalent inertia constant for one of them, $H_{eq(a)}$ is given by:

$$H_{eq(a)} = H_a / (1+ (H_a\ kva_a)/ (H_b\ kva_b))$$

In this method the acceleration, velocity, and phase relationship of the selected machine are obtained in relation to the other machine as reference. When losses, intermediate loads, or more than two machines are involved, it is necessary to use the more general method whereby the absolute acceleration, velocity, and phase relation for each machine are separately determined.

The most common disturbances that produce instability in industrial power systems are:

a) Short circuits
b) Loss of a tie circuit to a public utility
c) Loss of a portion of on-site generation
d) Starting a motor that is large relative to a system generating capacity
e) Switching operation
f) Impact loading on motors
g) Abrupt decrease in electrical load on generators

The most immediate hazards of asynchronous operation, caused by system instability, are the high transient mechanical torque and currents that usually occur. To prevent the transients from causing mechanical and thermal damage, synchronous machines are provided with protective relaying such as power factor relays and loss-of- field relays.

Stability studies have benefited from the advent of the computer and its increased capability and availability. This is primarily due to the fact that stability analysis requires a tremendous number of iterative calculations and the manipulation of a large amount of time and frequency variant data. The necessary data required to perform transient stability study are covered in the application guides for the particular programs used. The results of stability programs are fairly easy to understand once the user learns the basic fundamentals underlying stability analysis.

Section 8.7 is a summary of the so-called “things to look for” under different operating conditions and is recommended as a good checklist of operating conditions to review during conceptual engineering, preliminary engineering, and detailed engineering design of industrial power systems.

Chapter 9- Motor-starting studies

The design of electrical distribution systems for industrial facilities should always include an evaluation of the starting requirements for electric motors on the system. A starting voltage requirement and preferred locked-rotor current should always be stated as part of the motor specification for purchase of equipment. For all medium voltage motors on industrial systems a review of the specific equipment torque-speed requirements, starting times, and inertia should be reviewed as a minimum to identify any potential problems.

As a minimum the maximum voltage dip on the electrical distribution system should be determined to establish the design criteria for detail design. The results of the motor-starting studies including the starting times should be reviewed with respect to the electrical coordination study and for extreme starting times it may become necessary to adjust settings on protective devices.

When representing the source, whether a Utility or on-site generation, it should be based on the minimum capacity of the system to yield the most conservative result. This is in direct opposition to the approached used for a short-circuit analysis where the maximum available fault current is used. To model the affect of a close-connected generator on the maximum voltage drop during motor starting requires inclusion of generator transient reactance in series with other source reactances. In general, use of the transient reactance as the representation for the machine results in calculated bus voltages and, accordingly, voltage drops that are reasonably accurate and conservative.

In addition the torque-speed requirements for the load should be evaluated to determine the minimum torque requirements. For instance a centrifugal pump can be started open discharge valve (maximum torque-speed characteristics) or closed discharge valve (minimum torque-speed characteristics) depending on the configuration. These curves should be investigated to establish the minimum starting duty for the motor.

Chapter 10- Harmonic analysis studies

Details of electrical system modeling and applicable standards are discussed. This type of analysis is required when a large number of nonlinear loads (25% and greater of the total load on a bus or the system) are present or anticipated to be added.

There are several approaches to remedy the harmonics problem in a system. The chapter provides a general discussion of the solutions that are available.

Chapter 11- Switching transient studies

Unlike classical power system studies, switching transient studies are conducted less frequently in industrial power distribution systems. Capacitor and harmonic filter bank switching in industrial and utility systems account for most of such investigations, to assist in the resolution of certain transient questions in conjunction with the application or failure of a particular piece of equipment. Two basic approaches are used: direct transient measurements and computer modeling. Both approaches are discussed in this chapter.

Chapter 12- Reliability studies

System reliability assessment and evaluation methods based on probability theory allow the reliability of a proposed system to be assessed quantitatively. Quantitative reliability evaluation methods permit reliability indexes for any electric power system to be computed from knowledge of the reliability performance of the constituent components of the system. Therefore, alternative system designs can be studied to evaluate the impact on service reliability and cost of changes in component reliability, system configuration, protection and switching scheme, and system operating policy including maintenance practice.

For conceptual engineering the load interruption frequency and the expected duration of load interruption events can be converted to an average downtime per year. This can be converted to a cost by knowing the cost of downtime for the facility. Then the cost of modifications to improve system reliability can be evaluated as an investment and determine how long the modification takes to pay for itself based on reduction in average downtime per year. This method is useful in evaluating the need for redundancy and the relative merits of different electrical system configurations.

Chapter 13- Cable ampacity studies

The cables that provide the interconnections between equipment within a power system form the backbone of that system. Therefore it is warranted that a complete analysis of a power system should include an analysis of its cable ampacities. Ampacity is defined as: the current in amperes a conductor can carry continuously under the conditions of use without exceeding its temperature rating. Therefore, a cable ampacity study is the calculation of the temperature rise of the conductors in a cable system under steady-state conditions.

The ampacity values that are provided by cable manufacturers and/or installation codes and recommended practices (such as the NEC or IEEE 835-1994), are usually based on some very specific conditions relative to the cable's installation. For example, the ampacity may be based on 20° C or 40° C, installation in air or underground, direct buried or in conduit, or a single circuit or three circuits. In practice, the cable installation rarely matches those conditions for which the ampacity provided applies. Therefore adjustment factors are required to take into account the differences in the cable's actual installation and operating conditions from the base conditions. The proper selection of these adjustment factors is discussed in this chapter for various installation and operating conditions.

De-rating of cable ampacity is a complex and tedious process. The speed of the computer allows a software program to use a complex model, which considers factors specific to a particular installation and therefore provide for a more optimal cable raceway design. This optimization is important in the initial stages of cable design, especially for underground installations because changes to cables systems are costly. Also, the downtime required to correct a faulty cable design may be very costly.

Chapter 14- Ground mat studies

The primary purpose of a ground mat study is to determine that the neutral to ground voltages normally present during ground faults will be limited by the ground mat design to values that the average person can tolerate. Every exposed metallic object in an industrial facility is connected to ground by some means. During ground faults the potential of the grounding system will rise along any metallic object connected to it. Because most soils are poor conductors the flow of fault current through the earth will create definite and sometimes deadly potential gradients. Ground mat studies calculate the voltage difference between the grounding grid and points on the earth's surface and evaluate the shock hazard involved.

Electric shock effects are the result of current not voltage. Most ground mat studies use the threshold of ventricular fibrillation (100 mA) as their design criterion. Accordingly, most ground mats are designed to limit body currents below this value.

Equation 14-8 gives a quick and simple formula for the calculation of grid resistance when a minimum of design work has been completed. By inspecting this equation it becomes evident that adding grid conductors to a mat to reduce its resistance eventually becomes ineffective. As the conductors are crowded together, their mutual interference increases to the point where new conductors tend only to redistribute fault current around the grid, rather than lower its resistance.

Since grid resistance is viewed as a measure of the grid ability to disperse ground fault current, many designers are tempted to use resistance as an indicator of relative safety of a ground mesh. In general, however, there is no direct correlation between grid resistance and safety. At high fault currents, dangerous potentials exist within low resistance grids.

Although ground mat analysis programs provide an invaluable tool, they are by no means infallible. A follow-up investigation should be made of each ground grid after it has been installed. This should include a measurement of grid resistance at the very least, and preferably the measurement of the ac mesh potential at several locations within the grid. If these measured values differ appreciable from the calculated ones, the results of the grid study should be re-checked and supplemental rods or buried conductors provided as required to establish safe conditions.

Chapter 15- Coordination studies

This chapter addresses only one aspect of system protection, overcurrent protection, and is not a complete study of system protection. The operation of overcurrent devices can be estimated by graphic representation of the time-current characteristics curves (TCCs) for the devices studied. By plotting these devices on a common on a common graph, the relationship between the devices becomes apparent. The overlapping of curves and time intervals between curves are revealed. By indicating on the same graph damage curves for motors, transformers, and cables, and the maximum and minimum fault currents that can occur the performance of the protective devices can be evaluated and studied.

The application of the computer and computer software to time-current coordination studies is a viable alternative to the manual approach. There are several popular computer programs that are available using standard computer hardware that are a practical alternative to the manual method. These programs include libraries of protective devices compiled by user's groups to facilitate the use of these programs and minimize the need to build individual models for each protective device.

It is recommended that a single line be developed with protective devices and other information added using the normal conventions for coordination studies (Figure 15-3). Computer programs typically include software to automatically generate a single line diagram to assist in documenting the coordination study. With other programs, the single line diagram may be developed using popular CAD drafting software that is used to develop installation and construction drawings within the industry.

The use of coordination software programs early in the engineering phase of project development can identify problem areas early when more options are typically available. It is traditional to perform the coordination study and system protection study during the detail design phase of a project to establish the relay settings for all the protective devices. However, I would recommend a preliminary coordination study be performed during preliminary design using the available equipment information (sometimes typical data) to identify any potential problem areas. The use of computer programs for this preliminary study is a viable alternative that can be finalized during the detail design phase for the project.

Chapter 16- DC auxiliary power system analysis

The recent introduction of software specifically designed for analysis of dc power systems greatly simplifies computational tasks that have traditionally been done by hand. The elements of the analysis include system modeling, voltage drop, short-circuit, battery sizing, and charger sizing. For steady-state voltage drop the inductances are ignored and a resistance diagram results. Most loads can be modeled as having a constant resistance, constant power, or constant current characteristics.

The engineer must be familiar with the loads of the dc system because a lot of loads are intermittent and are not continuous. The types of loads typically encountered may be dc motors that are only required for starting equipment such as gas turbines, and dc motors used for spring charging on breaker mechanism for switchgear. The engineer may need to investigate the various operating configurations or other initiating events to establish the design basis (worse case loading) for the sizing of the dc system components. This is typically called the load profile for the system to accurately determine the system voltages during a discharge event. This load profile is typically current versus time. This profile is typically determined assuming a constant dc voltage for the loads during the profile. The voltage can be assumed to be an average (linear) between the beginning dc terminal voltage and end dc terminal voltage during a discharge, or it can be assumed to be the current required at the end of discharge (most conservative) during the entire discharge period. Typically the engineer must judge the importance of the system and its use to determine the types of assumptions made for the load profile.

The battery charger is typically sized to recharge a fully discharged battery to full charge in eight hours while providing a constant voltage source for the balance of the loads on the dc power system. For critical systems dc power systems are sometimes operated inn parallel or one in standby to provide redundancy and improved reliability.