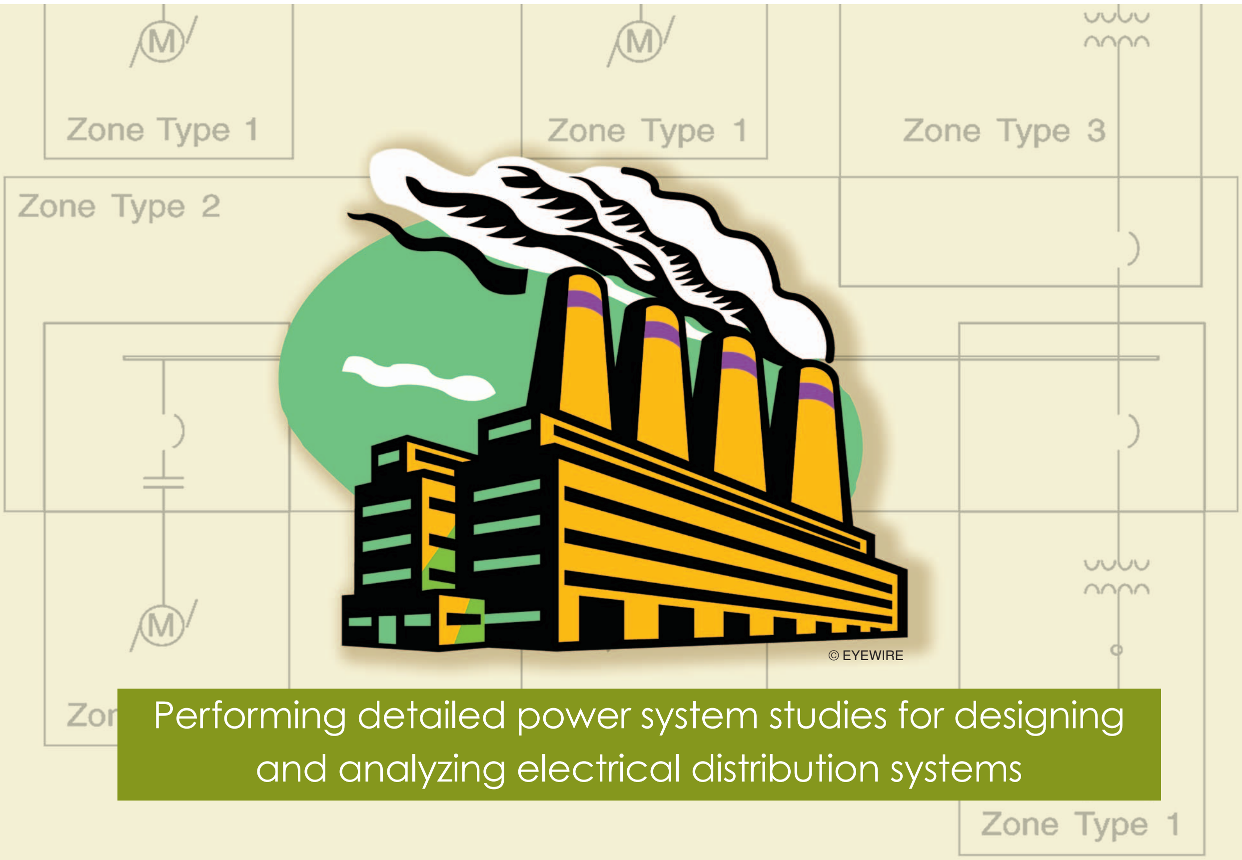

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Performing detailed power system studies for designing and analyzing electrical distribution systems

POWER SYSTEM STUDIES FOR CEMENT PLANTS

BY THOMAS P. SMITH

WHEN DESIGNING A NEW ELECTRICAL distribution system, it is imperative that a power system study be performed before any equipment is specified or purchased. The analysis should always consist of a short circuit, load flow, motor starting, over-current coordination, and arc flash hazard study. The output from the analysis is then used to specify equipment ratings. The engineer should perform the analysis with a well-defined list of electrical distribution system performance criteria in mind, as follows:

- to design an inherently safe system
- to standardize equipment sizing practices and protection methods
- to limit bus voltage drops to 5–8% under maximum load conditions and to 15–20% during large motor starting
- to set overcurrent devices to protect equipment from damage and to selectively shut down sections of the power system in response to a system disturbance
- to limit arc fault energy levels to 40 cal/cm^2 or below.

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When analyzing an existing electrical distribution system, the need to perform a load flow or motor-starting study is diminished. At this point, unless there is an obvious loading or motor-starting problem such as transformers running hot, low voltage under normal or motor-starting conditions, or motors failing prematurely, the effort should be focused in the areas of short circuit, overcurrent coordination, and arc flash. These studies are all life safety related, and if problems are found, they must be rectified immediately.

THERE ARE SEVERAL LOAD FLOW SOLUTION ALGORITHMS USED IN INDUSTRY: GAUSS-SEIDEL, NEWTON-RAPHSON, AND CURRENT INJECTION.

Short-Circuit Analysis

An up-to-date short-circuit study is required for every installation, as described in [1]:

> Equipment intended to interrupt current at fault levels shall have an interrupting rating sufficient for the nominal circuit voltage and the current that is available at the line terminals of the equipment.

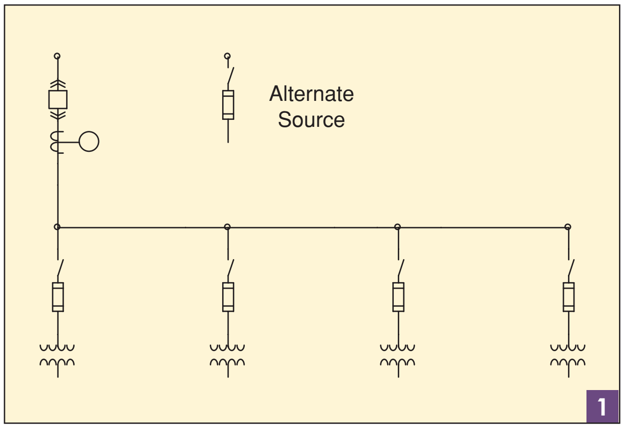
The purpose of the study is two-fold, and both are related to life-safety:

- to calculate the maximum available symmetrical fault duties to compare to low voltage (LV) equipment short-circuit ratings and medium voltage (MV) equipment interrupting ratings.
- to calculate the maximum available peak fault duties to compare to LV equipment unpublished peak ratings and MV equipment close and latching ratings

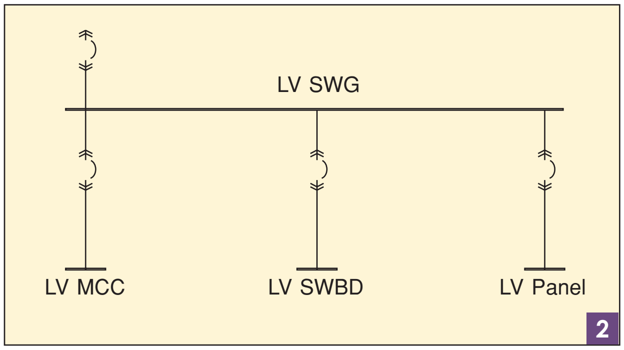
There are three industry-accepted fault calculation methods: classical, American National Standards Institute (ANSI), and International Electrotechnical Commission (IEC). The classical method is covered in every first-semester power systems analysis course [18], [23]–[26]. The ANSI and IEC methods are defined in the standards [3], [16], and [26].

The classical and ANSI methods are used for 60-Hz distribution systems. Further, engineers responsible for LV distribution systems more commonly use the classical method, while engineers responsible for MV distribution systems use the ANSI method. The classical and IEC methods are used for 50-Hz distribution systems.

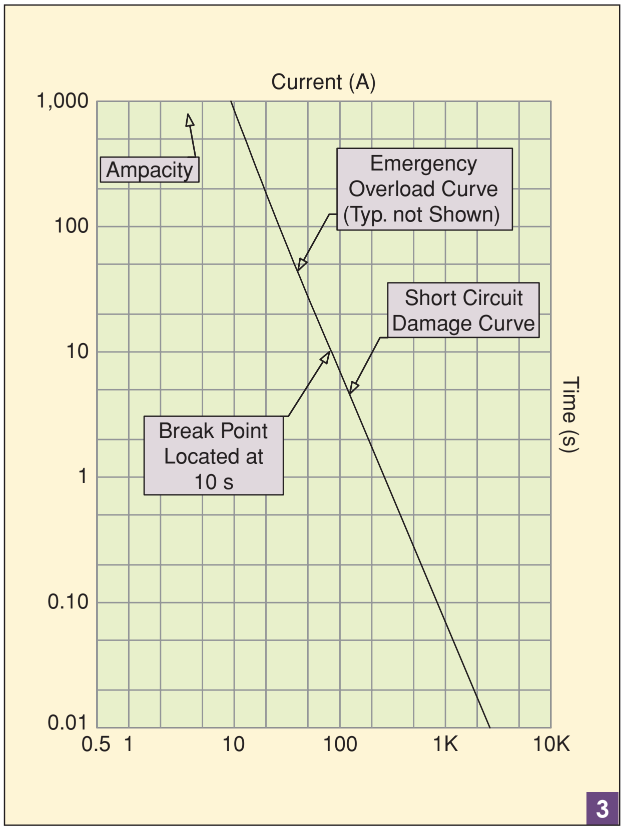
The classical method is characterized by developing an impedance network using X_d'' for all rotating equipment. The network is then reduced using Ohm's law to calculate the Thévenin equivalent fault impedance. It is standard



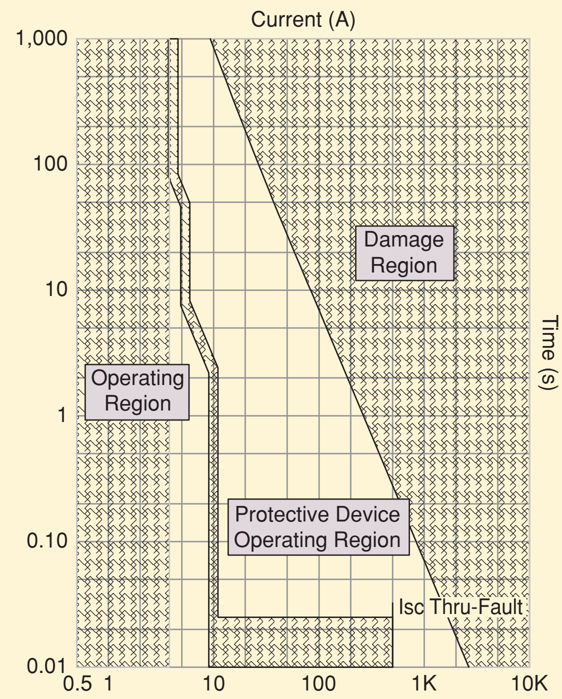
MV one-line diagram.



LV one-line diagram.



Cable TCC landmarks.



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Cable TCC regions.

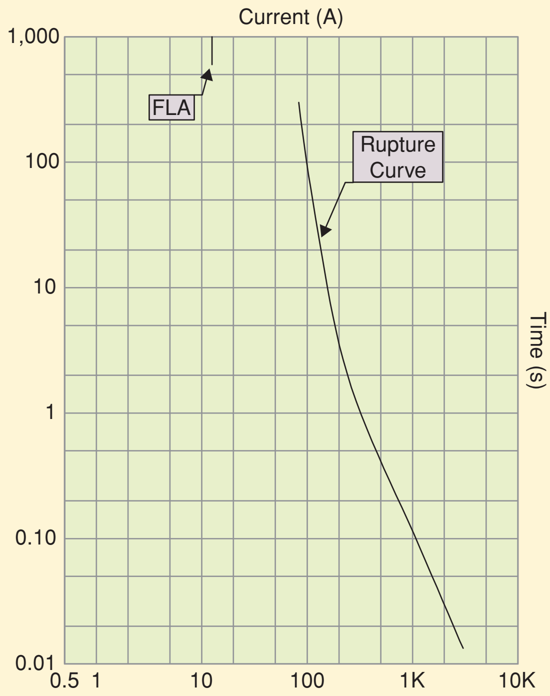
practice to assume that the network impedances and system frequency are constant for the duration of the fault, and that the prefault voltage is 1 Vp.u. Maximum peak and root mean square (RMS) symmetrical fault currents are then calculated and compared to equipment ratings.

In those cases where more accuracy is required, the classical method can be modified by separately analyzing a momentary impedance network and an interrupting impedance network. The momentary impedance network again utilizes X''_d for all rotating equipment and is applicable from time $0^+ < t < 1$ cycle after the fault. This network is used to calculate the RMS symmetrical and peak fault duties. The peak fault duties are compared to the peak ratings of all equipment. The RMS symmetrical duties are compared to LV equipment short-circuit ratings and all fuse short-circuit ratings.

A second interrupting network is then developed using X'_d for all rotating equipment and is applicable from $3 < t < 5$ cycles. This network is used to calculate the RMS symmetrical interrupting fault duty. These duties are compared to interrupting ratings of MV equipment controlled by relays.

Another modification used to increase accuracy includes setting the prefault voltage equal to the calculated load flow voltage. This technique requires a separate load flow analysis for each short-circuit configuration studied.

The ANSI method is characterized by developing separate resistance and reactance diagrams for both the momentary and interrupting impedance networks. Each impedance diagram is reduced using Ohm's law to calculate the Thévenin equivalent fault resistance and reactance.



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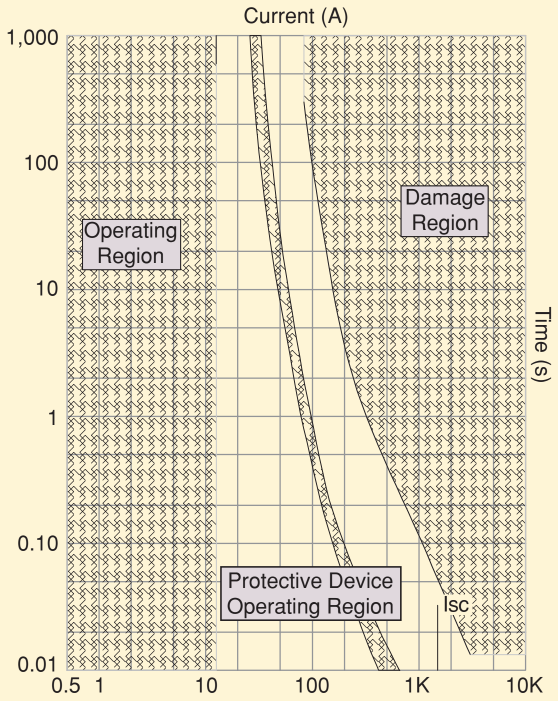
Capacitor TCC landmarks.



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Capacitor TCC regions.

The equivalent resistance and reactance are then combined to determine the total equivalent fault impedance. Note it is a simplification technique to model and reduce the resistance and reactance networks separately. It was developed at a time when hand calculations were the norm. The approach yields conservative results.

The momentary network is constructed using X_d'' for all rotating equipment. Fault point equivalent impedances are calculated and used to determine the peak fault duties. These duties are compared to the peak ratings of all equipment. The momentary network symmetrical duties are compared to LV equipment short-circuit ratings and all fuse short-circuit ratings.

The interrupting impedance network is developed by adjusting the subtransient reactance for all rotating equipment. The machine data is modified to account for the change in reactance from the subtransient to the transient state. This network is applicable to MV equipment controlled by relays. Fault point impedances are calculated and used to determine root mean square (RMS) symmetrical interrupting duties. Calculated duties are directly compared to published interrupting ratings, as long as the calculated X/R ratio is less than or equal to the short-circuit test X/R ratio as defined in the applicable equipment standard. If not, calculated interrupting duties are modified to determine minimum equipment ratings required for the application.

Load Flow Analysis

It is good engineering practice to have an up-to-date load flow study for every installation. The purpose of the study is two-fold:

- to calculate bus voltage levels to compare to equipment ratings and distribution system operating requirements
- to calculate branch current flows to compare to equipment ampacity ratings and protective device trip levels.

Depending on the type of plant and distribution system configuration, there could be dozens of load flow cases to study. The objective is to predict the best- and worst-case operating conditions. Unfortunately, in many cases, it is not intuitively obvious which operating conditions represent the best and worst cases.

There are several load flow solution algorithms used in industry: Gauss-Seidel, Newton-Raphson, and current injection. These methods are covered in first-semester power systems analysis courses [23]. Assumptions used when performing a load flow calculation include the following:

Network
- 3-Ø and balanced
- frequency is constant.

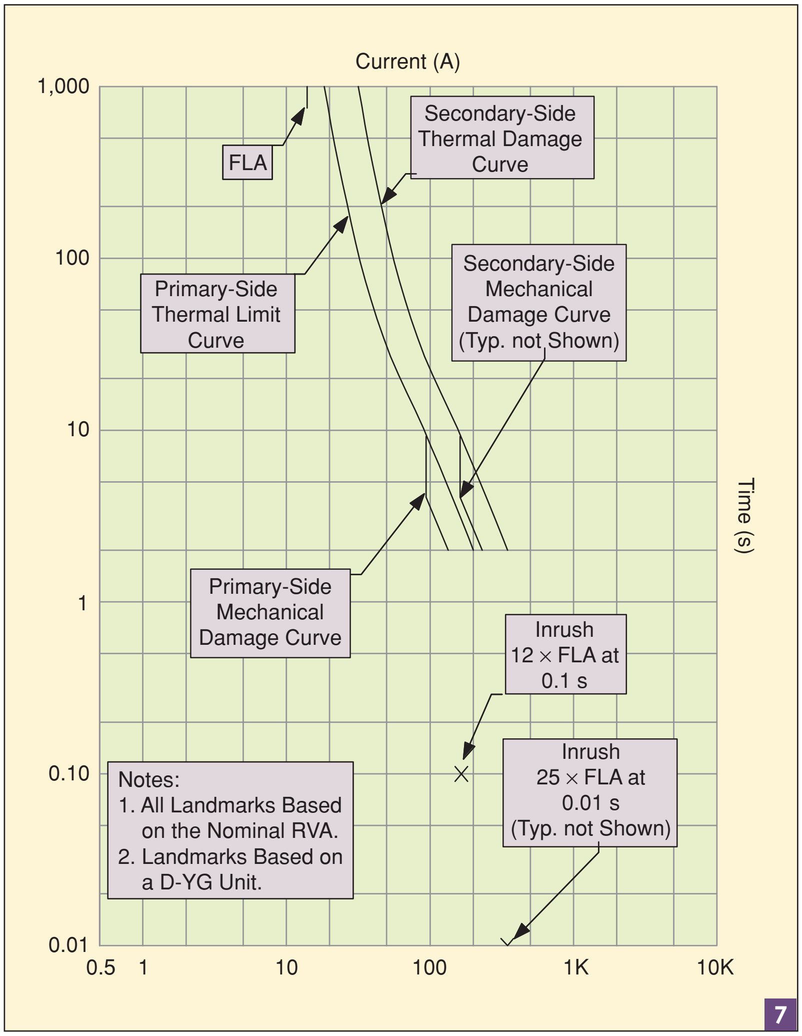
Load Models
- constant kVA model (kVA$_c$)—used to model running motors
- constant I model (I_c)—used to model ballast lighting and welding loads
- constant Z model (Z_c)—used to model starting motors, heaters, and capacitors.

Source Models
- voltage controlled bus (PV)—used to model a typical generator; watts and volts scheduled
- nonvoltage controlled bus (PQ)—used to study a specific loading condition of a generator or to model an induction generator; watts and vars scheduled
- swing bus (SB)—utility point of service; voltage and angle scheduled.

Load flow solution algorithms require at least one swing bus in the network. The utility point of service is always modeled as swing bus.

Motor-Starting Analysis

Motor-starting analysis is required when applying MV motors to an electric power system. The purpose of a motor-starting study is three-fold:



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Transformer TCC landmarks.

- to determine if the motor can accelerate the load
- to calculate the terminal current as the motor accelerates to set the motor protection device
- to calculate the terminal voltage as the motor accelerates to compare to utility, facility, and equipment voltage criteria limits.

The motor-starting solution algorithm assumes the power system is balanced and the frequency is constant. Another assumption is that the motor does not saturate while starting. This assumption allows the prediction of motor current and torque at voltages other than nameplate using the following relationships where all variables are in per unit

- $I_{\text{motor}} \propto V^{1}_{\text{motor}}$
- $TQ_{\text{motor}} \propto V^{2}_{\text{motor}}$.

The motor impedance versus speed curve is modeled as the inverse of the current versus speed curve. Finally, if the power factor versus speed curve is not available, assume the power factor under starting conditions is zero.

There are several machine models available to the engineer in the literature [27]. The most prevalent are the single rotor model, the double rotor model, and the graphical model. The single and double rotor models are best suited to study the behavior of induction motors operating between the breakdown torque and full-load torque speed points. They are commonly used to analyze the response of running motors to a system transient. The graphical model is the industry standard for motor-starting analysis. The graphical model consists of current and torque versus speed curves presented at 100% voltage and a data sheet listing rated HP, voltage, full load amps (FLA), speed, and inertia.

Graphical data is also used to model driven equipment such as compressors, pumps, and fans. This data consists of a torque versus speed curve and a data sheet listing rated power, speed, and inertia.

Starter model types used in these studies include full-voltage, unit transformer, reactor, capacitor, autotransformer, soft-starter, and variable frequency drive (VFD), of which the full-voltage type is the most prevalent.

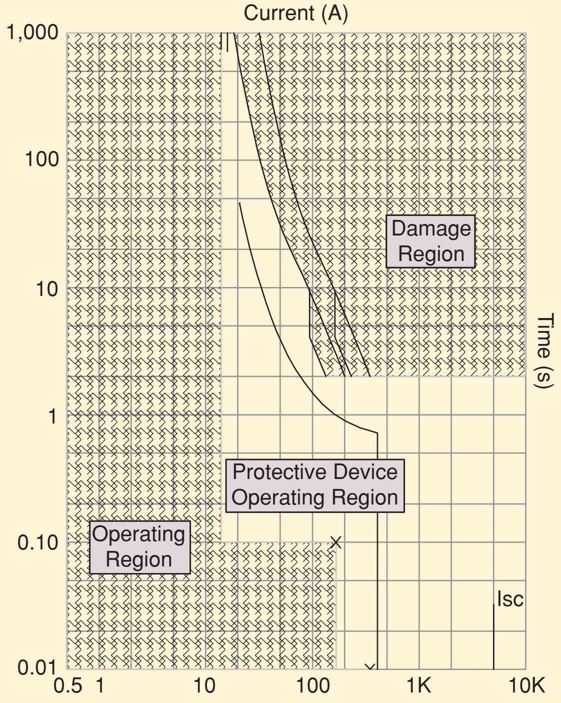
Overcurrent Coordination

An up-to-date facility overcurrent coordination study is required for every installation, as described in [1]:

> The overcurrent protective devices, the total impedance, the component short-circuit ratings, and other characteristics of the circuit to be protected shall be selected and coordinated to permit the circuit-protective devices used to clear a fault to do so without extensive damage to the electrical components of the circuit.

The meaning of selected and coordinated is three-fold:

- Life safety—to size and set protective devices within distribution equipment continuous current ratings and rated short-circuit test duration times
- Equipment protection—to size and set overcurrent protection devices to protect distribution equipment



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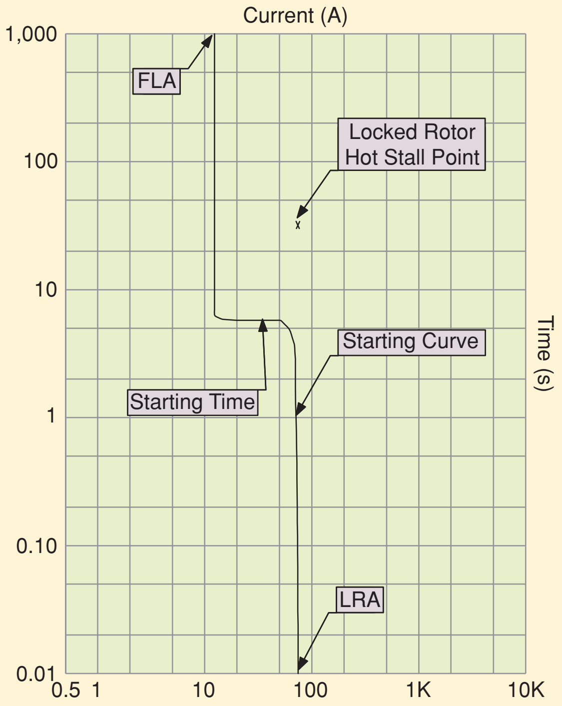
Transformer TCC regions.



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LV squirrel cage induction motor TCC landmark.

- Selectivity—to size and set overcurrent protection devices such that, in response to a system disturbance, the minimum area of the distribution system is removed from service.

The results of the load flow study are used to confirm minimum equipment continuous current ratings. The results of the short-circuit study are used to confirm minimum equipment interrupting and withstand ratings. To meet life safety requirements, the results of the overcurrent coordination study must confirm that protective device pickups are within equipment continuous current ratings and that protective device clearing times are within distribution equipment rated short-circuit duration times (see Table 1).

Consider the distribution system shown in Figure 1. It is common in industry to find an MV main circuit breaker relay pickup set above the continuous current rating of the breaker, or to find a fuse sized above the switch amp rating. This practice is said to be done for selectivity reasons. However, this practice is misguided; it introduces a life safety problem in situations where the continuous load current is below the protective device trip setting but above the equipment amp rating. In these situations, even though the equipment short-circuit interrupting and withstand ratings are above available fault duties, the equipment is not rated to safely operate under these conditions.

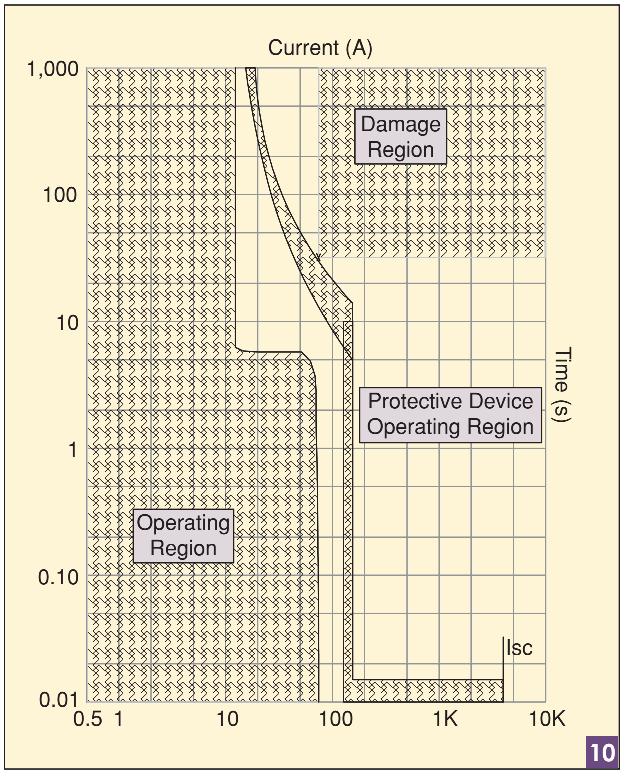
A second example of a life safety problem occurs when a main-lug-only panelboard, motor control center (MCC), or switchboard is fed from a power circuit breaker (Figure 2). In these situations, it is common practice in industry to remove the instantaneous function from the power circuit breaker, again for selectivity reasons. In these situations, the downstream equipment is required to endure a fault for much longer than the equipment-rated short-circuit duration time of three cycles.

To meet equipment protection goals, a basic understanding of power system component damage curves is required [4]–[12].

TABLE 1. SHORT-CIRCUIT DURATION LIMITS.

Equipment	Standard	Short-Circuit Duration
Panelboard	UL67	3 cycles
MCC	UL 845	3 cycles
Switchboard	UL 891	3 cycles
LV Switchgear	ANSI C37.50	30 cycles
MV Switchgear	ANSI C37.010	2 s

Cable characteristics plotted on a time-current curve (TCC) include the ampacity, emergency overload curve, and short-circuit damage curve [17] (Figure 3). The emergency overload curve is typically not shown. If current is allowed to exceed the ampacity and/or the emergency overload curve, cable insulation life is reduced. If current is allowed to exceed the short-circuit damage curve, the insulation will be damaged. Protective devices must be set at or below the cable ampacity in the long-time region and below the damage region (Figure 4). Protective device curves are plotted



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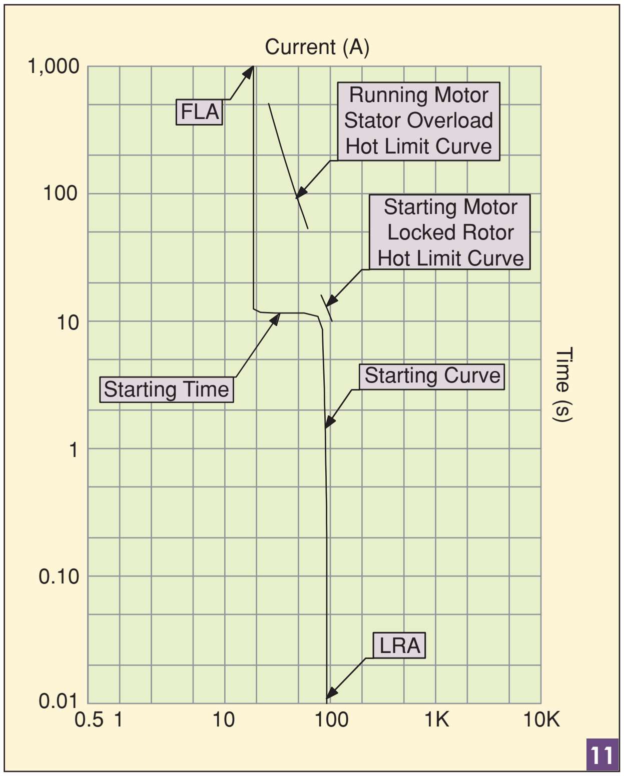
LV squirrel cage induction motor TCC regions.



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MV squirrel cage induction motor TCC landmarks.

on the TCC up to the maximum expected through fault current.

Characteristics for capacitors are shown in Figure 5. The rupture curve represents a gas pressure limit caused by an internal arcing fault that, if exceeded, will result in the rupture of the capacitor case. Rupture curves are provided by the manufacturer. Protective devices must be set above the full load amps and below the damage region (see Figure 6).

IT IS GOOD ENGINEERING PRACTICE TO HAVE AN UP-TO-DATE LOAD FLOW STUDY FOR EVERY INSTALLATION.

Characteristics for liquid-immersed transformers are shown in Figure 7. Through-fault current duration damage curves are defined in the standards [13] and [14]. Curves are impacted by winding connection [5], [17]. Protective devices must be set above the full-load amps and inrush points and below the damage region (see Figure 8).

Characteristics for LV squirrel cage induction motors are shown in Figure 9. If a motor is stalled for a time greater than the hot rotor limit point, motor damage will occur. Protective devices, e.g., a starter equipped with overloads and a motor circuit protector, must be set above the starting curve and below the damage region (see Figure 10).

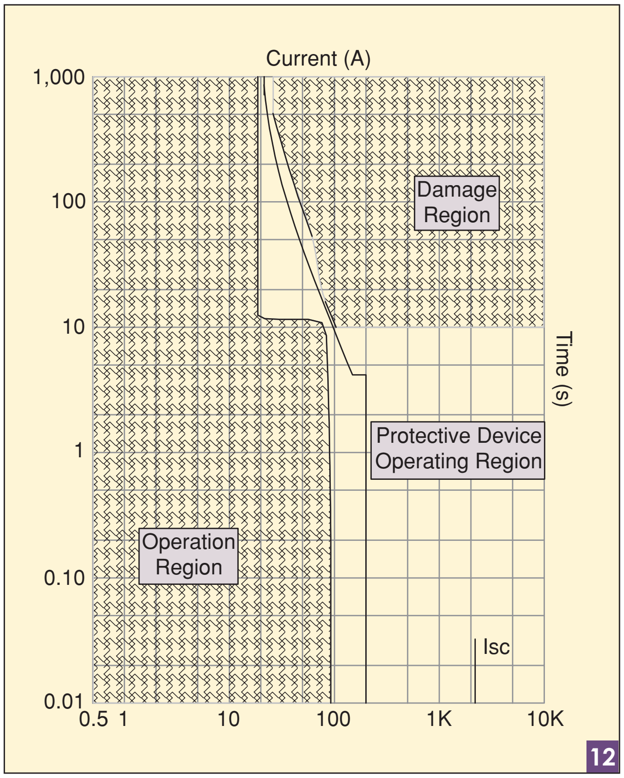
Characteristics for MV squirrel cage induction motors [15] are shown in Figure 11. If the current of a running motor exceeds the stator limit curve, insulation life is reduced. If a motor is stalled for a time greater than the hot rotor limit curve, motor damage will occur. Protective devices must be set above the starting curve and below the damage region (see Figure 12).

Characteristics for LV generators are shown in Figure 13. Protective devices must be set above the full-load amps and the total current decrement curve in the lowest decade of the TCC and below the damage region (see Figure 14). Protective devices must also be set to intersect with the decrement curve in the short-time region (0.1–0.5 s).

To meet selectivity goals, proper coordinating time intervals must be maintained between series relay characteristic curves on the TCC (see Table 2).

Coordinating time intervals are not applicable for LV thermal magnetic, insulated-case, or power circuit breaker characteristic curves on the TCC. As long as device curves do not touch, selectivity is achieved. The curves for breakers are shown as a band on the TCC (see Figure 15). The lower limit of the band indicates the current and time at which the breaker will begin to operate. The upper limit indicates the current and time at which all three poles of the breaker will be open with the arc extinguished.

Coordinating time intervals on the TCC are not applicable for fuses. In lieu of coordinating time intervals, fuse ratios between series devices must be maintained (see Table 3). Fuse ratio tables are manufacturer specific [17].



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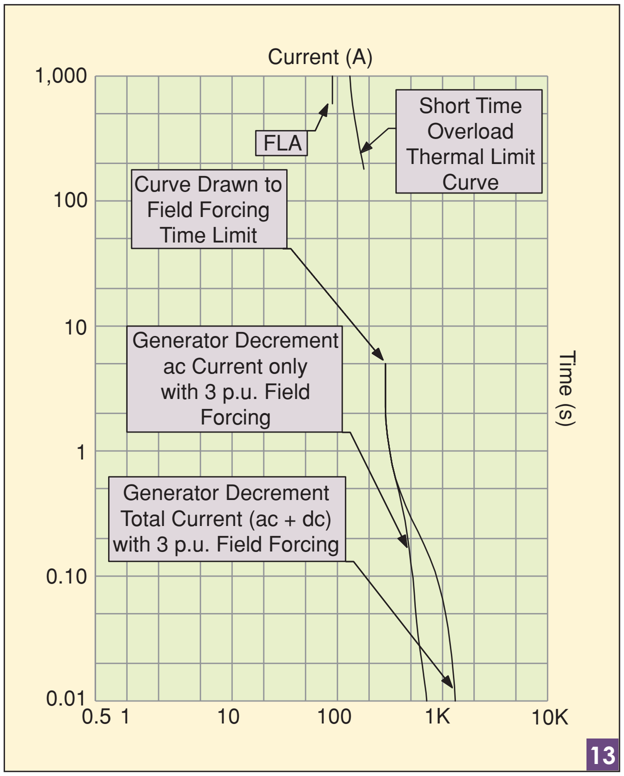
MV squirrel cage induction motor TCC regions.



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LV generator TCC landmarks.

TABLE 2. COORDINATING TIME INTERVALS.

Series Devices	Relay Disk Over-Travel	Relay Tolerance	Breaker Speed (s)	Total Time (s)
51 Relay	0.1	0.07	0.05	0.22
51 Relay			0.08	0.25
			0.13	0.30
		0.17	0.05	0.32
			0.08	0.35
			0.13	0.40
51 Relay	N/A	0.07	0.05	0.12
50 Relay			0.08	0.15
			0.13	0.20
		0.17	0.05	0.22
			0.08	0.25
			0.13	0.30

TABLE 3. LV FUSE SELECTIVITY SCHEDULE.

	Load-Side			
Line-Side	Class L	Class K1	Class J	Class K5
Class L	2:1	2:1	2:1	6:1
Class K1		2:1	3:1	8:1
Class J		3:1	3:1	8:1
Class K5		1.5:1	1.5:1	2:1

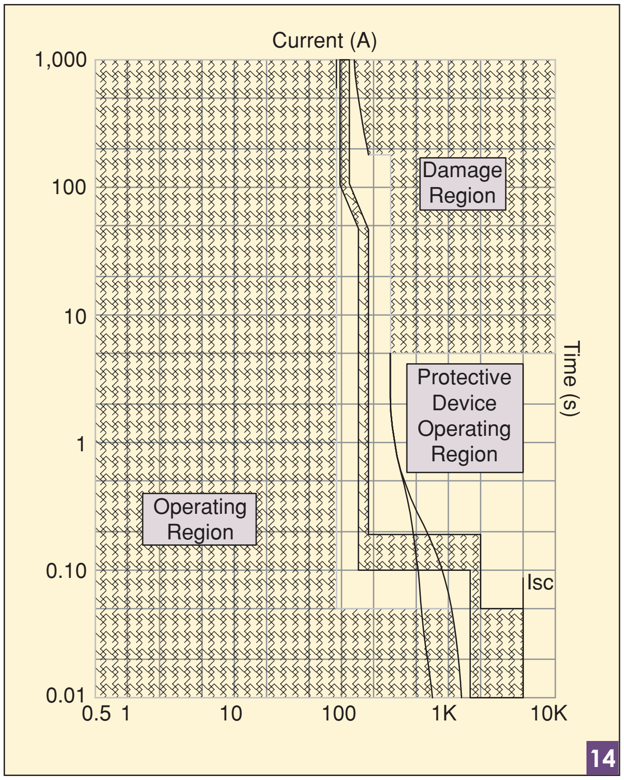
When performing overcurrent coordination studies, the proper procedure is to first break the power system into zones of protection on the plant one-line diagram, as shown in Figure 16 [23]. The boundary for each zone is established by a protective device. Each protective device is included in two zones. The second step is to set all the protective devices in zone type 1. Zone type 1 includes all directly connected loads at each voltage level in the distribution system. This includes the main breaker of lighting and receptacle panels serving single-phase loads. Coordination, or lack thereof, between the main and feeder breakers in these types of panels will be ignored. To complete the study, step through zone types 2, 3, 4, and 5, sequentially setting the next upstream device.

ARC Flash Hazard Analysis

An up-to-date arc flash hazard study is required for every installation, as described in [1]:

> Switchboards, panelboards, industrial control panels, meter socket enclosures, and motor control centers that are in other than dwelling occupancies and are likely to require examination, adjustment, servicing, or maintenance while energized shall be field marked to warn qualified persons of potential arc flash hazards.

The purpose of the study is two-fold, and both are related to life-safety:



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LV generator TCC regions.

- to identify and label the personal protective equipment (PPE) that must be worn by qualified workers while performing work on energized equipment
- to identify and label the arc flash boundary distance that must be maintained by an unprotected worker from the potential arc source while live work is performed.

Two approaches are available to determine the required PPE and boundary distance: a look-up table or detailed calculation. The industry standard approach is to perform a detailed calculation. There are two industry-accepted calculation methods: NFPA 70E and IEEE 1584 [2], [20]. The IEEE 1584 method is typically used throughout industry. The IEEE 1584 calculation method is applicable under the following boundary conditions:

- network is 3-Ø and balanced
- frequency is constant at 50–60 Hz
- system voltage from 208–15,000 V
- 3-Ø fault duty from 700–106,000 A
- grounding of all types
- commonly available equipment enclosures
- conductor gaps of 13–152 mm.

The IEEE 1584 method does not apply to the following types of distribution systems or equipment:

- dc, 25-Hz, or 400-Hz systems
- LV networks with over 106 kA available
- systems with 27- and 38-kV switchgear.

Do not apply the IEEE 1584 equations in these situations to determine the PPE or boundary distance. In these situations, the proper approach is to deenergize the equipment to perform all work until the standard is updated to cover these situations.

Arc flash hazard study assumptions commonly used in industry include:

- ignore ground fault protection devices
- include induction motor contributions for five cycles
- include arc duration times for up to 2 s.

The maximum arc duration time or two-second rule [20] originates from the following rationalization:

> If the time is longer than two seconds, consider how long a person is likely to remain in the location of the arc flash. It is likely that the person exposed to arc flash will move away quickly if it is physically possible and two seconds is a reasonable maximum time for calculations. A person in a bucket truck or a person who has crawled into equipment will need more time to move away.

It is recommended that one should never begin the calculation using the two-second rule without first reading the arc duration clearing time from the overcurrent protective device clearing curve on the TCC. High clearing times generally indicate basic problems with the distribution system design and/or protective device settings.

Finally, a common misconception is to assume that maximum energy levels occur at maximum short-circuit levels. This is not true when the controlling protective device is operating in an inverse-time region. A second arc flash analysis should always be performed at minimum short-circuit levels.

Prestudy Preparation Work

To begin a power system study, an up-to-date set of single line diagrams is required with the following information:

- utility point of service minimum and maximum short-circuit capacities and X/R ratios
- feeder size, length, type
- transformer kVA, connection, impedance and X/R ratio, grounding method.
- rotating equipment size, voltage, and X''_d
- distribution equipment ratings.

An up-to-date certified test report for all relays and circuit breakers greatly reduces the time and money spent on a site survey.

Study Procedure

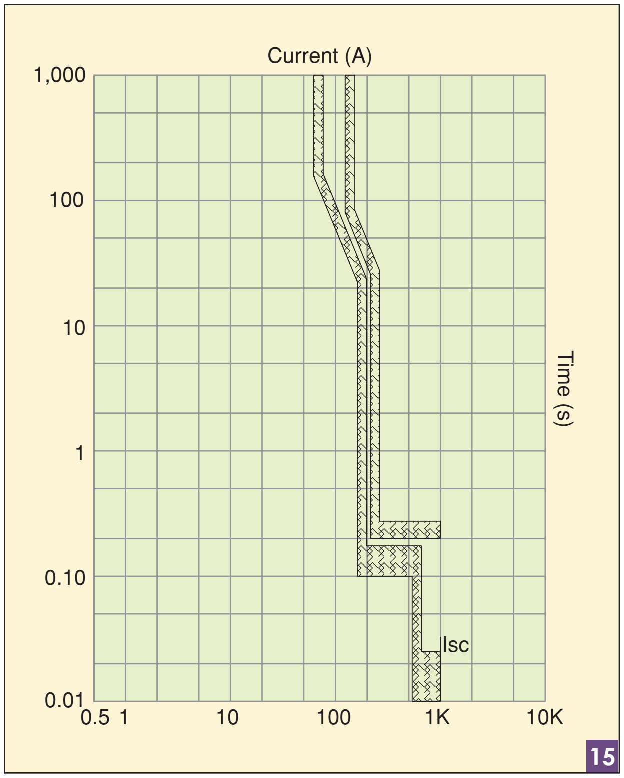
Analyzing an electrical distribution system is a five-step procedure.

Step 1—Build the distribution network model.
Step 2—Perform short-circuit and load flow studies.
Step 3—Perform motor-starting studies.
Step 4—Perform overcurrent coordination.
Step 5—Perform arc flash hazard analysis.

Conclusions

The following conclusions can be made.

1) Power system studies should always be computer based.
2) The report documents should be direct outputs from the software package in the form of summary tables or one-line diagrams.



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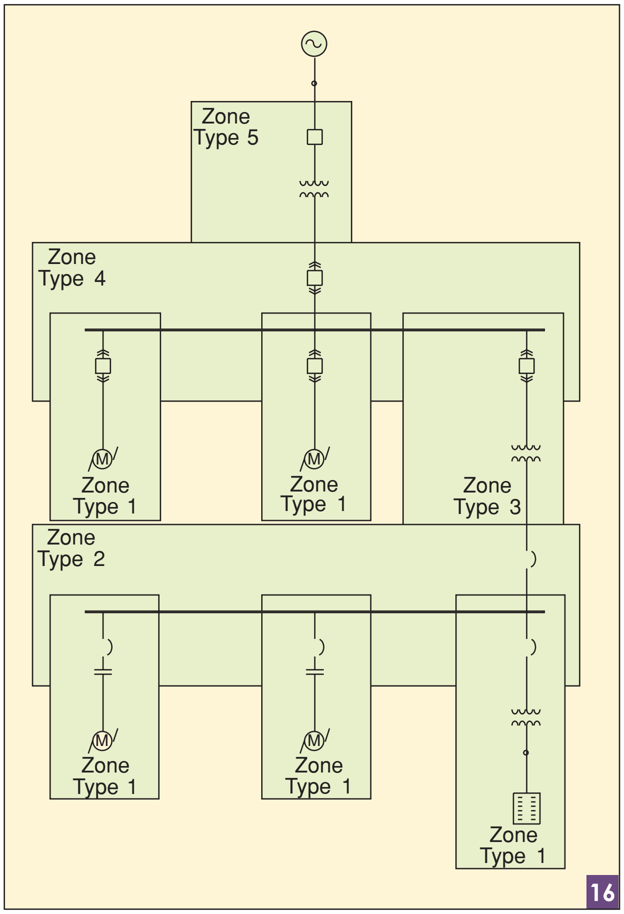
LV circuit breaker.



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Zones of protection.

3) Document all input data assumptions with references used to complete the analysis for data that is unavailable. For instance,
   - all LV motors start in 5 s
   - all LV motors LRA = 6 x FLA
   - all LV motors $X''_d = \text{LRA}^{-1}$.

4) State all operating modes to be studied:
   - normal or emergency operating mode
   - tie breakers closed.

5) State the short-circuit calculation method used to complete the analysis: classical, ANSI, or IEC.

6) The computer output short-circuit reports should list distribution equipment short-circuit ratings, available fault duties, and percent margins. Clearly identify all safety problems with solutions.

7) The load flow study report should list equipment ampacity ratings, current flows, and percent margins and include an equipment list that states voltage ratings, calculated bus voltage levels, and percent voltage levels. An alternate approach is to summarize data on the computer model one-line diagrams.

8) The motor-starting study results should always be presented graphically in the form of two plots. The first plot should display motor speed, current, voltage, and net torque. The second plot should display bus voltage profiles at every point in the power system that a voltage criterion was specified to confirm performance.

9) The overcurrent coordination study results should be presented by distribution equipment in the form of a set of time-current curves and protective device setting tables. The time-current curves and setting tables should clearly identify each device by manufacturer, type, and setting. A simple one-line diagram should be included on each TCC for reference. All problem areas should be grouped into three categories: life safety, equipment protection, and selectivity. Provide corrective measures for each problem identified.

10) State the arc flash calculation method and assumptions used to complete the analysis.

11) The arc flash hazard results should list available energy levels, PPE, and boundary distances for every point in the distribution system where work on energized equipment may be performed. Corresponding equipment labels should then be made for field installation.

12) The computer model should be maintained and actively used to investigate proposed changes to the distribution system.

13) The report should be updated as changes are implemented.

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Thomas P. Smith (tomsmithpsa@aol.com) is with Power Systems Analysis in Allentown, Pennsylvania. He is an IEEE Member. This article first appeared as "Power System Studies for Cement Plants" at the 2006 Cement Industry Conference.