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METHODS FOR COORDINATING SYSTEM PROTECTIVE EQUIPMENT

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PART I - PROTECTIVE DEVICES

Today, protective devices, including fuses, circuit breakers, and relays of various types, are quite sophisticated compared to the ones used 20 years ago. The protective device provides a form of insurance for high-cost electrical equipment. Protection of electrical power systems can reduce the extent and duration of an interruption, as well as reduce equipment damage or personal injury. if a protective device operates, it does so because it reacts to a problem in the system. It is vital then, to investigate the cause and location of the problem; to merely replace the fuse element or reset the protective device does not eliminate the problem. If the cause of the problem cannot be found, contact D-8440 or D-8450 as to possible reasons the protective device operated.

1. FUSES

A fuse appears to be a simple device, but study of the numerous types and circuit applications reveals that it is a complex equipment protection device. Various circuit applications require that fuses satisfy many requirements including different interrupting ratings, peak let-through current, (I^2t) characteristics, and melting time-current characteristics. A fuse is a thermal tripping device in an electric circuit the operation of which depends on thermal capacity of the fuse element, its melting temperature (to some extent), and the current flow previous to the fault condition.

The fusible element may be composed of any of the following metals: bismuth, cadmium, lead, tin, silver, copper, aluminum, or any alloy of these elements, to achieve thermal characteristics necessary for best system protection. Measurement of capacity of a particular fuse to perform a certain job depends largely upon the accuracy with which it was manufactured, the correctness of application, and the quality of maintenance after installation. A fuse improperly applied or maintained might fail to disconnect the circuit when required, which might result in considerable damage to costly equipment.

A dual element or time-delay fuse has current response elements of two different fusing characteristics in series in a single cartridge. A fast-acting element protects against short-circuit currents similar to all ordinary standard fuse. A time-delay element permits short duration overloads but melts if an overload is sustained. The most important application of this type of fuses is for motor or transformer protection because it does not open on motor starting or transformer magnetizing inrush currents but prevents damage from sustained overloads

Where new protective equipment is being prescribed such as distribution cutouts, fuse links, secondary fuses, power fuses, distribution enclosed single-pole air switches, fuse disconnecting switches, and accessories for use under unusual conditions, D-8440 should be requested to provide assistance during design and installation of the equipment.

Unusual or extreme operating conditions for a fuse could be: explosive dust or gas, excessive or abrasive dust, corrosive or conductive vapors, steam, salt water, excessive moisture or dripping water, excessive vibration or shock, or unusually low temperatures. Unusual conditions are sometimes created by poor storage, transportation, or limited space conditions, frequencies other than 60 Hz, poor maintenance, and infrequency of operation.

Unusual operating conditions due to ambient temperature above 40 EC (100 EF):

> Equipment designed for standard temperature rise may be used at the normal rated continuous current without exceeding ultimate standard temperature limits, provided the ambient temperature does not exceed 40 EC (100 EF) times the ambient temperature factor (table 1) which corresponds to the altitude where the equipment will operate.

Unusual operating conditions due to altitudes higher than 1000 m (3300 ft) above sea level:

> Equipment that depends on air for insulating and cooling will have a larger temperature rise.

and lower dielectric value and current rating, when operating above 1000 m (3300 ft) elevation. The dielectric-strength factor and continuous-current factor (table 1) must be multiplied by the respective values according to the altitude where the equipment will operate.

1.1 LOW-VOLTAGE FUSES.-Design features for fuse applications of 600 V or lower must correspond to UL (Underwriters Laboratories) standards in order to be considered for proper selection, as follows:

Frequency rating
Maximum peak let-through current
Maximum clearing thermal energy (I^2t)

Interrupting rating.-Determine the maximum symmetrical short-circuit available on the system at the fuse location. Select a fuse having an interrupting capacity greater than, the available short-circuit current.

*Voltage rating.-V*oltage rating of a fuse should be selected as equal to, or greater than, the nominal system voltage on which it is used. This rating is not a measure of its ability to withstand a specified voltage while carrying current, but rather it is the ability of the fuse to prevent the open-circuit voltage of the system from restriking and establishing an arc once the fuse link has parted. Standard low-voltage ratings are 600, 300, 250, and 125 V.

Continuous current rating.-The continuous-current rating of a fuse should be equal to, or slightly less than, the current-carrying capacity of the circuit it is protecting. Only in unusual cases (as mentioned earlier) should the fuse rating be greater than the current-carrying capacity of the circuit.

- For overload and short-circuit protection (generally) select the fuse ampere rating at 125 percent of the full-load amperes.

- For short-circuit-only protection, select fuse ampere rating at 150 to 300 percent of equipment or circuit rating.

- The ambient temperature affects the current-carrying capacity of fuses (table 1).

Time-current characteristic.-The fuse time-current characteristic should be compatible with the time-current characteristic of the load and the time- current characteristic of the circuit components to be protected.

- Select very fast-acting fuses to protect very low withstand components, such as semiconductors.

- Select non-time-delay fuses for resistance currents or other currents where no transients or surges are encountered (usually sized at 125 percent of full- load amperes).

- Select a dual-element, time-delay fuse where high inrush or starting loads are present as with motors, solenoids, or control transformers (usually sized at 125 percent of full-load amperes).

- Select a limiter, or non-time-delay fuse, where short-circuit protection only is required (usually sized at 150 to 300 percent of circuit ampere rating).

- Test the selected fuse in the intended circuit under all normal circuit conditions. This may include transient, inrush, or any other non-steady-state currents.

1.1.1. Plug fuses.-Low-voltage fuses are of two general types, plug and cartridge. Plug fuses are rated at 125 V or less and up to 30 A maximum and have no interrupting rating. They are subject to one alternating-current, short-circuit test with an available current not over 10,000 A, rms.

1.1.2. Cartridge fuses.-Cartridge fuses can be either renewable or nonrenewable. A renewable-fuse can be disassembled to replace the fused element but is generally

Table 1. - Altitude correction factors

Altitude above sea level Meters	(Feet)	Factor to be applied to rated: Dialectric strength	Continuous Temperature	Ambient current
1000	3 000	1.00	1.00	1.000
1200	4 000	0.98	0.99	0.992
1500	5 000	0.95	0.99	0.980
1800	6 000	0.92	0.98	0.968
2100	7 000	0.89	0.98	0.958
2400	8 000	0.86	0.97	0.944
2700	9 000	0.83	0.96	0.932
3000	10 000	0.80	0.96	0.920
3600	12 000	0.75	0.95	0.896
4300	14 000	0.70	0.93	0.872
4900	16 000	0.65	0.92	0.848
5500	18 000	0.61	0.91	0.824
6100	20 000	0.56	0.90	0.800

NOTE: Use one correction factor from column 2 or 3, but not both, for any one application. If the derating as determined from the table is significant, equipment of suitable higher rating should be chosen to meet requirements after the correction factor has been applied.

not available in higher current interrupting ratings. The nonrenewable fuse must be completely replaced when expended. Current-limiting fuses, a type of cartridge fuse, place a definite upper limit on the peak current and thermal energy and provide equipment protection against damage from excessive thermal energy and magnetic stresses. The current- limiting fuse is most widely used in fused motor starters and switches, fused circuit breakers, and feeder circuits for protection of busways and cable.

1.1.2.1. *Class K high interrupting-capacity fuses, nonrenewable.-*

Class K1 -High degree of current limitation

Class K5 -Moderate degree of current limitation

Class K9 -Fair degree of current limitation

- Short-circuit interrupting ratings are 50,000, 100,000, and 200,000 A, rms, symmetrical.
- Current ratings up to 600 A.
- Voltage ratings of 250 and 600 V alternating current only.
- Interchangeable with UL class H, NEMA class H, and UL class RK1 and RK5 fuses in equipment provided with class H fuseholders.
- If fuse is time delay, 10-second delay at 500 percent rating is required.

1.1.2.2. *Class R current-limiting fuse, nonrenewable.-*

Class RK1 - High degree of current limitations

Class RK5 - Moderate degree of current limitations

- Short-circuit interrupting rating of 200,000 A, symmetrical.
- Current rating up to 600 A.
- Voltage rating of 250 and 600 V alternating current only.
- Interchangeable with UL class H, NEMA class H, and UL classes K1, K5, and K9 in equipment provided with class H fuseholders. Not interchangeable with any other fuse class in equipment provided with class H fuseholders.
- Time delay optional, minimum 10-second delay at 500 percent current rating.

1.1.2.3. *Class J current-limiting fuses, nonrenewable.-*

Short-circuit interrupting rating of 200,000 A, rms, symmetrical.

Current rating up to 600 A.

- Voltage rating of 600 V alternating current only.
- Not interchangeable with any other fuse class. Fuses having a time delay characteristic are available in class J dimensional sizes although they do not meet the UL standards for current-limiting performance.

1.1.2.4. *Class L current-limiting fuses, nonrenewable.-*

- Short-circuit interrupting rating of 200,000 A, rms, symmetrical.
- Current rating of 601 to 6,000 A.
- Voltage rating of 600 V alternating current only.
- Not interchangeable with any other fuse class.
- Fuses may be marked "time delay" although UL does not investigate time delay characteristics of such fuses.

1.1.2.5. *Class H non-current-limiting fuses* constructed in both renewable (time delay optional) and nonrenewable (no time delay) configurations.-

- Short-circuit rating cannot be over 10,000 A, rms, symmetrical.
- Current ratings up to 600 A.
- Voltage rating of 250 and 600 V alternating current only.
- Interchangeable with UL classes K1, K5, and K9, NEMA class H, and UL classes RK1 and RK5 fuses in equipment provided with class H fuseholders.
- May or may not be dual element, if labeled as "time delay" it must have a minimum 10-second delay at 500 percent current rating.

1.2. POWER FUSES.-The selection of a power fuse, which is a fuse rated over 600 V, should be based on the following considerations. A power fuse consists of an assembly of a fuse support and a fuseholder which may or may not include the refill unit or fuse link. Power fuses provide consistent and fast protection for equipment short circuits where it is not economically advisable to use a circuit breaker. Power fuses are usually used for primary or secondary protection of power transformers but are also used for feeder circuits and capacitor banks. Because power fuses are not designed for automatic restoration of service but require manual replacement of the fused element, it is not advisable to use them where overloads may occur frequently.

1.2.1. Current-limiting fuses.-To obtain a high-interrupting capacity starter on systems above 600 V, these fuses were primarily developed for use with motor-starting contactors to limit the short-circuit current to a value within the "withstand capabilities" of the contactors. Other typical applications of current-limiting fuses are protection of potential transformers and protection of small loads on high-capacity circuits. Due to the time-current characteristics of power fuses being near vertical, it makes them difficult to coordinate with overcurrent relays on their load side.

1.2.2. Expulsion-type fuses.-Generally used in distribution system cutouts or disconnecting switches, this type of fuse must use an arc-confining tube with deionizing fiber liner to interrupt a fault current. The arc is interrupted by the rapid production of the pressurized gas within the fuse tube which extinguishes the arc by expulsion from the open end, or ends, of the fuse. This process is comparatively noisy and, if applied with an enclosure, care must be taken to vent any ionized gases which would cause a flash-over between internal live parts.

1.2.3. Power fuse element characteristics.-For any given element melting time, the maximum steady-state symmetrical current shall not exceed the minimum by more than 20 percent.

Most power fuse elements comply with NEMA standard "E" rating which has the following characteristic requirements:

- The current rating of the fuse must be carried continuously.
- Fuses rated at 100 A or less shall melt in 300 seconds at an rms current within the rate of 200 to 240 percent of the continuous rating of the fuse element.
- Fuses rated above 100 A shall melt in 600 seconds at an rms current within the range of 220 to 264 percent of the continuous rating of the fuse element.

Some power fuse elements comply with the NEMA standard "N" rating which has the following characteristic requirements:

- The current rating of the fuse must be carried continuously.
- The element will melt in 300 to 600 seconds at an rms current within 115 to 125 percent of the continuous rating.

To provide the best possible coordination, power fuse elements are available in three speed ratios: fast, medium, and low. The speed ratio of a fuse element is defined as the ratio of the minimum melting current at 0.1 second to the minimum melting current at 300 seconds for fuses rated 100 A or less and 600 seconds for fuses rated above 100 A. These values can be obtained from the manufacturer (time-current characteristic curves on the particular ampere rating and type of fuse element).

1.2.4. Power fuse ratings.-Power fuses should be selected on the basis of the following ratings:

1.2.4.1. *Current rating.-The* current rating of a fuse element must be large enough to handle the following normal short-time overloads, energizing, and switching surges under normal operating conditions without operating.

- Short-time daily overloads within the limits recommended by ANSI C57.92, 1962.
- Transformer magnetizing inrush current of 12 times the transformer full-load current for 0.1 second (the inrush current may be as high as 20 to 25 times full-load current for some dry-type transformers).

- Switching surges normally experienced on a utility system.

- Ambient temperature up to 40EC.

1.2.4.2. *Voltage rating.-The* voltage rating of a fuse should be selected as equal to or greater than the nominal system voltage on which it is used.

1.2.4.3. *Interrupting current rating.-De*termine the maximum asymmetrical short-circuit current available on the system at the fuse location. Select a fuse having a current interrupting rating greater than the available short-circuit current.

1.2.4.4. *Frequency rating.-Fifty* or sixty hertz.

1.2.5. Inspection of power fuses.-Inspection of power fuses should be done at intervals that are a function of the conditions at a given fuse location and must be determined by the user (generally 1-year intervals). A summary of special considerations based on ANSI C37.48 for fuse inspection follows:

- Make sure that the fuse is disconnected from all power sources before servicing

- If applicable, clean the insulators and inspect them for breaks, cracks, or burns. The insulators should be clean to avoid flashover as a result of accumulation of foreign substances on insulator surfaces where abnormal conditions exist.

- Check the lock or latch, and check for loss and condition of bolts, nuts, washers, pins, and terminal connectors.

- Inspect contact surfaces for burning, pressure, pitting, and alignment. Badly pitted or burned contacts should be replaced.

- Refinish fuse tubes made of organic (class "A") material as required and specified by the manufacturer.

- Examine the fuse tube, renewable element, and fuse unit for corrosion of the fuse element or connecting conductors, excessive erosion of the inside of fuse tubes, discharge (tracking) and dirt on the outside of the fuse tube, and improper assembly that may prevent proper operation. Replace fuse units or tubes that show signs of deterioration.

1.2.6. Power fuse tests.-Refer to ANSI C37.41 and figure 1 for procedure in fuse tests and test procedure of fuse-mounting equipment. Refer to ANSI C37.46 for performance characteristics of fuse units, refill units, and fuse links for power fuses.

2. MOLDED-CASE CIRCUIT BREAKERS

2.1 GENERAL.-New models of molded-case circuit breakers are available, equipped with such features as adjustable long-time delay elements and solid- state construction. The basic design is an electromechanical-type trip device rated to carry 100 percent of rated continuous current when tested in the open at 25 EC ambient temperature (location in an enclosure requires derating and a thermal trip element having a special 40 EC ambient temperature calibration compensation). The proper application of a molded-case circuit breaker goes beyond consideration of the basic voltage, current, and interrupting rating. Coordination between source and load side protective devices is required. A typical time-current characteristic curve (fig. 2) for a circuit breaker is shown. The units are sealed, and maintenance of the internal mechanism is not possible.

If a molded-case circuit breaker is equipped with time delay and adjustable instantaneous trip element, adjust the instantaneous trip no higher than necessary to avoid nuisance tripping. Make sure that the instantaneous trip settings do not exceed the available short-circuit current at the location of the circuit breaker on the system. The time delay characteristic is generally a thermal element composed of a bimetal strip; however, some manufacturers use a magnetic sensing device with a dashpot for the time delay characteristic.

2.2. MAINTENANCE.-Keep the circuit breakers clean and dry. If a breaker is located in a dirty or dusty atmosphere, frequently remove and blow it out with clean, dry, low-pressure air.

Caution: **DO NOT** blow the dirt into the recesses of the unit.

Check for heating due to poor electrical connections, improper trip unit alignment, or improper mechanical connections within the circuit breaker housing. Abnormal heating is evident by discoloration of terminals, deterioration of molded material, or nuisance tripping. If any of these abnormal heating symptoms exist, locate the cause by making the following checks:

- Check the load current.-The current in each of the individual poles should be less than the circuit breaker rating; if not, all bolted connections and contacts should be examined and tightened to the manufacturer's specifications.

- Check the movement of the trip bar.-Excessive friction or binding of the trip bar will not allow the bimetal to exert sufficient pressure to move the trip bar. The mechanism should be adjusted or lubricated.

- Check the bimetal or dashpot.-A defective bimetal or dashpot could alter the operating characteristics.

- Check the trip coil.-An open turn or terminal could cause failure to trip.

- Foreign matter may be preventing movement of the following breaker parts: trip bar, armature, latch release, trigger, bimetal, bellows or dashpot, or spring assemblies.

The testing procedure of molded-case circuit breakers (IEEE Standard 242-1975, paragraph 15.3.1.) or NEMA publication "Procedures for Verifying Performance of Molded-Case Circuit Breakers" may be used as an alternate guide for testing molded-case circuit breakers.

3. OVERCURRENT RELAYS

Electromagnetic attraction, induction, and solid-state overcurrent relays are usually used for short-circuit protection of low-voltage systems. When a relay operates, it initiates a circuit breaker tripping operation to isolate the fault from the rest of the system. Overcurrent relays with voltage control can distinguish between overload and fault conditions because a short circuit on an electrical system is always followed by a corresponding voltage dip; whereas, an overload causes only a moderate dip.

There are two types of overcurrent relays:

- Instantaneous overcurrent relays operate without intentional time delay.

- Time delay relays to allow transient currents caused by sudden overloads of brief duration. Most overcurrent relays are of this type, with time delay features to allow current several times in excess of the setting for a limited time without closing the contacts. A relay with an inverse time characteristic operates faster as current increases.

PART II-COORDINATION STUDY, CHARACTERISTICS

The objective of a coordination study is to determine the characteristics, ratings, and settings of overcurrent protective devices which will ensure that minimum unfaulted load is interrupted when protective devices isolate a fault or overload anywhere in the system. A coordination study should be conducted in the early planning stages of a new system to tentatively select protection and utilization equipment. In the case where an existing system is modified and new loads are installed, or when existing equipment is replaced with higher rated equipment, a coordination study should be conducted.

The following paragraphs describe briefly the information required for performing a coordination study:

4. ONE-LINE DIAGRAM

Whether the study is on an existing or a new system, obtain or produce a one- line diagram of the system or the portion of the system involved. When plotting time-current coordination curves, certain time intervals must be maintained between curves or various protection devices in order to ensure correct sequential operation of the devices. These protective (time) margins allow for mechanical overtravel, time delays in circuit opening, manufacturer's tolerance, and calibration error.

The diagram should show the following data:

- Apparent power and voltage ratings as well as the impedance ratings and connections of all transformers.
- Normal and emergency switching conditions.
- Nameplate ratings and subtransient reactance of all major motors and generators as well as transient reactances of synchronous motors and generators, plus synchronous reactances of generators.
- Conductor sizes, types, and configurations.
- Current transformer ratios.
- Relay, circuit breaker and fuse ratings, characteristics, and ranges of adjustment.

5. SHORT-CIRCUIT STUDY

Obtain or perform a complete short-circuit study providing momentary and interrupting ratings. The study should also include maximum and minimum expected fault interrupting duties, as well as contributions from each short-circuit current source. Gather time-current characteristic curves for each protective device under consideration.

6. CURRENT SCALE SELECTION

Because the overall objective of the coordination study is to achieve time- sequenced tripping of overcurrent protective devices, such that the device closest to the fault condition trips first, the characteristic curve of the device closest to the load is plotted as far to the left of a 4- by 4-cycle log-log graph as possible so that the source side characteristic curves are not crowded to the right of the paper. The maximum short-circuit current of the system is the right-hand limit of the curves.

7. CHARACTERISTIC CURVES

Plot on the time-current, log-log paper the fixed and continuous points of all electrical devices under consideration. A typical coordination plot for protection of a transformer is shown (fig. 3).

> Note: In the process of plotting the time-current characteristic curves, it must be remembered that all currents must be referred to a common voltage, either primary or secondary, before attempting to determine coordination. On a delta-wye system, the current that the primary fuse sees due to a secondary fault depends on the type of fault, as well as the severity of the fault. Figure 4 shows several unbalanced faults for delta-wye and wye-delta transformers and the current relationships of the windings and line conductors.

- Plot the total symmetrical and asymmetrical short-circuit current available to the power system at the fault point (plot both three-phase and line ground fault-current magnitudes).

- Also plot the full-load current and heating curve of every transformer (from tile transformer manufacturer).

- Plot the short-circuit capability (transformer damage curve) curve. If this curve is not available from the manufacturer, the data in Table 2 below from American Standard C57.12-1968 may be used for oil-cooled transformers. Line currents should be used, otherwise for a delta-wye system a shift of the plot by 0.577 or $1/\sqrt{3}$ is required.

- Plot the transformer inrush current point, which is normally 12 times full- load current at 0.1 second.

- Plot the locked rotor current, acceleration time, and full-load current of large motors.

- Plot the time-current characteristics of all relays, circuit breakers, and fuses.

8. SELECTIVE COORDINATION

The time-current characteristic curves of protective devices should not overlap if selective coordination is to be achieved, nor should the primary device of the transformer trip on inrush. The protective devices must be set to protect cables, motors, and system equipment from over lap as well as short- circuit conditions.

The time intervals shown below must be maintained between the curves of various protection devices to allow for mechanical overtravel, time delays in circuit opening, manufacturer's tolerance, and calibration error:

8.1 RELAYS require a protection margin (with 0.3 to 0.4 second allowed between device curves to ensure noncascading) between device curves of:

- Circuit breaker opening time 0.08 second.

- Circuit breaker overtravel 0.10 second.

- Safety factor 0.12 to 0.22 second.

8.2. FUSES require a protection margin between device curves, which is determined by plotting both total clearing time curve and minimum melting time curve. One essential rule for application of fuse links states that the rnaximum clearing time of the downstream (protecting) link shall not exceed 75 percent of the minimum melt time of the next upstream (protected) link. This principle assures that the protecting link will interrupt and clear the fault before the protected link is damaged in any way. This is usually about 0.1 second.

8.3 LOW-VOLTAGE CIRCUIT BREAKER curves can get close but should not overlap. This lack of a defined time margin is explained by the incorporation of all variables plus the circuit breaker operating times of these devices within a band of the device characteristic curve.

Table 2 - Transformer Winding Short-Circuit Capability

Symmetrical Current in Any Winding	Time Period in Seconds
25 times base current	2
20 times base current	3
16.6 times base current	4
14.3 times base current	5

The base current is from the self-cooled (OA) rating

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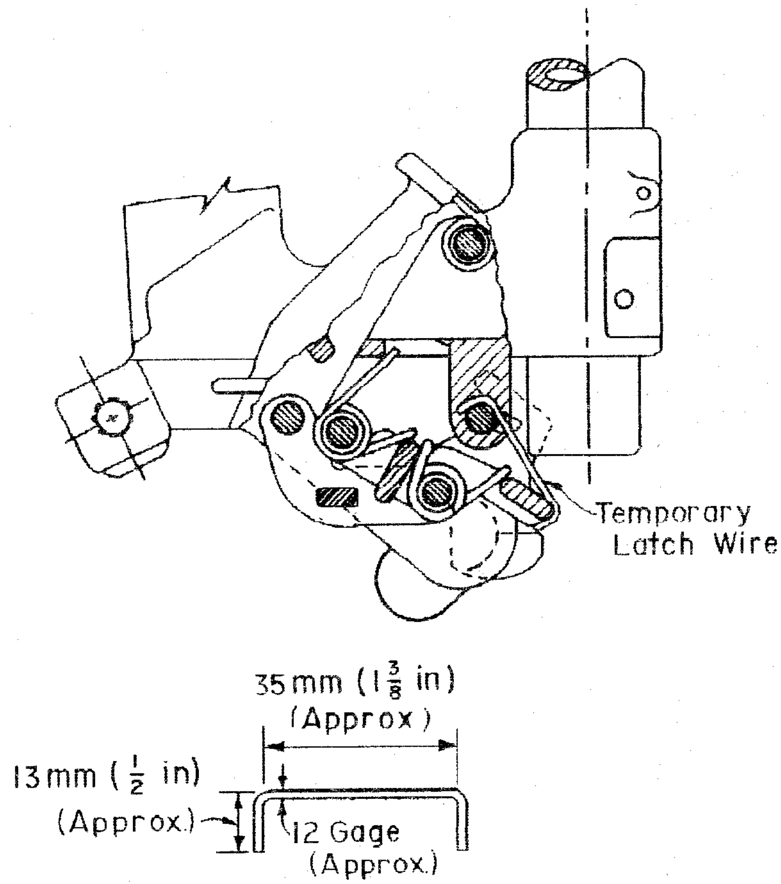

Temporary Latch Wire

1. Remove fuseholder from fuse mounting.
2. Remove fuse link from fuseholder.
3. Make from any convenient wire (approximately No. 12-gage wire) the temporary latch wire as shown.
4. Close hinge-end assembly by placing latch casting over latch pin.
5. Place temporary latch wire over latch pin and link erector casting in the manner shown in the sketch.
6. Replace holder in fuse mounting and close into jaw.
7. By convenient means, remove temporary latch wire. Holder should drop out, if this does not occur, then check all adjustments for improper adjustment. Repeat test after adjustments.
8. Replace fuse link in fuseholder and return to service.

Figure 1 - Power fuse dropout test instructions

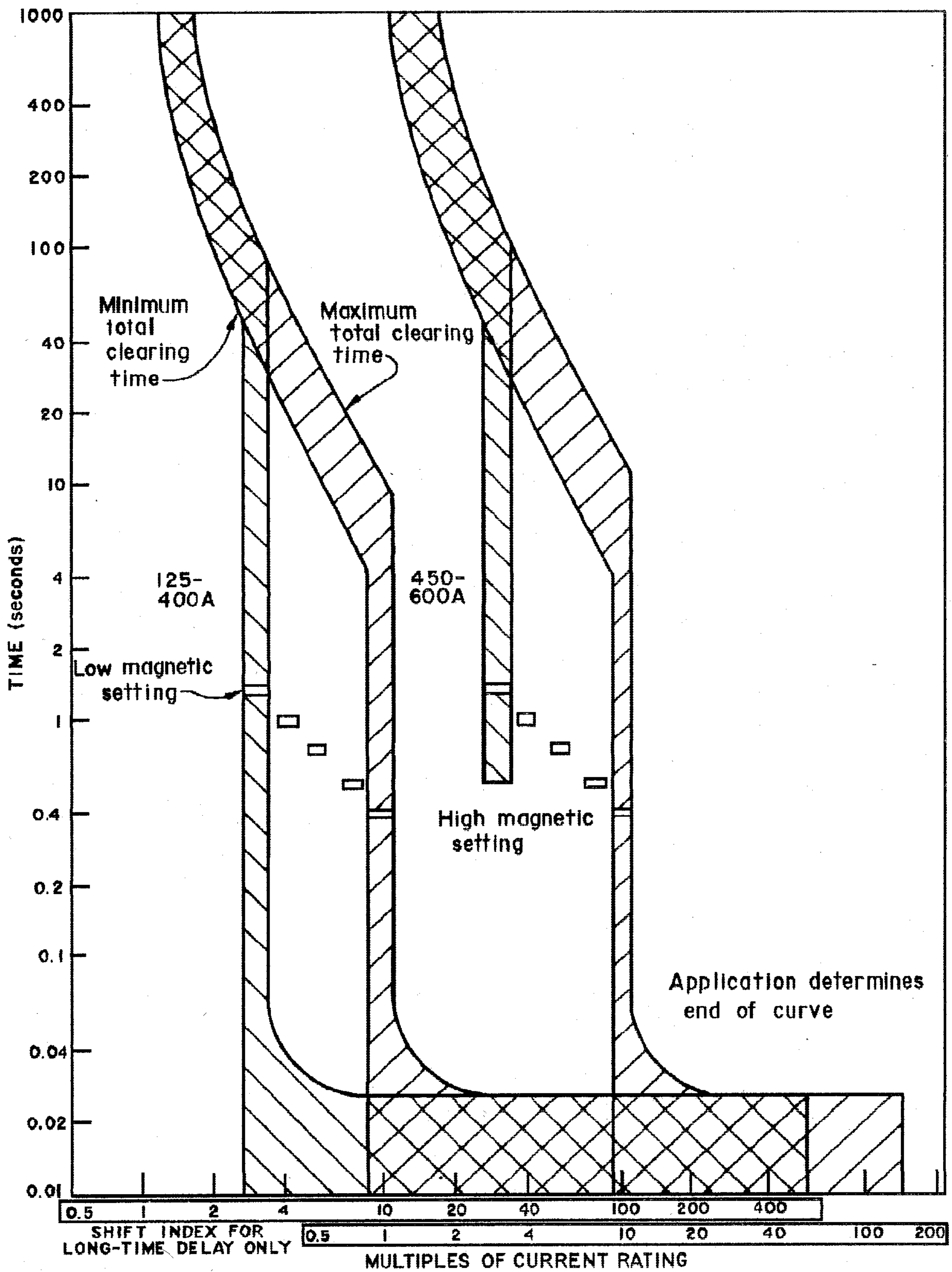

Figure 2. - Typical time-current curves of a 600-A framesize, molded case circuit breaker

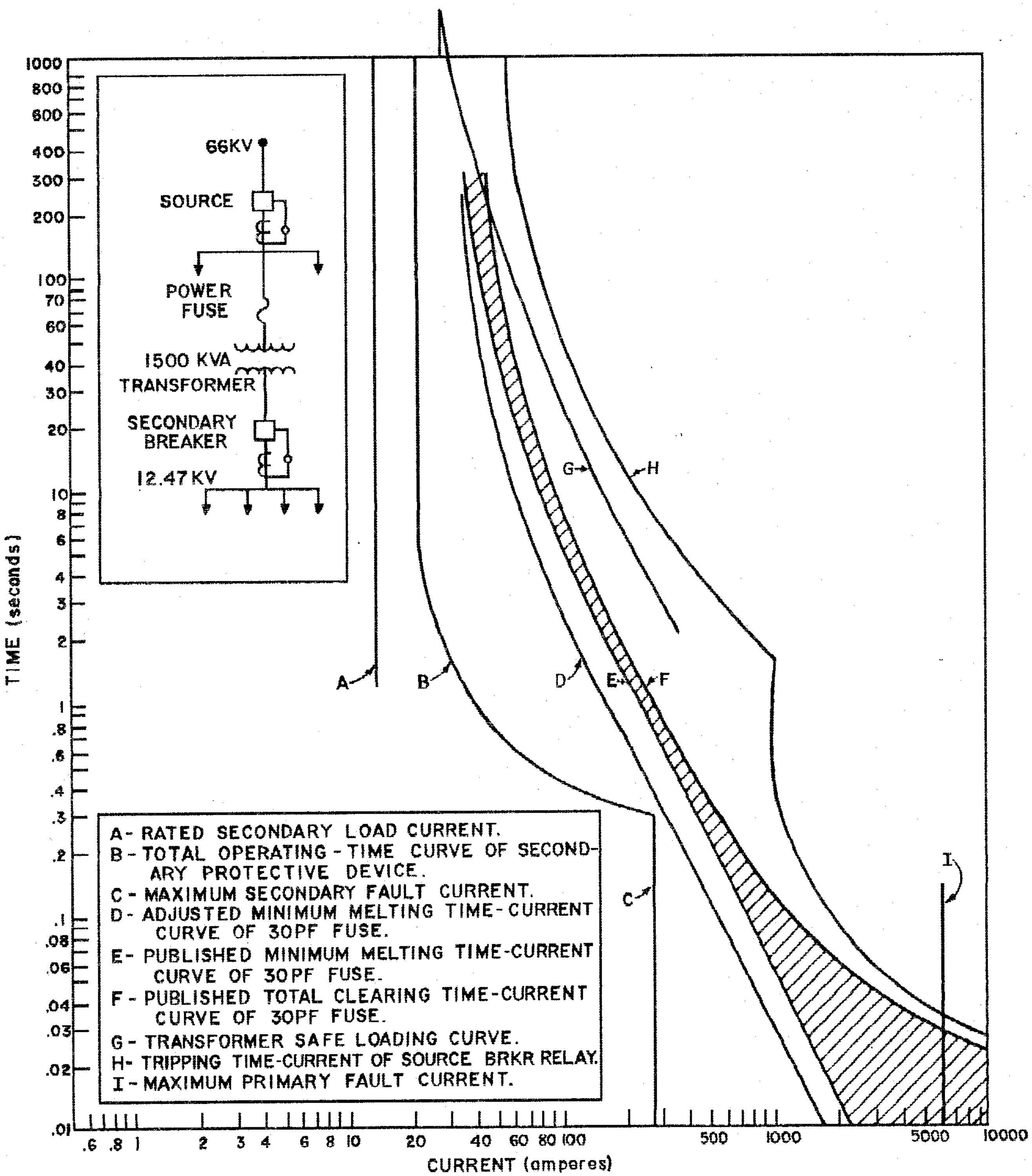

Figure 3. - typical coordination of transformers, fuses, relays, and breakers. (All currents referred to the transformer primary.)

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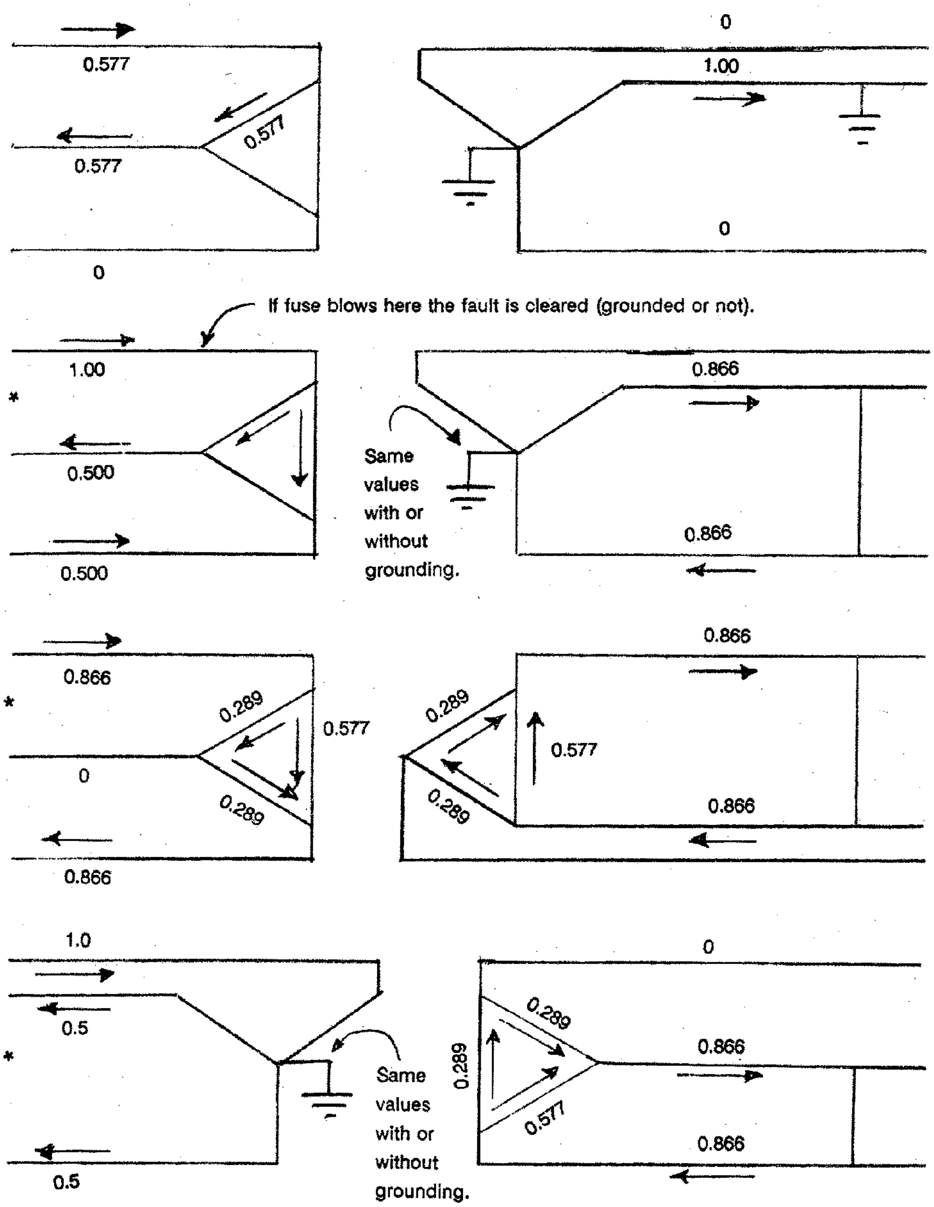
CHKD BY J.E.S.	DATE	FEATURE	
DETAILS	The material shown in these shetches for delta wye transformer faults was prepared by John Grimm and John Skuderna of the Electrical Branch, Chief Engineer's Office.		

FAULT CURRENTS IN PER UNIT OF 3-PHASE-FAULT CURRENTS FOR VARIOUS FAULTS AND TRANSFORMER CONNECTIONS. (Only magnitudes are shown.)

All currents are correct if $Z_1 = Z_2 = Z_0$
*Cases Marked with asterisk do not involve Z_0 and are thus correct regardless of the value of Z_0.
Transformer voltage ratio (LL) is taken as unity.

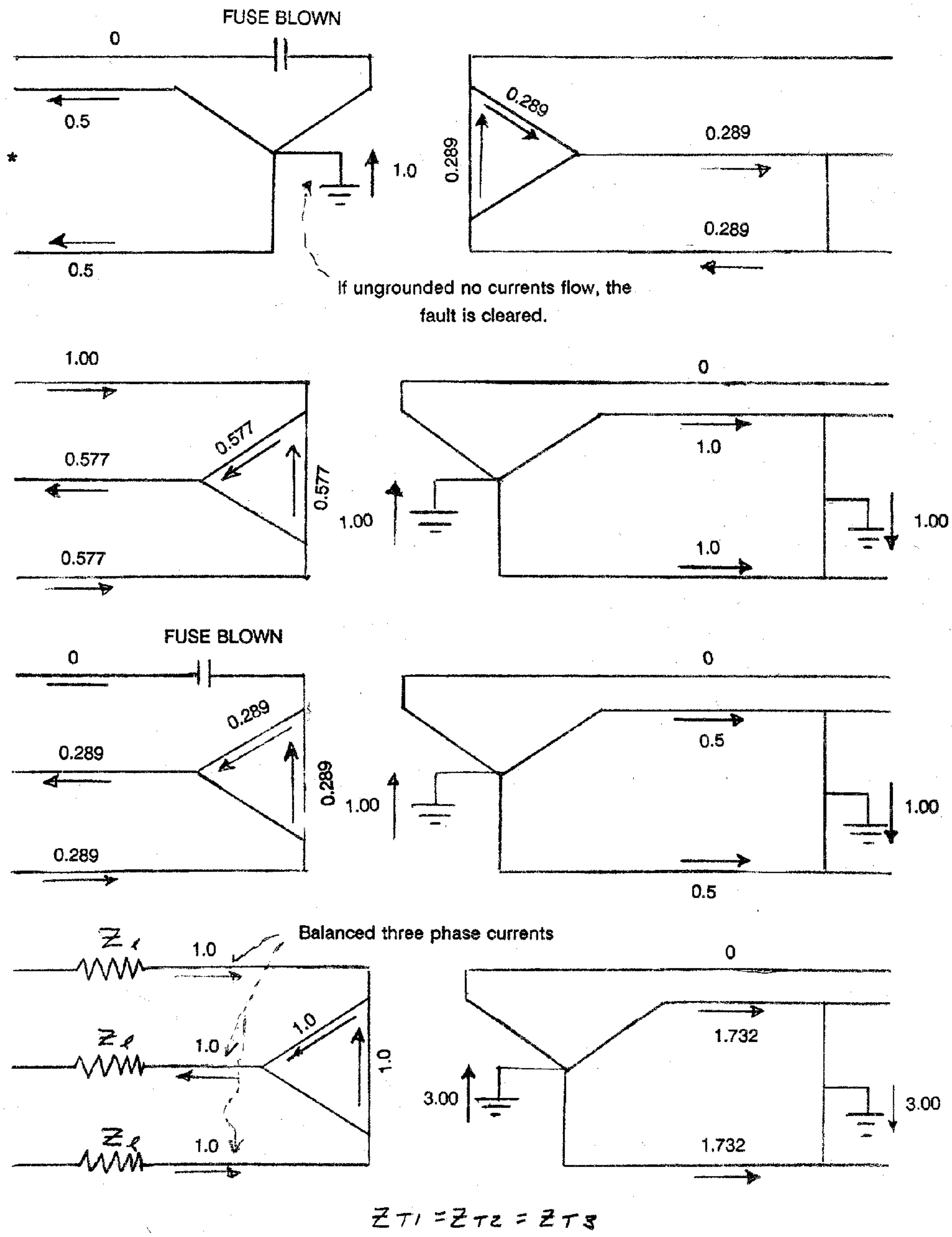


COMPUTATION SHEET

7-1654 (7-73)
Bureau of Reclamation

BY J.O.G.	DATE 12/15/53	PROJECT	SHEET 2 OF
CHKD BY J.E.S.	DATE	FEATURE	
DETAILS			

FAULT CURRENTS IN PER UNIT OF 3-PHASE-FAULT CURRENTS FOR VARIOUS FAULTS AND TRANSFORMER CONNECTIONS. (Continued)



For this case the fault appears exactly like a 3 phase fault when seen from the far end of the line.