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FUSE SAVING VS. TRIP SAVING

Seung Cho

Snohomish County Public Utility District
System Planning & Protection
Everett, Washington

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INTRODUCTION

In distribution feeder overcurrent protection, the fuse saving scheme has been used by a majority of electric utilities for decades. Basically, this scheme prevents fuses from blowing on temporary faults by employing a sequence of at least one instantaneous trip, automatic reclosing, and at least one time-delayed trip at the feeder breaker. On the other hand, the trip saving scheme uses no instantaneous trip at all such that feeder breakers will trip only on main trunk faults. Some of main advantages the fuse saving scheme offers are:

- Minimizes unnecessary fuse replacement (materials and labor).
- Reduces customer outage minutes and revenue loss.
- Minimizes line apparatus damages.

The fuse saving scheme may momentarily de-energize an entire feeder for a fault on a branch circuit, so all customers served off the same feeder may experience electronic clock blinking or similar symptoms. For this very reason, the fuse saving scheme has been challenged by irate customers, power quality engineers, and upper management. This paper presents pros and cons of both schemes with technical details for system protection & control engineers and also emphasizes the importance of instantaneous tripping to minimize problems associated with undercurrent, overcurrent, undervoltage, and overvoltage. The following simplified three-line distribution circuit diagram in Fig. 1 illustrates certain power quality problems.

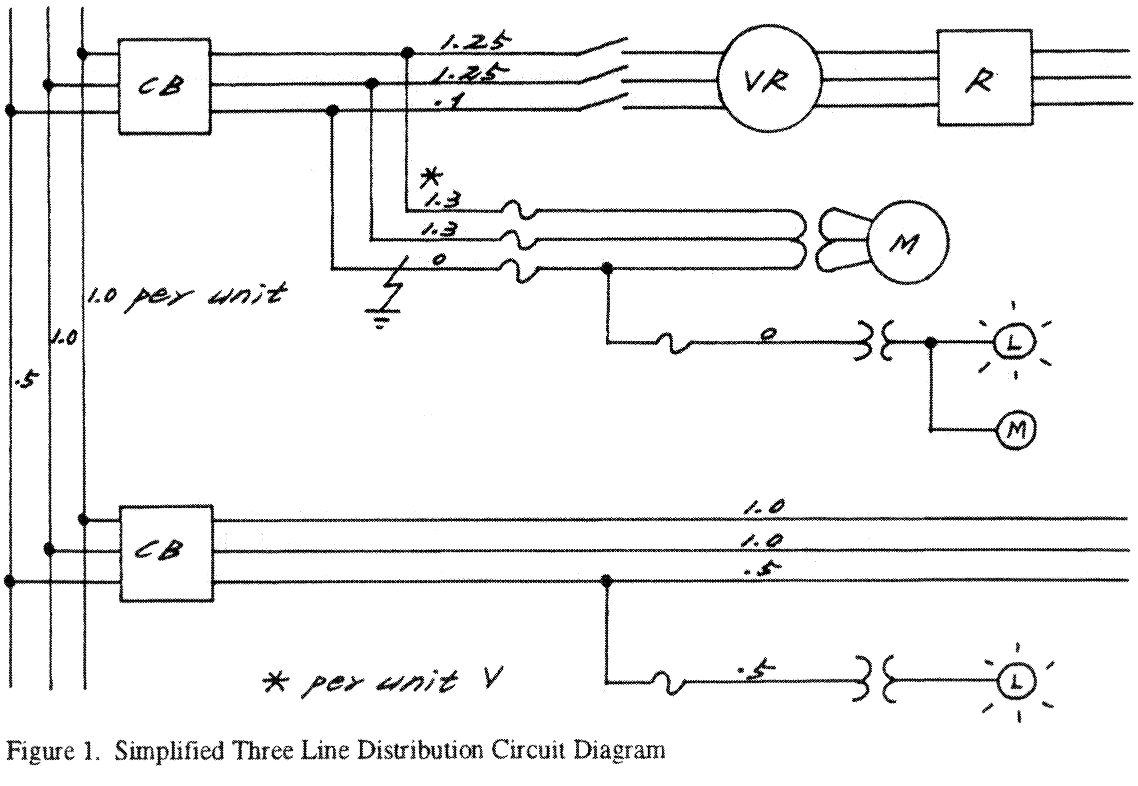

Figure 1. Simplified Three Line Distribution Circuit Diagram

ELECTRIC UTILITIES' DISTRIBUTION PROTECTION PRACTICES

To consider converting the existing fuse saving scheme to the new trip saving scheme, one must understand the existing distribution protection practices in one's distribution system. It may be politically important to know industry standards (or practices) and neighboring electric utilities' practices. This section is intended as a review of existing distribution protection practices and also potential issues with the trip saving scheme.

IEEE Industry Survey Results

The term instantaneous indicates that no delay is purposely introduced in the operation. Per the latest IEEE Distribution Line Protection Practices – Industry Survey Results, 86 of the 95 respondents (91%) apply overcurrent protection devices with the instantaneous trip for the purpose of "fuse saving." Of the 86 utilities that used the instantaneous trip for the purpose of "fuse saving," only eight utilities reported that they had data on how successful their "fuse saving" has been. Of these eight utilities, only five utilities reported actual percentages of their success. These percentages are: 30%, 50%, 55%, 83.5%, and 90%.

Snohomish County PUD's and Northwest Utilities' Practices

The following is a summary of Snohomish County PUD's (Snohomish PUD hereafter) and some neighboring northwest utilities' distribution protection practices:

- As of May 1995, a total of 54 feeder breakers (out of approximately 280 feeders in the Snohomish PUD service area) did not employ instantaneous tripping at all because of major shopping malls, hospitals, major industrial processing facilities, major commercial customers, long underground cable sections, sewer lift stations, downstream reclosers, and/or power quality complaints.

- As of May 1995, a total of 45 feeder breakers in the Snohomish PUD service area had high-set instantaneous trip because of downstream reclosers (reasons given later). Practically speaking, there is no fuse saving for a feeder with the high-set instantaneous trip, but some fuse saving may be realized for all branch circuits protected by reclosers.

- The Snohomish PUD's distribution feeder protection is designed to protect upstream substation power transformers against high through-fault currents, downstream conductors and cables, downstream disconnect switches, and downstream voltage regulators. The same overcurrent protection is typically designed not to operate on cold loads. It is also designed to coordinate with load tap changers (LTC), voltage regulators, switched capacitor banks, and automatic transfer switches. Therefore, removal of the instantaneous trip may require a complete review of coordinating time intervals between protective devices and also an increase of delay times on LTCs, voltage regulators, switched capacitor banks, and automatic transfer switches.

- Currently, no instantaneous reclosing is allowed in the Snohomish PUD service area. However, there are many utilities employing instantaneous reclosing for distribution protection. For those utilities, removal of the instantaneous trip may require removal of instantaneous reclosing (or may require installation of time-delayed reclosing).

- The instantaneous trip (or fuse saving scheme) has been applied selectively on a case-by-case basis to less than 65% of all feeder breakers in the Snohomish PUD service area. A typical ground instantaneous relay pickup is 600 A primary and a typical phase instantaneous relay pickup is 1200 A primary.

- Only one major utility in the northwest area applies overcurrent protection devices without the instantaneous trip, that is, they use the trip saving scheme.

Switching and Clearance Procedures

As mentioned above, Snohomish PUD applies the high-set instantaneous trip to feeder breakers for feeders with at least one downstream recloser. For the high-set instantaneous trip, the instantaneous relay pickup is set high enough not to reach the downstream recloser. This is necessary to comply with the Snohomish PUD Safe Clearance Procedures allowing only one non-reclose tag per one hot line work and also to prevent both a substation feeder breaker and a downstream recloser from locking out for an accidental fault beyond the recloser during hot line work beyond the same relcoser. Therefore, installation of downstream reclosers will require modification of the fuse saving scheme.

The major northwest utility (mentioned previously) applying overcurrent protection devices without the instantaneous trip for normal operation does place the instantaneous trip in service during the hot line work. One instantaneous bypass switch per each feeder breaker is installed and it is typically used to bypass the instantaneous trip during the normal operation.

In general, all protective devices are not installed to protect human beings, but installed to protect major apparatus. However, line construction workers want the instantaneous trip in service during the hot line work because they believe that the instantaneous trip may minimize bodily injuries. The resistance of a 150-lb man is estimated to be 500 – 1000 ohms, excluding skin resistance. Therefore, no sizable fault current can flow through a human body until actual liquid/solid breakdown (basically, arcing through a human body) occurs. Once actual arcing through a human body occurs, the fault current level may be high enough for the instantaneous relay to operate.

Per the latest ANSI/IEEE Std. 80, IEEE Guide for Safety in AC Substation Grounding, one important incentive to use the instantaneous trip (fault clearing times less than 0.5 second) results from the research done by Biegelmeier and Lee. Their research provides some evidence that a human heart becomes increasingly susceptible to ventricular fibrillation when the time of exposure to current approaches the heartbeat period, but that the danger is much smaller if the time of exposure to current is in the region of 0.06 – 0.3 second.

ELECTRIC UTILITIES' SUBSTATION GROUNDING PRACTICES

It is customary to have 0.5 ohm or less grounding impedance for switching stations and to have 1 ohm or less grounding impedance for distribution substations. At some Snohomish PUD distribution substations the power transformer secondary neutral is grounded through a 0.5 ohm neutral reactor to reduce the maximum calculated single-line-to-ground fault current level to below the standard open cutout interrupting rating of 7,100 A symmetrical.

Both the maximum allowable touch potential and the maximum allowable step potential are proportional to one over the square of shock current duration in seconds. They are also proportional to the grounding impedance. Therefore, it is very important for electric utilities to ensure small grounding impedance at all times and also fast breaker operation (requiring the instantaneous trip in service) for all ground faults.

To reduce substation construction costs, some substation design engineers assume that there will be instantaneous trip available at all times. With the instantaneous trip available at all times, design engineers may be able to build an inexpensive groundmat complying with the allowable step & touch potential requirements. Therefore, removal of instantaneous trip operation may require upgrading the existing groundmat.

MAJOR APPARATUS DAMAGE CHARACTERISTICS

It is very important for system protection & control engineers to understand damage characteristics of major apparatus because removal of the instantaneous trip will appreciably lengthen major apparatus' exposure to high fault currents. As mentioned previously, the Snohomish PUD's feeder protection is designed to protect certain major apparatus such as upstream power transformers against high through-fault currents, downstream main trunk conductors and cables, downstream disconnect switches and downstream voltage regulators. Some of major apparatus damage characteristics are:

- Per the latest ANSI/IEEE Std. C57.15, Requirements, Terminology, and Test Code for Step-Voltage and Induction-Voltage Regulators, liquid-filled regulators shall be designed and constructed to withstand the mechanical and thermal stresses produced by external short circuits of 25 times the base rms symmetrical current for 2 seconds. Single-phase regulators rated 500 kVA and below shall be capable of withstanding rms symmetrical short circuit current of 40 times the base current rating or 20,000 A, whichever is less for 0.8 second without injury.

- For liquid-filled distribution and power transformers, damage characteristics are shown in the latest ANSI/IEEE Std. C57.109, IEEE Guide for Transformer Through-Fault-Current Duration.

- Per the latest ANSI/IEEE Std. C37.30, American National Standard Definitions and Requirements for High-Voltage Air Switches, Insulators, and Bus Supports, the rated momentary current of an air switch is the rms total current which the switch shall be required to carry for at least one cycle and the rated 3-second current of an air switch is the rms total current, including the direct current component, if present, which the switch shall be required to carry for 3 seconds. The 3-second rating of popular distribution pole-top disconnect switches in the Snohomish PUD distribution system is 25,000 A symmetrical and the momentary rating is 40,000 A asymmetrical.

In general, damage (or reduction of apparatus life) is proportional to I^2t. Therefore, the protection without the instantaneous trip will reduce the life of protected downstream apparatus such as voltage regulators and disconnect switches, and also reduce the life of upstream apparatus such as power transformers.

MAJOR APPARATUS OPERATING LIMITS

In the past, the phase voltages during faults generally were not of too much practical use in protection. However, increasing use of sensitive electronic devices is forcing system protection & control engineers and power quality engineers to pay more attention to phase voltages. For single-line-to-ground faults, the faulted phase line-to-neutral voltage is very small, but the unfaulted phase line-to-neutral voltages may reach 1.35 per unit and this overvoltage may last several seconds especially without the instantaneous trip. In general, the 1.35 per unit overvoltage may not damage any apparatus instantaneously, but it may create a variety of undesirable problems such as mechanical vibration, magnetic saturation, sensitive electronic device lock-up, etc. Therefore, it is extremely important for system protection & control engineers and power quality engineers to thoroughly understand all major apparatus operating limits. Operating limits of some major apparatus are:

- Per the latest ANSI/IEEE Std. C57.15, IEEE Standard Requirements, Terminology, and Test Code for Step-Voltage and Induction-Voltage Regulators, regulators including their controls shall be suitable for operation within the following limits of voltage provided that the rated load current is not exceeded:

  - A minimum input voltage of 97.75 V times the ratio of voltage transformer
  - A maximum input voltage at the rated load A of 1.05 times the rated input voltage of the regulator or 137.5 V times the ratio of voltage transformer, whichever is less
  - A maximum input voltage at no load of 1.1 times the rated input voltage of the regulator or 137.5 V times the ratio of voltage transformer, whichever is less
  - A minimum output voltage of 103.5 V times the ratio of voltage transformer
  - A maximum output voltage of 1.1 times the rated voltage of the regulator or 137.5 V times the ratio of voltage transformer whichever is less.

- Per the latest ANSI/IEEE Std. C57.12, IEEE General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers, transformers shall be capable of operating continuously above the rated voltage or below the rated frequency, at maximum rated kilovoltamperes for any tap, without exceeding limits of observable temperature rise in accordance with 5.11.1 when all of the following conditions prevail:

    - Secondary voltage and volts per hertz do not exceed 105% of rated values.
    - Load power factor is 80% or higher.
    - Frequency is at least 95% of rated value.

  Transformers shall be capable of operating continuously above the rated voltage or below the rated frequency on any tap at no load, without exceeding limits of observable temperature rise in accordance with 5.11.1 when neither the voltage nor volts per hertz exceed 110% of rated values. The generalized short term overexcitation limit characteristic based on three manufacturers' curves (shown in the latest IEEE Std. C37.91, IEEE Guide for Protective Relay Applications to Power Transformers) is illustrated in Fig. 2.

- Per the latest ANSI Std. C50.41, motors shall be capable of momentary operation (for up to 60 seconds) under running conditions at the rated load and frequency with a minimum of 75% of the rated voltage at the motor terminals. Per the latest NEMA Std. MG-1, induction motors shall operate successfully under running conditions at the rated load with a variation in voltage plus or minus 10% of the rated voltage at the rated frequency.

- The maximum continuous operating voltage (commonly known as MCOV) rating of metal oxide varistor arresters is typically 0.84 times the arrester rating and the temporary overvoltage capability of one manufacturer's MOV gapless arresters is illustrated in Fig. 3.

- The voltage dip tolerance of ballasts is defined as the ability of a ballast to operate a lamp during sudden voltage drops caused when other loads such as motors, compressors, induction furnaces, arc welders, etc., are switched on line. If the ballast is not capable of riding through the voltage dip and sustaining the lamp, the lamp will extinguish and recycle. The voltage dip tolerance characteristics of three different ballast types are illustrated in Fig. 4.

- Fig. 5 illustrates life expectancy (or effect of operating a lamp at other than its rated voltage) of general service gas-filled incandescent lamps.

- The generalized voltage sag ride-through capability (Computer & Business Equipment Manufacturers' Association (CBEMA) curve) of electronic devices is illustrated in Fig. 6.

- Voltage sag ride-through capability examples (taken from EPRI BR-105763, Impact of Voltage Sags on Customer Loads, and EPRI TR-101140, Adjustable Speed Drives: Applications Guide) of several electronic controllers are illustrated in Fig. 7.

Unfaulted Phase Line-to-Neutral Voltage and Line-to-Ground Voltage

For single-line-to-ground faults, unfaulted phase line-to-ground voltages at the fault point can be as high as 1.732 per unit and unfaulted phase line-to-neutral voltages at the fault point can be greater than 1.0 per unit, realistically up to 1.35 per unit. This high line-to-neutral voltage will occur when the zero sequence impedance to the fault is greater than the positive sequence impedance. Using reactance values only with $X_1 = X_2$ and letting $X_0 = KX_1$, it can be shown that (taken from J. Lewis Blackburn, Symmetrical Components for Power Systems Engineering)

$$V_{unfaulted\ \phi} = \frac{\sqrt{3}\,K\angle -150^\circ - j\sqrt{3}}{K + 2}$$

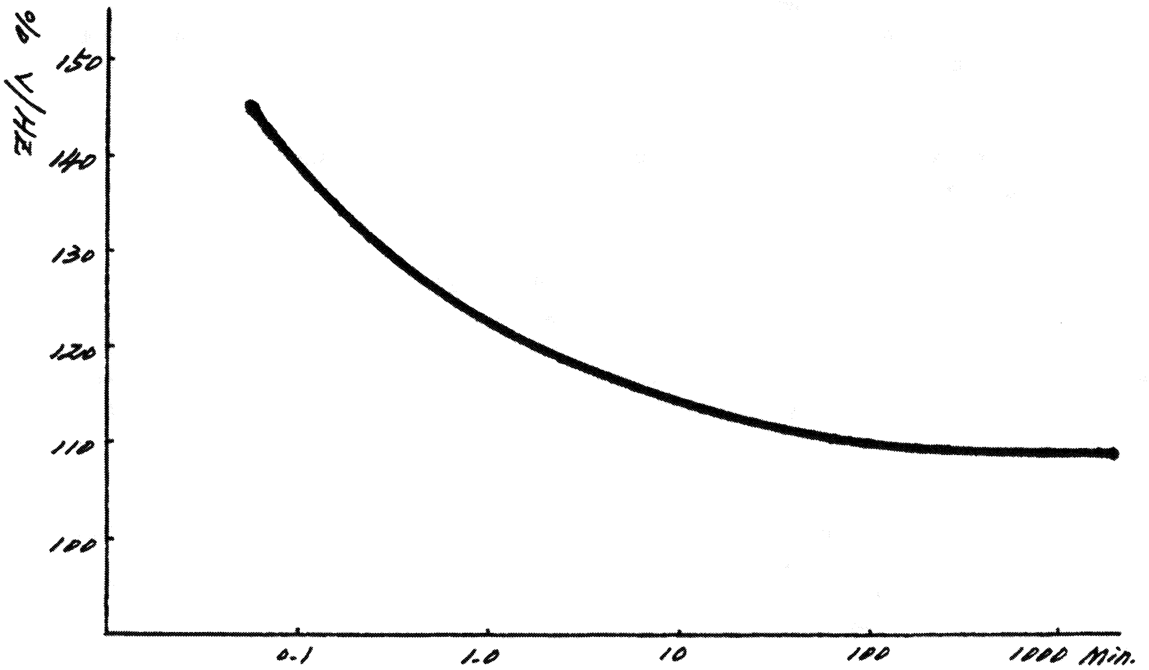

Figure 2. Generalized Short Term Overexcitation Characteristic of Transformers

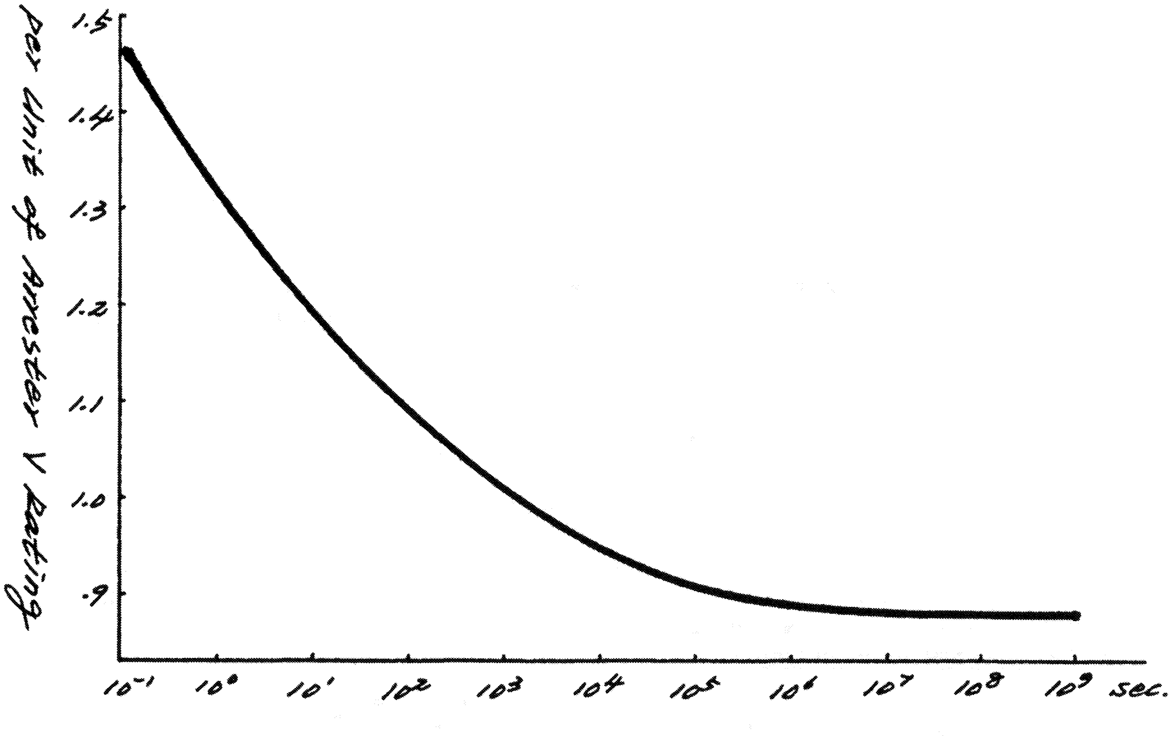

Figure 3. Temporary Overvoltage Capability of Metal Oxide Gapless Arresters

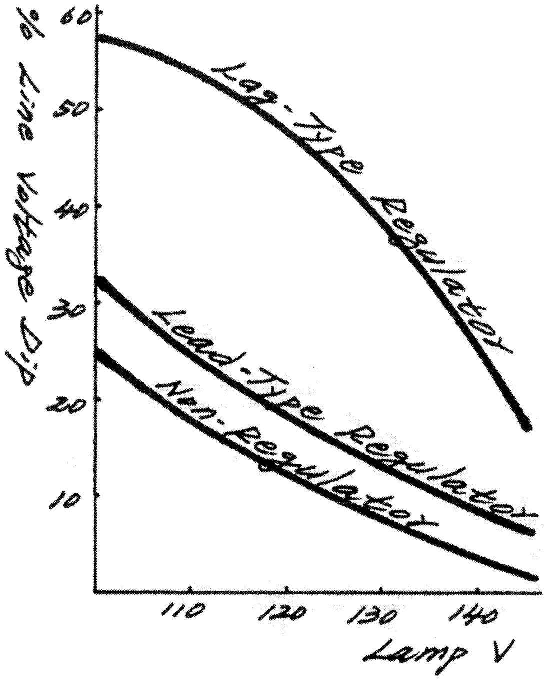

Figure 4. Voltage Dip Tolerances

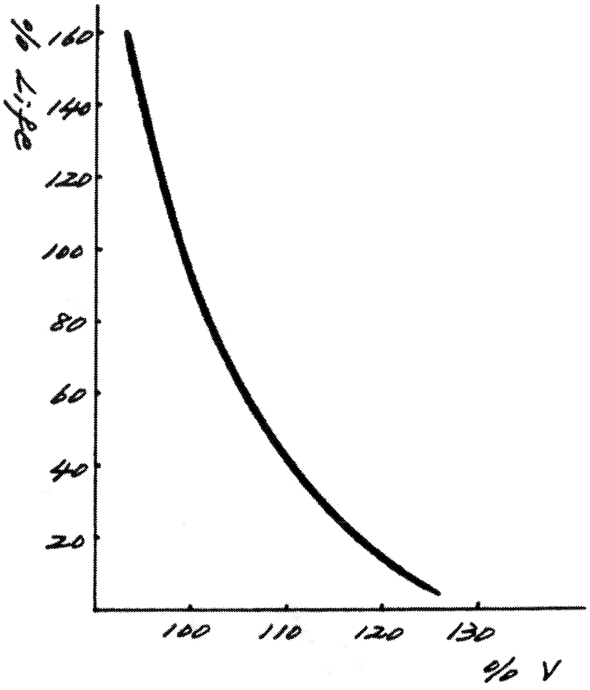

Figure 5. Incandescent Light Bulb Life

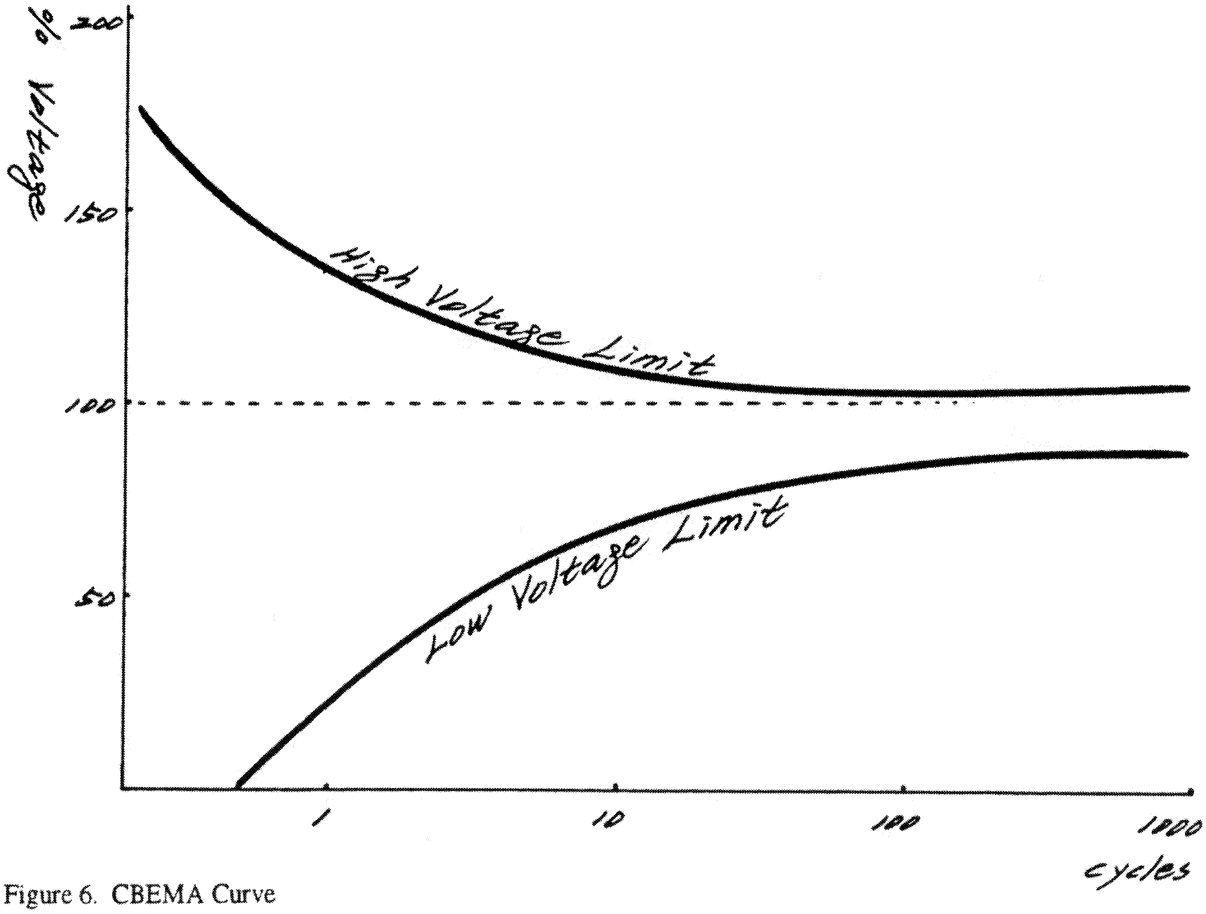

Figure 6. CBEMA Curve

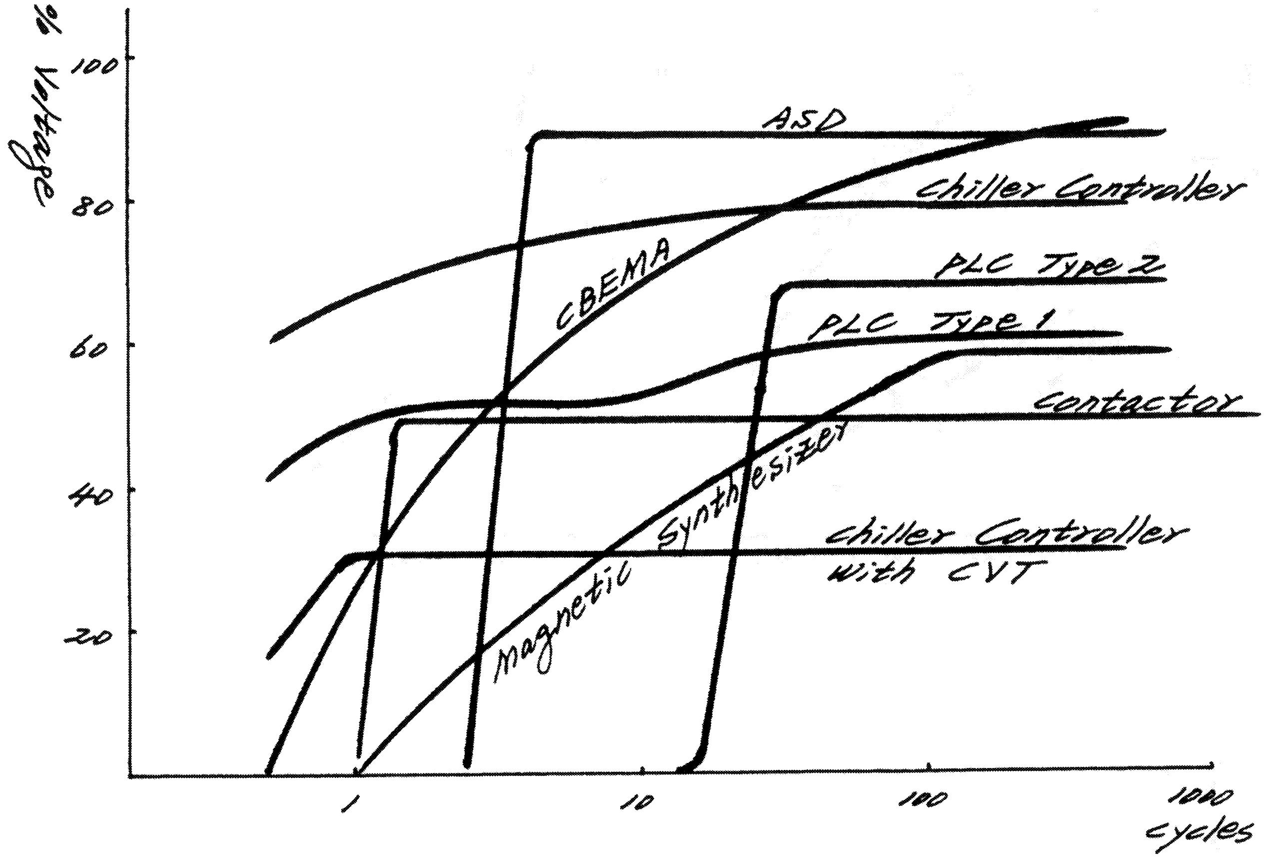

Figure 7. Voltage Sag Ride-Through Characteristics of Various Controllers

FUSE CHARACTERISTICS

To evaluate performance of the fuse saving scheme accurately, it is very important to understand fuse characteristics thoroughly because small fuse sizes may not render any fuse saving at all. This section is intended as a review of fuse characteristics and some information is taken directly from the Cooper Power Systems Fusing Manual.

To develop a set of fuse time current characteristic (TCC) curves (see Fig. 8), a fuse is tested at different levels to establish the average melting time and the arcing time at those current levels. From the test results, a minimum melting TCC and a total clearing TCC are developed. The average melting times from testing results are plotted as an average melting curve. 10% is subtracted on the current axis to define the published minimum melting TCC. 10% is added to the average melting curve on the current axis to establish a maximum melting curve. The arcing times from testing are added to the maximum melting curve on the time axis to define the published total clear TCC.

Tests have shown that fuses can be damaged when currents are high enough to approach the minimum melt time of the fuse TCC. This pre-damage may change the fuse characteristic significantly such that in the next fault occurrence the fuse performance would not be predicted accurately by the TCCs. This pre-damage can occur with both tin and silver fuses. Tests have shown that the pre-damage can occur for currents that exist for times exceeding:

- 90% of the minimum melt time of tin fuses
- 95% of the minimum melt time of silver fuses.

Fuse melting and clearing characteristics are developed by standards on the basis of no pre-loading. The flow of current through the fuse prior to fault initiation will raise the fuse's temperature and, therefore, reduce the melting time. This, again, is a difficult characteristic to evaluate since the ratio of pre-loading of protected fuse to protecting fuse will vary for most situations. The most conservative situation is probably to consider 0% pre-loading at the protecting fuse and some level of pre-loading (50 – 100% of rating) for the protected fuse.

Various factors (tolerances of TCCs, ambient temperature, pre-loading and pre-damage) could be considered separately, but this would require an in-depth study each time fuses were coordinated. As a rule of thumb, adequate coordination is accomplished by assuring that the maximum clearing time of the protecting fuse to be no greater than a certain percentage (normally 75%) of the minimum melting time of the protected fuse. This 75% curve is sometimes called "fuse damage characteristic."

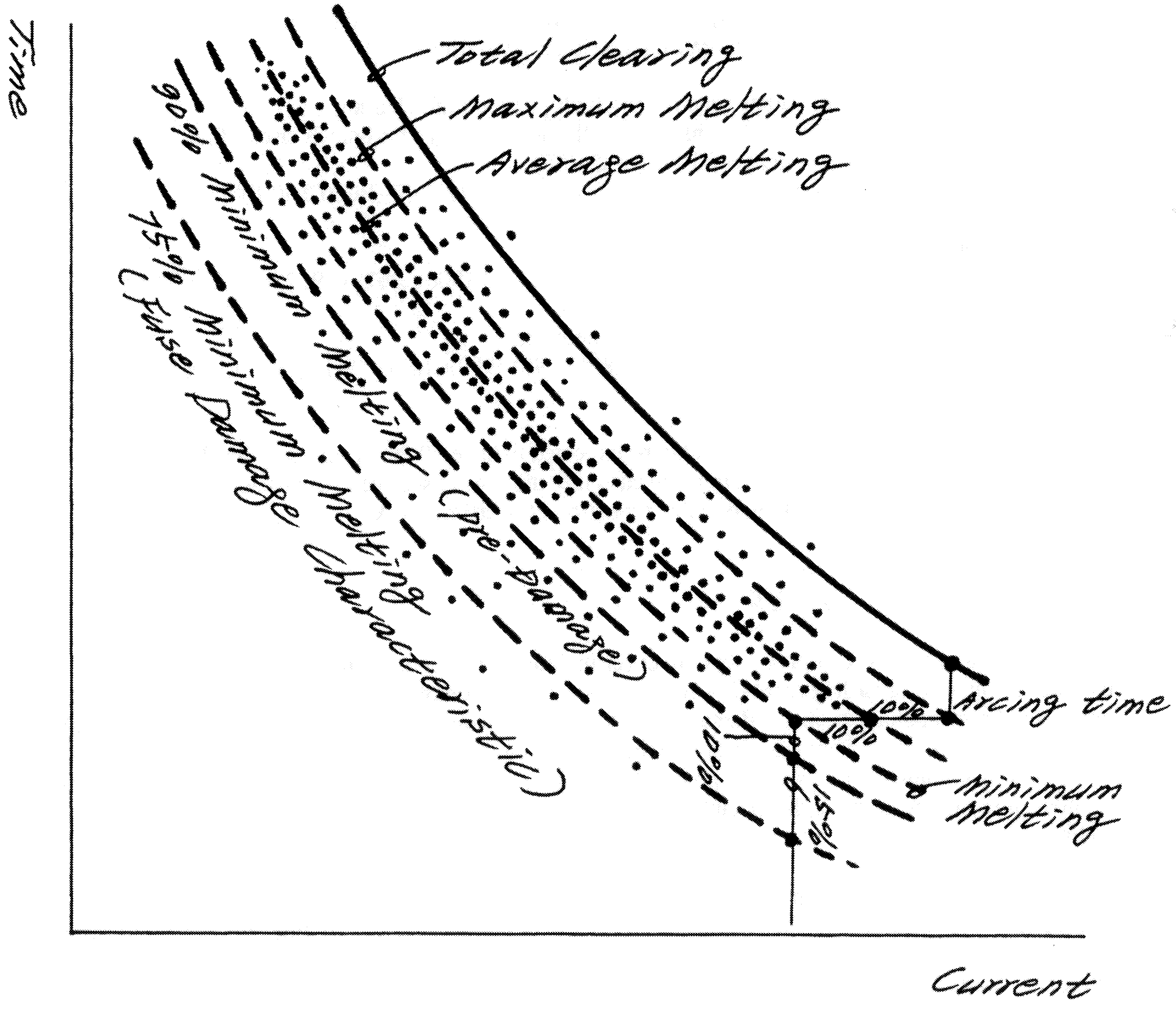

Figure 8. Minimum Melting TCC and Total Clearing TCC

SYSTEM AVERAGE INTERRUPTION DURATION INDEX (SAIDI)

SAIDI is an indicator of electric system reliability, also referred to as system downtime. It is calculated by dividing the total customer minutes of outage time by the number of customers served. Many utilities spend millions of dollars annually to reduce customer outage minutes. The following analysis by using relatively realistic numbers is done to demonstrate how the fuse saving scheme can contribute to outage-minute reduction:

# of customers on the circuit (C) = 900
# of customers/lateral subject to fuse saving (CL) = 90
(Fuse sizes subject to fuse saving: 40, 50, 65, 80 and 100. 65 A was used here.)
Ratio of permanent faults to total faults (P) = .286
(based on the SCADA alarm and event summary from 1/1/1996 to 12/31/96)
Ratio of fault exposure of feeder with only breaker protection to total circuit fault exposure (F) = .1 (estimated)
Anticipated time from start of outage to restoration for permanent faults cleared by a blown fuse (PF) = 90 minutes (estimated)
Ratio of total # of faults to single-line-to-ground faults (RC) = 1.25 (estimated)
Anticipated time for restoration for temporary faults when a breaker clears the fault (TF) = .167 minutes (based on a typical reclosing relay setting)

Expected customer minutes of outage time for any fault prior to fault clearing
= (Expected outage for main trunk fault) + (Expected outage for branch circuit fault)
Expected outage for main trunk fault = 2(F)(1-P)(C)(PF)
Expected outage for branch circuit fault = (1-F)(1-P)(C)(TF) + (1-F)(P)(RC)(CL)(PF)

Expected customer outage minutes with instantaneous trip
= 2(.1)(.714)(900)(.167) + .1(.286)(900)(90) + .9(.714)(900)(.167) + .9(.286)(1.25)(90)(90)
= 5,040 minutes/feeder/fault
Expected customer outage minutes without instantaneous trip
= 2(.1)(.714)(900)(.167) + .1(.286)(900)(90) + .9(0)(900)(.167) + .9(1.0)(1.25)(90)(90)
=11,451 minutes/feeder/fault

If the circuit in this example could reasonably be expected to have 10 faults per year, then having the instantaneous trip would result in 64,110 more customer minutes of service to the customers, not to mention the revenue increase and the possible reduction of overtime work.

POWER QUALITY ISSUES

Power quality alone is too complex a topic to cover in detail here. Electric utilities receive numerous customer complaints regarding short (5 – 10 seconds) outages, blinking electronic clocks, surge-caused damages to home appliances, motor damages due to single phasing, popped incandescent lamps, processing facility shut-downs, etc. Electric utilities also receive numerous damage claims ranging $50 to $250,000. This section is not intended to cover all power quality issues. However, it is important to understand that the often suggested removal of the instantaneous trip does not guarantee "no more blinking electronic clocks."

A single-line-to-ground fault can create electrical problems such as undercurrent, overcurrent, undervoltage, overvoltage, and single phasing. It is especially important to recognize that overvoltages at or beyond the fault point on unfaulted phases may also cause sensitive electronic device lock-ups and damages to home appliances. With the instantaneous trip, customers off unfaulted feeders may experience light dimming due to undervoltage for typically less than a half second and also experience electronic clock blinking. Without the instantaneous trip, customers off unfaulted feeders may also experience light dimming for several seconds or longer and electronic clock blinking.

CONCLUSION

Throughout this paper some pros and cons of both the fuse saving scheme and the trip saving scheme were presented, especially pros of the fuse saving scheme. In addition to customer outage minute (SAIDI) reduction, a major emphasis was made on the importance of fast tripping, which supports the fuse saving scheme. The author also recognizes that the best engineering decision may not be the best decision. Nonetheless, Snohomish PUD continues to employ the fuse saving scheme based on our understanding of engineering issues, political issues, economic issues, and sound engineering practices.

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