Power Quality and Protective Device Coordination:
Problems & Solutions Part 2
“High Inrush Currents for Dry Type Transformers”

by Robert E. Fuhr, P.E.

INTRODUCTION

The use of electronic equipment has dramatically increased during the last 20 years. Some of these electronic devices include variable speed drives, programmable controllers, computers, and even solid state protective relays. Electronic equipment is much more sensitive to power quality. A lot of attention has been given to power quality in the last several years. Most of this focus has been on harmonics, power sags, and surges.

One important aspect of power quality that is extremely important is Protective Device Coordination. Protective Device Coordination Studies determine settings for circuit breakers and relays. These studies also verify the correct fuse size and determine the protection required for conductors, transformers, and other equipment. The goal of this study is to determine settings which would reduce damage to equipment and to isolate only the circuit that has a short circuit or fault. This causes the least amount of disturbance to the remainder of the distribution system.

POWER QUALITY AND PROTECTIVE DEVICE COORDINATION: PROBLEMS & SOLUTIONS Part 1 & Part 2 will focus on two unique problems that are affecting power system protection, owners, and design engineers. These two problems are:

- Part 1 - Under-sizing of utility main service transformers for buildings, plants, and facilities.
- Part 2 - High inrush currents on low temperature or K-Rated transformers.

Under-sizing of utility main service transformers for buildings, plants, and facilities (Part 1) was discussed in a previous publication. This article (Part 2) of this article deals with unexpected high inrush currents from low temperature and K-rated transformers. The inrush current is a high non-sinusoidal current that flows when a transformer is energized. All transformers have an inrush current but the current level changes for different sizes and types of manufacturers. If the current is high enough, then the primary breaker feeding the transformer can trip. This will cause an outage for all of the loads downstream of the transformer.

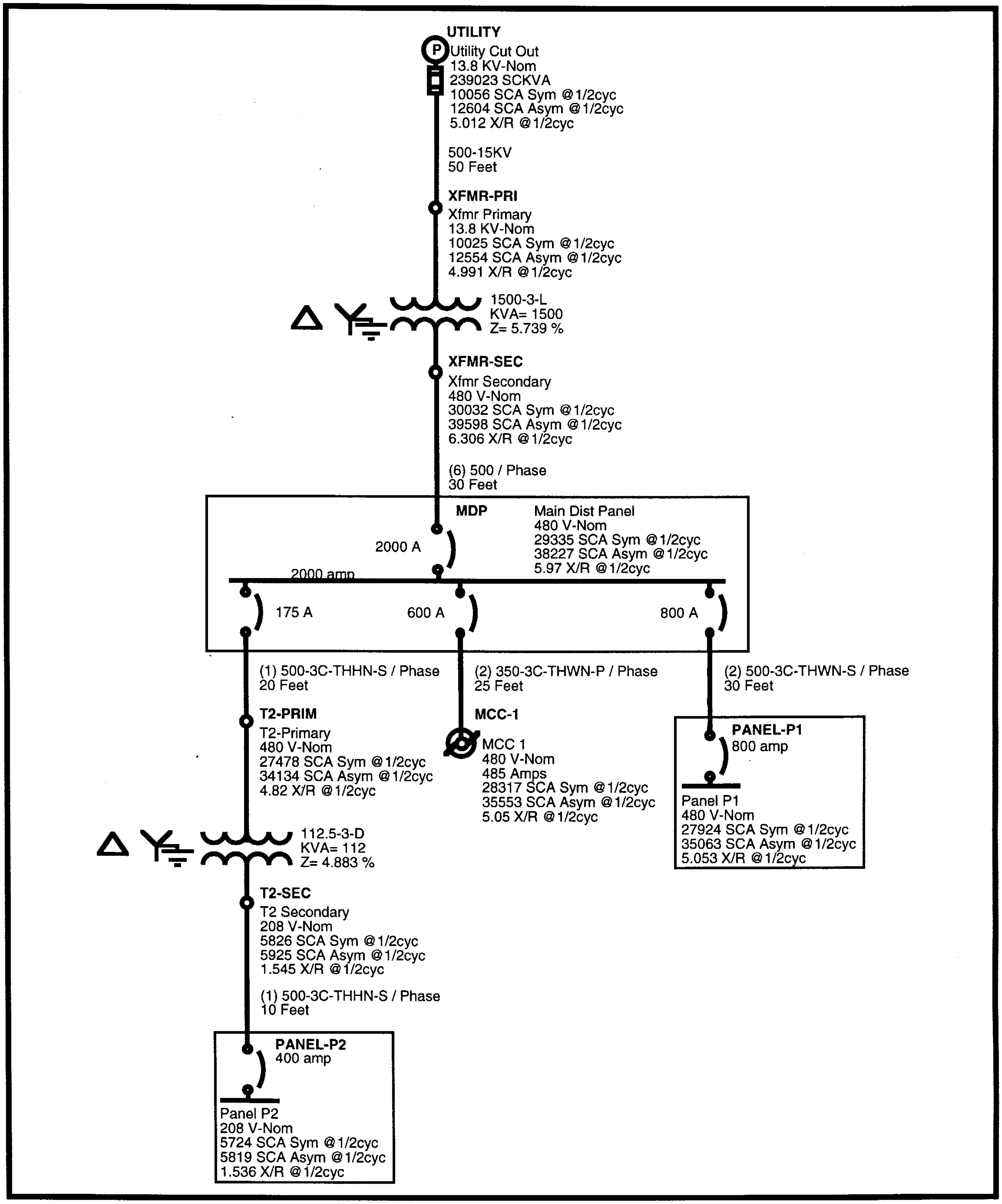
BACKGROUND/HISTORICAL PERSPECTIVE

Transformers have been used in facility distribution systems ever since the world adopted AC power. In fact, the main reason that AC power was so attractive was that the power could be brought in at a higher voltage with smaller conductors and then transformed to a lower voltage. The transformer changes this high voltage, smaller conductor system to a lower voltage, larger conductor system. The losses on the higher voltage system are less, resulting in a more efficient system.

The main device that converts this high voltage to low voltage is, of course, the transformer. This device, in its simplest form, consists of two sets of coils wrapped around a metal core.

PROBLEM

The characteristics of AC current cause transformer inrush current. Every transformer has stored residual magnetism in the iron core. The magnetism that is generated the instant the transformer is turned on, can



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Example
One Line Drawing

Sheet P1-1

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be out of phase with this stored residual magnetism. At that instant, the core is highly saturated and the maximum inrush will be obtained.

The transformer inrush current is highly non-linear. It peaks at 1/2 cycle (0.008 sec) after the transformer is energized. The current then drops to normal after about six cycles (0.1 sec). The magnitude of the inrush current depends on the:

1. Time that you throw the switch!
2. Length and size of the conductors feeding the transformer.
3. Stiffness of the system feeding the transformer. (Available fault current)
4. The size of the transformer.
5. The type of the transformer (liquid, dry, 80C,..etc.)

To understand how a breaker can trip due to inrush currents, we look at time current graphs and breaker time current curves. The time current graph is log-log graph of time versus current. Each breaker, fuse, and relay has a time current characteristic curve published by the manufacturer. The manufacturer tests the devices and plots the tripping time versus current on industry standard log-log graph paper. An example of a time current curve is shown on Sheet P2-1.

Sheet P2-1 shows the available fault current, which is a short circuit going phase-to-phase. The graph shows the 175 ampere primary circuit breaker time current characteristic and the 112.5 kVA transformer damage curve (see Part 1). The approximate transformer inrush current is also shown.

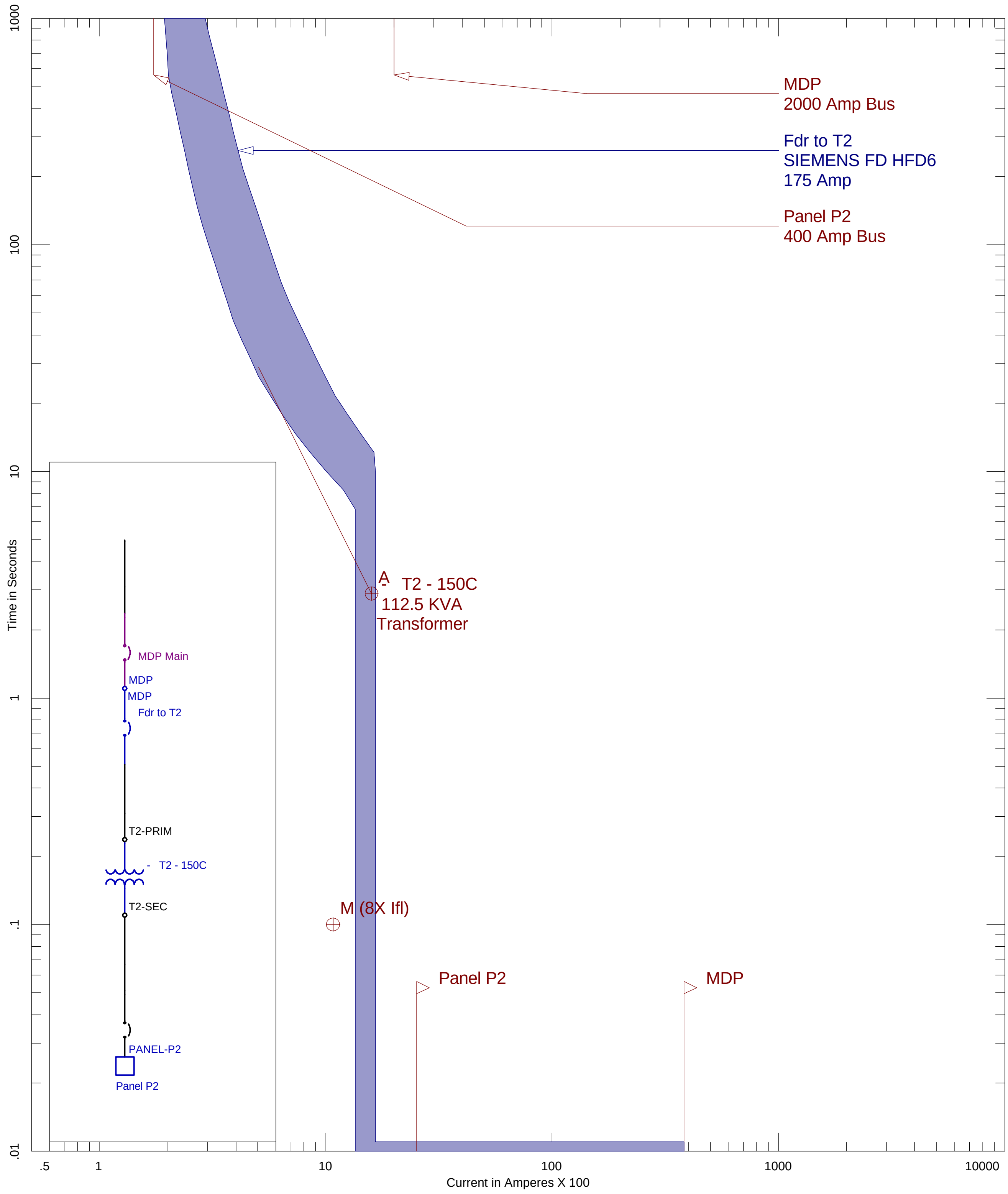
If fault or inrush current is high enough and it intersects with the breaker time current characteristic, then the breaker will trip. Sheet P2-1 shows a flag marked “Panel P2” near the bottom of the time current curve. This is the maximum short circuit current that will occur in Panel P2. By inspection, we can see that this flag lies on top of the breaker curve. If a bolted fault occurs in the panelboard, the breaker will trip.

If the inrush current lies to the left of the breaker curve, then the breaker will not trip. The breaker may trip if the inrush fault current lies on the vertical portion of the curve. If the inrush current lies to the right of the breaker curve, then the breaker will trip.

As stated earlier, transformers have been used for many years. The circuit breaker manufacturers have designed circuit breakers with time current characteristics that have been able to withstand the inrush currents for typical standard installations. However, more and more electrical designers are specifying low temperature and K-rated transformers. These transformers have a higher inrush current than standard units.

Transformers have several different insulation classes. The insulation letter code describes the type of insulation class, i.e.. A, B, F, & H.
From this code, we can determine the average:

1. <u>Average Conductor Temperature Rise</u> - Maximum temperature rise of the transformer windings.
2. <u>Hot-spot Temperature Gradient</u> - The difference between the average conductor temperature and the highest temperature at any point.
3. <u>Ultimate permissible temperature</u> - Sum of ambient, average conductor temperature rise, and hot spot temperature gradient. (Note: Ambient temperature is always assumed to be 40 Degrees Celsius (104 Degrees F).)



480 Volt Phase 9/23/99

Time-Current Characteristic Curves 9:53:50am

Sheet P2-1 T2 - 150C Xmfr, Primary Feeder Breaker to T2

The following table summarizes these ratings for the various dry type insulation classes.

Insulation Class	Ambient Temperature	Average Conductor Temperature Rise	Hot-Spot Temperature Gradient	Total Permissible Ultimate Temperature
A	40C	55C	10C	105C
B	40C	80C	30C	150C
F	40C	115C	30C	185C
H	40C	150C	30C	220C

Table P2-1 *Dry Type Transformer Insulation Temperature Ratings*

The table shows that lower temperature rated transformers have a lower total permissible ultimate temperature (those with insulation class of A or B). In theory, this translates to the transformer having lower losses and longer life spans. These transformers are also more expensive that Class F and H.

K-Rated Transformers are being used more because the use of electronic equipment has grown. Electronic loads are non-linear and produce harmonics. The K rating is given to a transformer that indicates the ability to supply non-linear (harmonic) loads without excessive heating or damage. The harmonic currents tend to overheat normal non-K-rated transformers. The extra heating shortens the life of the transformer.

How are some k-rated and lower temperature transformers made? How do they differ from standard F (115C) & H (150C) insulation class units? Many, but not all, manufacturers use larger framed H (150C) insulation class transformers, derate, and re-label them for K-rated or lower temperature units. There is more core steel and larger coil conductors for a 150 kVA unit than a 112.5 kVA unit. A 150 kVA unit can be de-rated for 112.5 kVA and be able to handle more harmonic current than a standard 112.5 kVA transformer.

The similar situation occurs for a lower temperature rated transformer. A standard Class H (150C) 150 kVA transformer feeding the same load as a Class H (150C) 112.5 kVA transformer will operate at a lower temperature. The manufacturer can de-rate the 150 kVA unit and re-label the transformer as 112.5 kVA. This should not be considered a dishonest practice. The transformers still meet the ANSI/NEMA Standards and will carry the loads without excessive heating or damage, which is what the specifier and owner desires.

This method may be satisfactory for the transformer manufacturer, but it can problematic after the equipment is installed and energized. When the manufacturer de-rates a larger transformer and re-labels it, the physical size of the unit is not reduced. There is more core steel and larger conductors. This results in a higher magnitude of inrush current.

Why are inrush currents sometimes a problem? Most design engineers use molded or insulated case circuit breakers to feed a low voltage transformer. By ANSI standards, these devices must have an instantaneous setting. Most molded or insulated case circuit breakers have a maximum instantaneous setting of 10 times higher than the trip settings. If the breaker is too small or the inrush is high, it will trip out.

Table P2-2 shows the inrush values in multiples of transformer full load current (Ifl). These values are for Siemens transformers. Note that for a given kVA size, the inrush usually increases as the temperature rating of the transformer decreases. The inrush currents sometimes are larger for K-rated transformers than for standard rated.

kVA	Ifl @ 480V (amperes)	Multiples of Ifl			Rating
		150C	115C	80C	
112.5	136	11X	16X	20X	Standard
150	180	12X	15X	15X	Standard
112.5	136	13X	14X	14X	K-13
150	180	11X	11X	16X	K-13

Table P2-2 *Inrush Values for Siemens Dry Type Transformers*

Table P2-3 shows typical inrush values for the same size transformer (standard rated), but for Siemens and Square D transformers. The two tables show that the inrush varies depending on transformer size and manufacturer. There is no pattern or simple equation that can be used to predict the inrush currents.

kVA	Ifl @ 480V (amperes)	Multiples of Ifl			non K-Rated Mfg.
		150C	115C	80C	
112.5	136	11X	16X	20X	Siemens
112.5	136	8.7X	7.2X	17X	Square D
150	180	12X	15X	15X	Siemens
150	180	5.4X	7.5X	7.5X	Square D

Table P2-3 *Inrush Values for Siemens & Square D Non K-rated Dry Type Transformers*

The only way to find out what the inrush may be is to contact the manufacturer. This is a problem for the design engineer who rarely knows who will be the manufacturer of the transformers they are specifying. This is usually not known until after the electrical contractor has been selected and the equipment submittals are generated.

Even if the inrush value is known from the manufacturer, the actual value may be less. The available fault current and long conductor lengths feeding the transformer will reduce this maximum value.

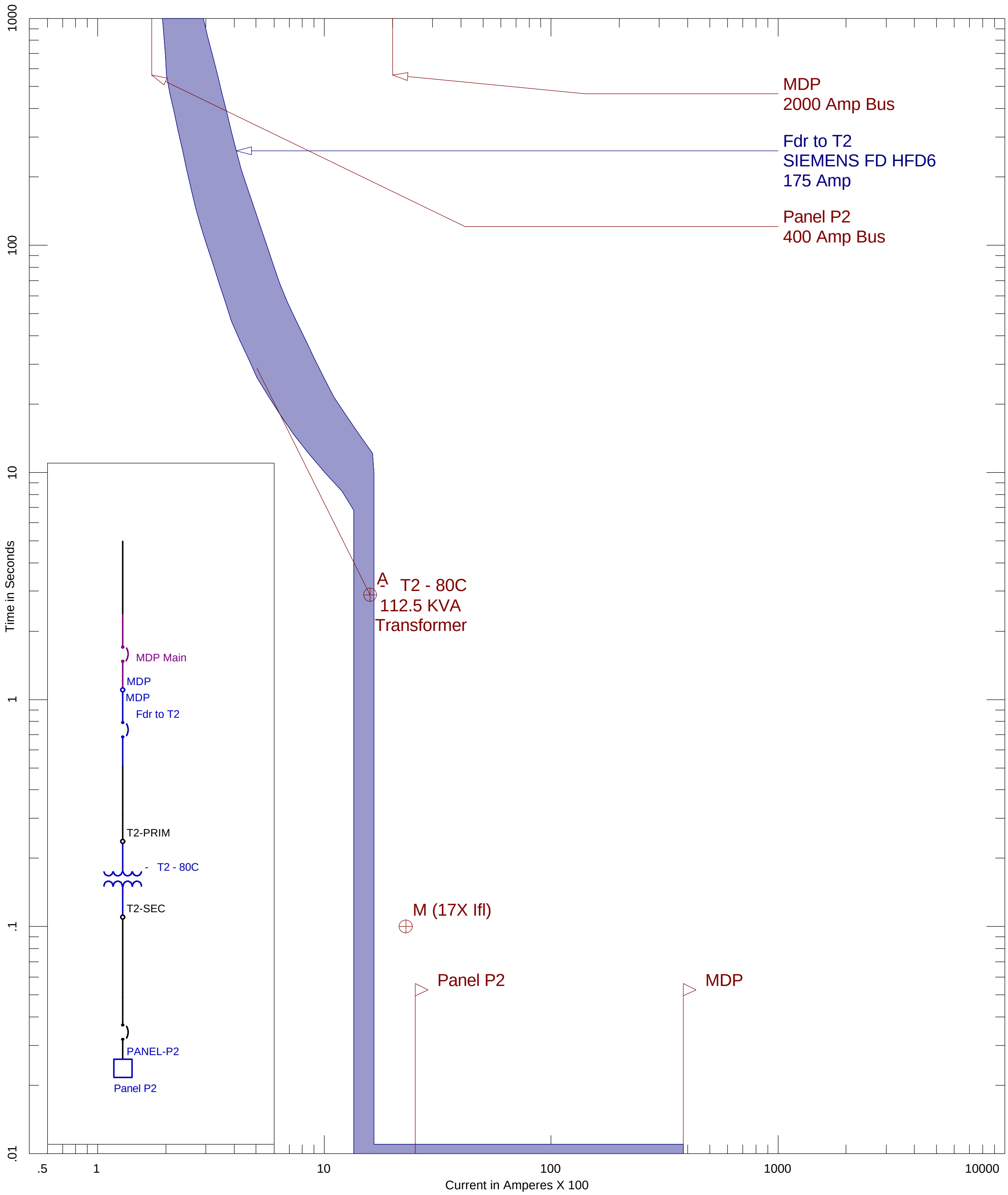
An example of this inrush problem is shown on Sheet P2-1 and P2-2. Sheet P2-1 shows a 175 ampere primary feeder breaker feeding a 112.5 kVA transformer. The transformer full load current is 136 amperes. The 175 ampere breaker trip rating is 128% of the transformer full load current. Sheet P2-1 shows that the transformer inrush point lies to the left of the breaker time current curve with the instantaneous adjustment set to maximum. The breaker will not trip when it is closed.

Sheet P2-2 shows the same equipment except the transformer is now an 80C unit. The inrush is now 20 times the full load current. The inrush point lies on the right side of the breaker instantaneous curve. The breaker will usually trip when it is closed.

SOLUTIONS

What are some design methods that can be used to avoid the problem of the primary breaker tripping? This involves looking at the National Electric Code (NEC). The following is from the NEC code:

> **NEC Section 450-3 (b) Transformers 600 Volts, Nominal, or Less**
> Overcurrent protection of transformers rated 600 volts, nominal, or less shall comply with (1) or (2) below:



480 Volt Phase

Time-Current Characteristic Curves

Sheet P2-2 T2 - 80C Xmfr, Primary Feeder Breaker to T2

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> (1) Primary. Each transformer 600 volts, nominal, or less, shall be protected by an individual overcurrent device on the primary side, rated or set at not more than 125 percent of the rated primary current of the transformer.
>
> Exception No. 1 **-** Where the rated primary current of a transformer is 9 amperes or more and 125% of this current does not correspond to a standard rating of a fuse or non-adjustable circuit breaker, the next higher standard rating described in Section 240-6 shall be permitted.
>
> (2) Primary and Secondary. A transformer 600 volts, nominal, or less, having an overcurrent device on the secondary side rated or set at not more than 125 percent of rated secondary current of the transformer shall not be required to have an individual overcurrent device on the primary side if the primary feeder overcurrent device is rated or set at a current value of not more than 250% of the rated primary current of the transformer.
>
> Exception **-** Where the rated primary current of a transformer is 9 amperes or more and 125% of the rated secondary current does not correspond to a standard rating of a fuse or non-adjustable circuit breaker, the next higher standard rating described in Section 240-6 shall be permitted.

It can be seen from the code that if the transformers have primary and secondary protection, the primary feeder breaker can have a trip rating up to 2.5 times the transformer full load rating. Note that 2.5 times the transformer full load rating of 136 amperes is 340 amperes. Assuming that the breaker will have an instantaneous setting of 10 times, the instantaneous trip will be 25 times the full load current. This is well above the maximum inrush values shown in the Tables P2-2 and P2-3. Sheet P2-3 shows the 112.5 kVA 80C unit with a 300 ampere primary feeder breaker.

Other tricks can be played without having to install secondary protection. This is done by using solid state breakers that have a rating plug that is at least 250% of the transformer full load. The instantaneous setting must be adjustable in multiples of the rating plug and the breaker must have a long time pick up or current setting.

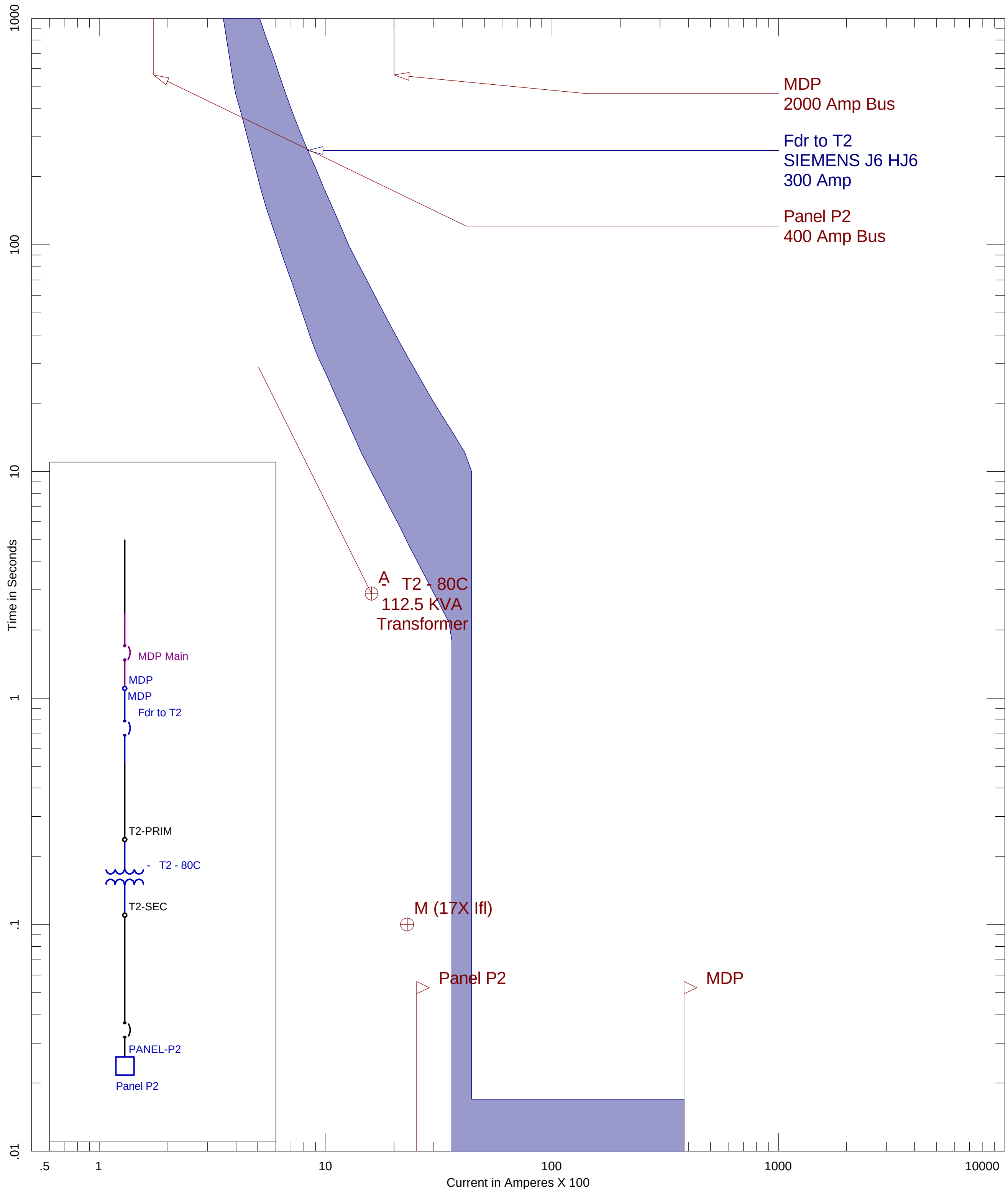
The engineer can then set the long time pick up or current settings below 250% of the transformer full load rating. The instantaneous can be set to 25 times the transformer full load to prevent inrush tripping.

For our 80C unit example, we used a GE type SG breaker with 400 ampere current sensor and 300 ampere rating plug (see sheet P2-4). The long time pick up is set to 0.5 times the rating plug. This makes the trip rating 150 amperes. The instantaneous can be set for 10X times the rating plug or 3,000 amperes. This is 22 times the transformer full load rating. The breaker will not trip due to inrush. Note that not all breakers behave the same way as the GE type SG breaker. Many breakers have instantaneous settings that are multiples of the current setting or long time pick up settings.

The designer can sometimes specify breakers with a solid state trip unit and a high fixed instantaneous override option. This feature has a non-adjustable instantaneous setting usually fixed between 10,000 amperes and the breakers interrupting rating. Again, this will vary between breaker types and manufacturers.

SUMMARY

Low temperature and K-rated transformers tend to have a higher inrush than normal transformers. There are many things that affect the inrush magnitude. These include the time the switch is thrown, available fault current, conductor size, conductor length, size of the transformer and type of transformer. The inrush currents are highly unpredictable and impossible to calculate.



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Time-Current Characteristic Curves

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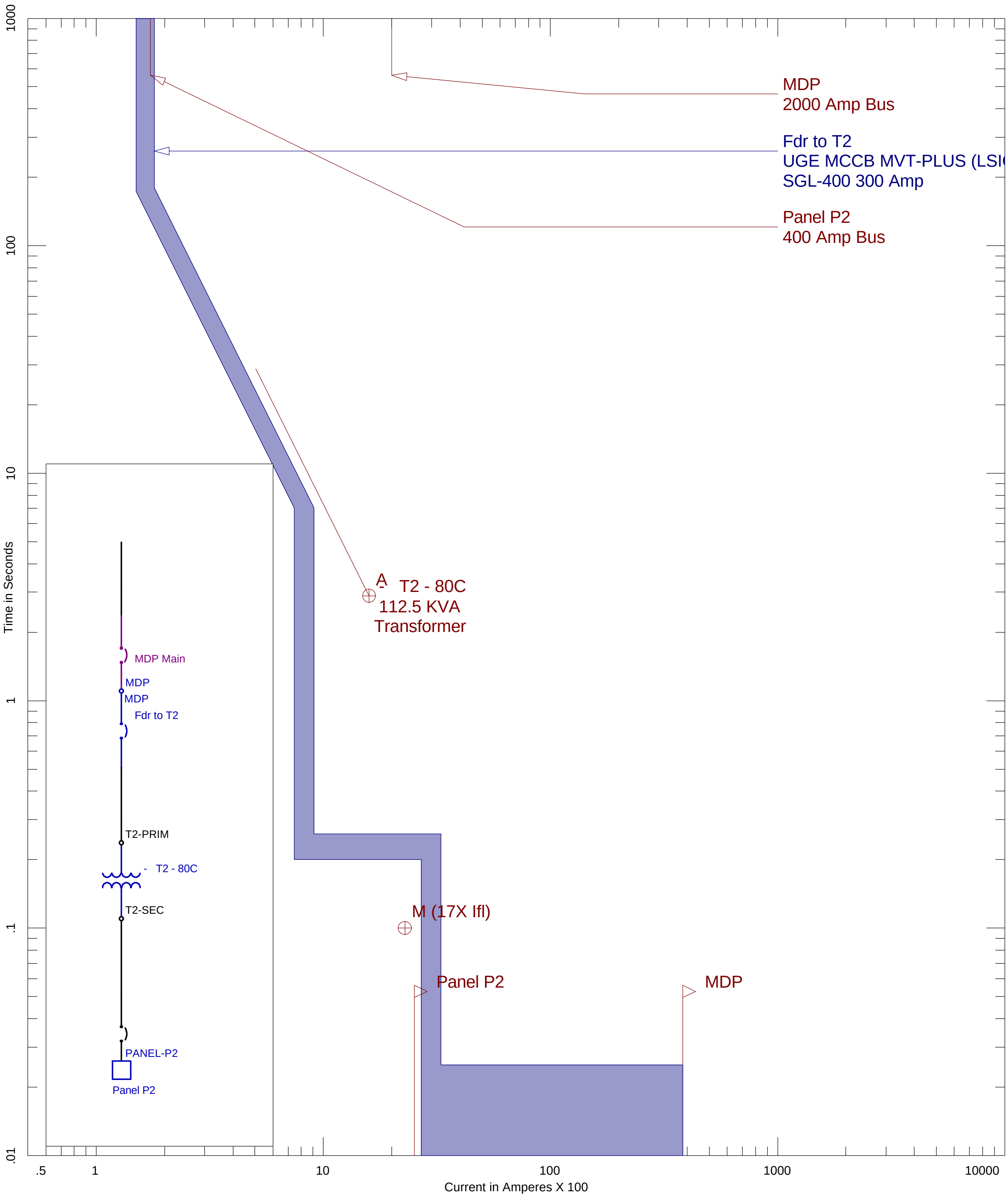
Sheet P2-3 T2 - 80C Xmfr, Larger Primary Feeder Breaker



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Time-Current Characteristic Curves
Sheet P2-4 T2 - 80C Xmfr, Solid State Primary Feeder Breaker

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RECOMMENDATIONS

If your design uses K-rated or Low Temperature transformers:

1. Always set the primary breaker instantaneous setting to maximum,
2. and use
    - A. secondary protection set at 125% of rated secondary current and use primary protection set as high as possible not to exceed 250% of primary current, or
    - B. use solid state trip devices with large rating plugs, adjustable trip rating, and adjustable instantaneous trip in multiples of the rating plug, or
    - C. use solid state trip devices with a fixed instantaneous override feature.

Using the methods outlined above will eliminate some of the guess work and the problem of inrush tripping. This will increase system reliability and overall power quality.

ABOUT THE AUTHOR:

Robert E. Fuhr graduated with a B.S.E.E. from the University of Wisconsin in 1980. Before graduating, Mr. Fuhr worked for Madison Gas and Electric in Madison, WI and Tennessee Valley Authority in Knoxville, TN. After graduation, he worked for General Electric Company from 1980 to 1986 as a Field Engineer. From 1986 to 1989 he worked as a Senior Facilities Engineer at the University of Washington. In 1986, he established Power Systems Engineering , a consulting firm that specializes in power systems studies. As Power Systems Engineering's Senior Electrical Engineer, he has performed power studies for many commercial buildings and large industrial facilities. He is the sales agent for EDSA Power System Analysis Software. He also teaches classes in electrical safety, power factor correction, harmonics and filter design. Mr. Fuhr is a Professional Engineer registered in Washington, Oregon, California, and Alaska.

Bob has been actively involved in IEEE and the Industrial Applications Society since 1986. He has served as an officer for IAS from 1988 to 1992. He was the 1991 to 92 Chairperson of IAS. He was a Member-at-large for the Seattle Section of IEEE for 1992-93. He is a board member of Power Quality Interest Group and is a member of the Electric League of the Pacific Northwest.