

Data Bulletin

Low Voltage Transformer Through-Fault Protection: A System Approach

Introduction

Power system modeling and analysis software packages plot ANSI/IEEE through-fault curves for low voltage, dry-type transformers. The use of this plotting feature has led to application issues when evaluating the ability of circuit breakers to protect transformers, specifically the ability of certain thermal-magnetic trip, primary circuit breakers to provide the apparent required through-fault protection. This paper discusses the protection criteria for low voltage transformers and describes a system approach to evaluating ANSI through-fault protection curves and low voltage circuit breakers.

Low Voltage Transformer Protection Criteria

Discussion of low voltage, dry-type transformer overcurrent protection begins with the published standards and guides:

- NEC® Article 450, *Transformers and Transformer Vaults (Including Secondary Ties)*, (NFPA 70®, 2008 Edition) contains installation requirements for overload protection of low voltage transformers
- NEMA ST 20-1992 (R1997), *Dry Type Transformers for General Applications*, contains short-circuit withstand and testing requirements for low voltage transformer designs
- ANSI/IEEE C57.12.01-2005, *IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers*, to which NEMA ST 20-1992 refers for prototype short-circuit withstand requirements
- ANSI/IEEE C57.12.91-2001, *IEEE Standard Test Code for Dry-Type Distribution and Power Transformers*, to which NEMA ST 20-1992 refers for prototype testing requirements
- ANSI/IEEE C57.12.59-2001, *IEEE Guide for Dry-Type Transformer Through-Fault Current Duration*

NEC Article 450

Transformers and Transformer Vaults (Including Secondary Ties)

Section 450.4, *Autotransformers 600 Volts, Nominal, or Less*, of NEC Article 450 provides primary and, when necessary, secondary overcurrent protective device trip levels. It defines transformer overload protection requirements in percentages of the transformer's rated currents and applies the requirements in terms of protective device continuous current ratings. The "Primary only protection" limits in NEC Table 450.3(B) (reproduced below) are not typically used since the equipment fed by the transformer, such as secondary conductors, may require overcurrent protection.

NEC Table 450.3(B) Maximum Rating or Setting of Overcurrent Protection for Transformers 600 Volts and Less (as a Percentage of Transformer-Rated Current)

Protection Method	Primary Protection			Secondary Protection ²	
	Currents of 9 Amperes or More	Currents Less Than 9 Amperes	Currents Less Than 2 Amperes	Currents of 9 Amperes or More	Currents Less Than 9 Amperes
Primary only protection	125% ¹	167%	300%	Not required	Not required
Primary and secondary protection	250% ³	250% ³	250% ³	125% ²	167%

¹ Where 125 percent of this current does not correspond to a standard rating of a fuse or nonadjustable circuit breaker, a higher rating that does not exceed the next higher standard rating shall be permitted.

² Where secondary overcurrent protection is required, the secondary overcurrent device shall be permitted to consist of not more than six circuit breakers or six sets of fuses grouped in one location. Where multiple overcurrent devices are utilized, the total of all the device ratings shall not exceed the allowed value of a single overcurrent device.

³ A transformer equipped with coordinated thermal overload protection by the manufacturer and arranged to interrupt the primary current shall be permitted to have primary overcurrent protection rated or set at a current value that is not more than six times the rated current of the transformer for transformers having not more than 6% impedance and not more than four times the rated current of the transformer for transformers having more than 6 percent but not more than 10% impedance.

NEMA ST 20-1992 (R1997)
Dry Type Transformers for General Applications

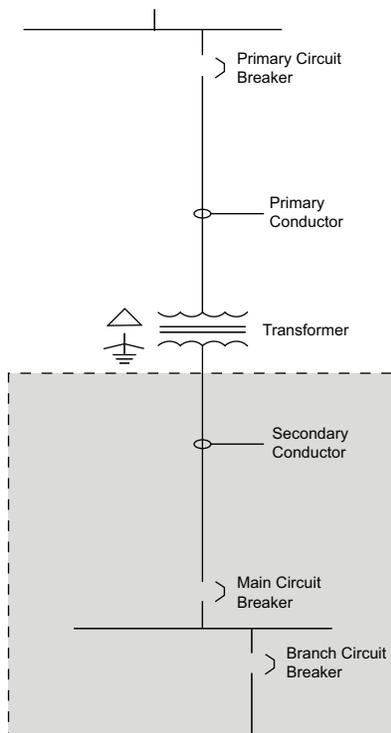
NEMA ST 20-1992 “includes ratings and information on the application, design, construction, installation, operation, inspection, and maintenance” of dry-type transformers. It specifies prototype short-circuit testing (Paragraph 4.2.13) by referring to ANSI/IEEE C57.12.01-2005 (short-circuit requirements) and ANSI/IEEE C57.12.91 (short-circuit test descriptions). In the past, the short-circuit requirements of NEMA ST 20-1992 (typically, 25 times full-load current at 2 seconds) were plotted against overcurrent protective device time-current curves to evaluate transformer overcurrent protection.

ANSI/IEEE C57.12.59-2001
IEEE Guide for Dry-Type Transformer Through-Fault Current Duration

ANSI/IEEE C57.12.59-2001 defines time-current curves (through-fault curves) against which the characteristics of transformer overcurrent protective devices can be compared. These curves recognize the cumulative effects, both mechanical and thermal, of through-faults over the operational life of the transformer. The guide’s intent, as described in its scope, is not to define overload capability, but rather to recommend fault-level damage thresholds.

C57.12.59-2001, as a system design and application guide, also acknowledges that exposure to through-faults differs, based on a transformer’s application and the through-fault’s location in the system. Figure 1 shows the transformer through-fault protection zone in a one-line context—the system portion which is load side of the transformer’s secondary terminals. The system approach discussed later in this document relies on the guide’s recognition of transformer application and fault location to apply a system of overcurrent protective devices to provide through-fault protection.

Figure 1: Transformer Through-Fault Protection Zone



NOTE: The shaded area is the transformer’s through-fault protection zone

Unlike the prototype short-circuit withstands required by NEMA ST 20-1992 and ANSI/IEEE C57.12.01-2005, C57.12.59-2001 states that the damage limit curves cannot be demonstrated by testing, given the cumulative and progressive effects of through-faults over a transformer’s lifetime, saying, “The curves are based principally on informed engineering judgment and favorable historical experience.”

The scope of C57.12.59-2001 states that the guide applies to transformer categories I and II as defined in C57.12.01-2005, Table 14 (reproduced below).

Dry-Type Transformer Rating Categories

Category ¹	Single Phase (kVA)	Three Phase (kVA)
I	1–500	15–500
II	501–1667	501–5000
III	1668–10000	5001–30000

¹ Autotransformers of 500 kVA or less (equivalent two-winding) shall be included in Category I even though their nameplate power rating may exceed 500 kVA.

Given that the scope of C57.12.01-2005 excludes low voltage (≤ 600 V) transformers, there is sufficient reason to question whether the through-fault curves in C57.12.59-2001 (see Figure 2 on page 3) apply to low voltage transformers. However, because commercially available power system analysis software plots the transformer through-fault curves by default, a generally accepted and expected practice among consulting engineers and some authorities having jurisdiction examines the guide’s curves with respect to overcurrent protective devices.

For Category I transformers, the through-fault curve is defined as:

$$I^2 t = 1250$$

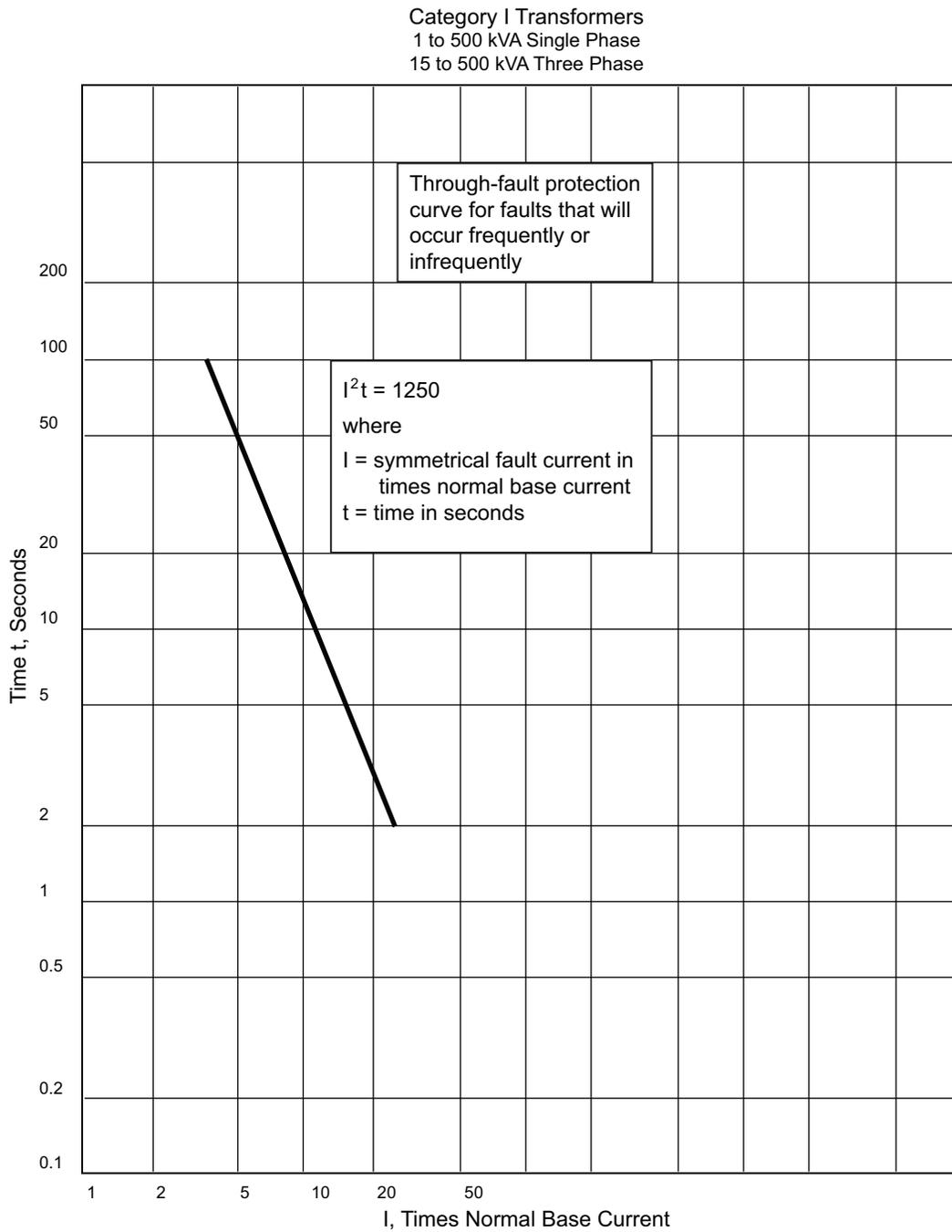
where

I = symmetrical fault current in times normal base current

and

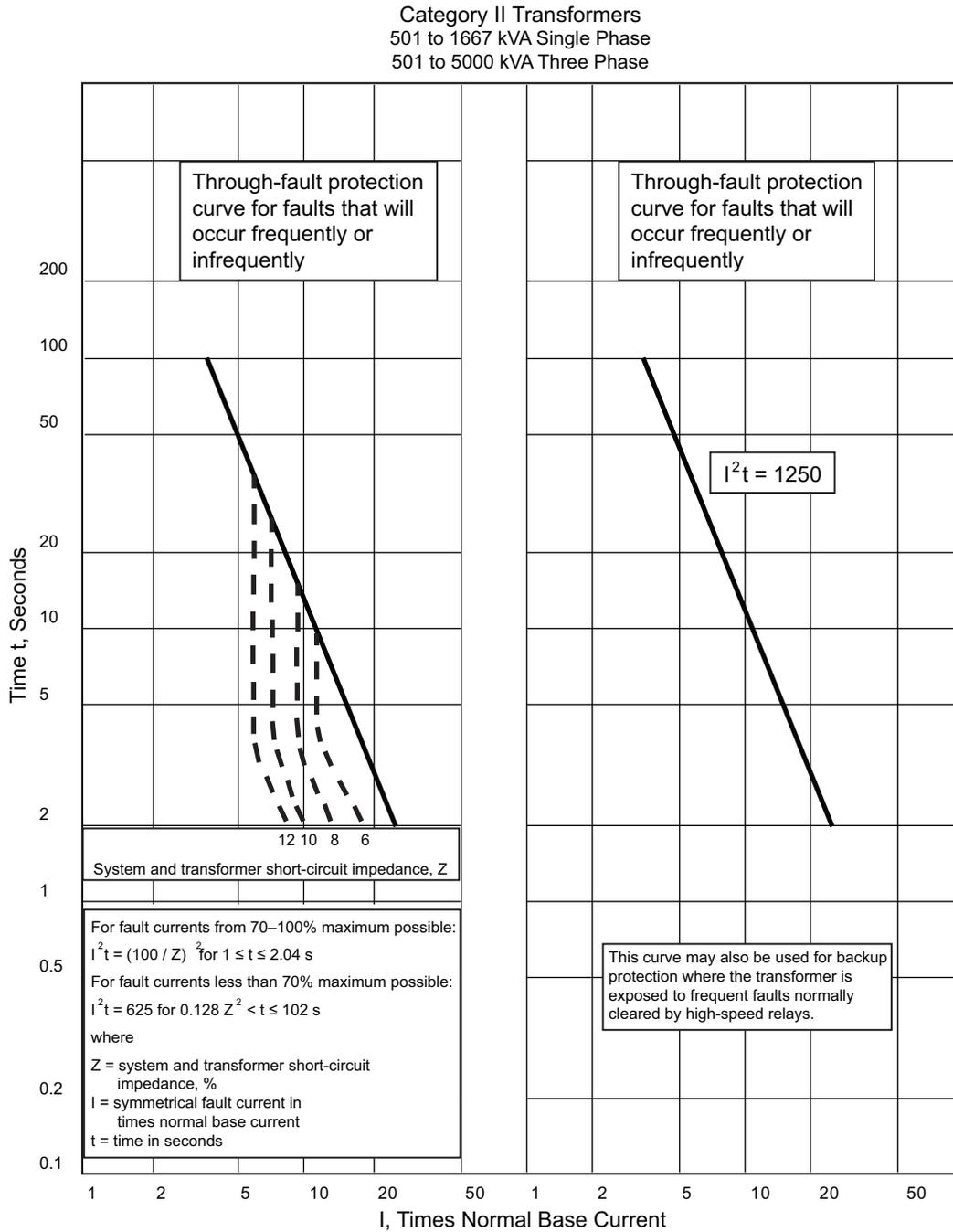
t = time in seconds

Figure 2: Category I Transformers Through-Fault Curve



For Category II transformers, C57.12.59-2001 differentiates between frequent and infrequent faults, stating that frequent faults are those occurring more than 10 times over the lifetime of the transformer. For these frequent faults, the guide defines another curve portion (Figure 3) to be applied between 70% and 100% of the maximum possible fault current, keyed to the worst case I^2t and dependent on the short-circuit impedances of the system and transformer.

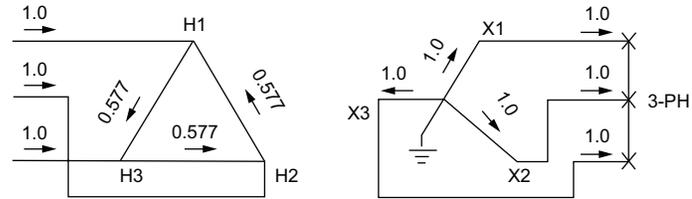
Figure 3: Category II Transformers Through-Fault Curve



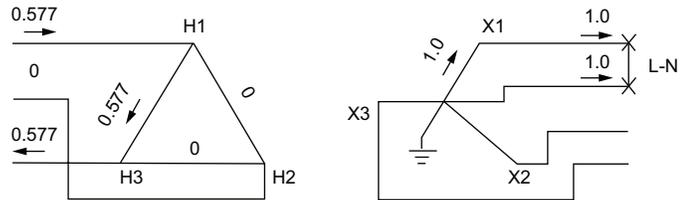
Since the majority of low voltage transformer applications are 500 kVA and below, the rest of this document will focus on Category I through-fault curves.

For certain unbalanced secondary faults on delta-to-solidly grounded wye- and delta-to-delta-connected transformers, adjustments to the through-fault curves are necessary to evaluate primary overcurrent devices. See Figures 4 and 5.

Figure 4: Line-Neutral Fault Effects, Referenced to the Primary of a Delta-to-Solidly Grounded Wye Transformer

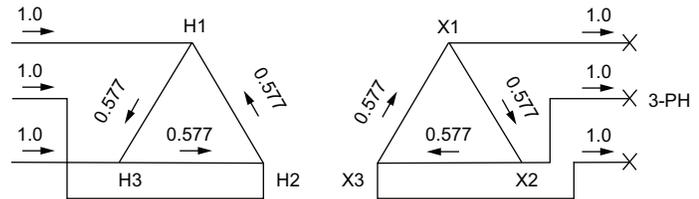


3-phase (3-PH) Fault: Current values are per unit of the 3-phase fault current.

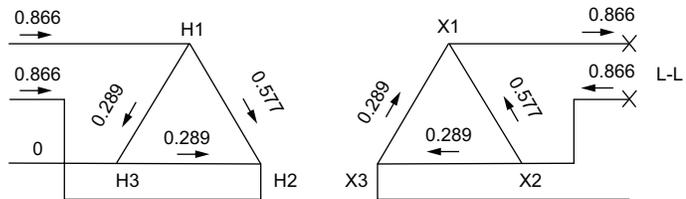


Line-Neutral (L-N) Fault: Current values are per unit of the 3-phase fault current.

Figure 5: Line-Line Fault Effects, Referenced to the Primary of a Delta-to-Delta Transformer



3-phase (3-PH) Fault: Current values are per unit of the 3-phase fault current.



Line-Line (L-L) Fault: Current values are per unit of the 3-phase fault current.

To account for these unbalanced secondary faults, the through-fault curves are adjusted for comparison with primary overcurrent protective devices—by a factor of 0.577 for delta-to-solidly grounded wye transformers and by a factor of 0.866 for delta-to-delta transformers. The commercial software packages typically plot two curves: the unadjusted through-fault characteristic, and the adjusted for unbalanced faults (sometimes referred to as the “three-phase” and “single-phase” through-fault curves). It is important to note these adjusted curves only apply for comparison with the primary overcurrent device.

System Approach to Transformer Through-Fault Protection

Applying Transformer Through-Fault Curves

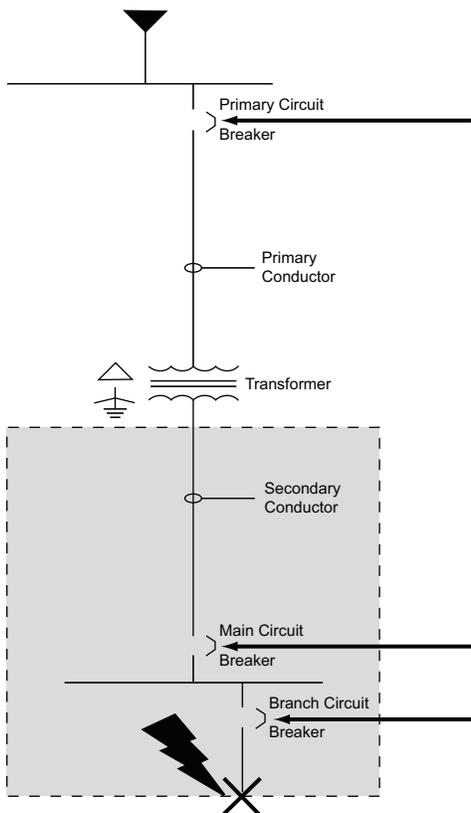
Ideally, the characteristic of the primary overcurrent protective device for the transformer would protect (fall below and to the left of) the adjusted through-fault curve. However, primary overcurrent devices must also be selected to carry the transformer's energizing current and selectively coordinate with line and load side devices. For more stringent selective coordination requirements (< 0.1s operating time), primary devices may be selected so that they do not operate for any secondary short-circuit current level.

These conflicting requirements can lead to potentially complicated and cost-prohibitive solutions for what have been traditionally simple applications. Further, in the absence of specific application recommendations from ANSI/IEEE C57.12.59-2001, engineering judgment should be exercised and industry experience should not be ignored in evaluating transformer through-fault protection.

Primary and Secondary Breakers as a Through-Fault Protection System

Given the practical limitations of providing transformer through-fault protection solely with the primary breaker, an approach considering the secondary main breaker and the largest secondary feeder or branch breaker is recommended.

Figure 6: System Approach to Transformer Through-Fault Protection



NOTE: The shaded area is the transformer's through-fault protection zone; the lightning bolt is the most likely through-fault location; the left-pointing arrows identify the system of circuit breakers providing the transformer's through-fault protection.

Figure 6 depicts a typical low voltage transformer application. NEC 240.21 effectively restricts the secondary conductor run length to 25 feet or less, for most applications. Given this relatively short and protected secondary conductor run, the most likely through-fault locations to which the transformer will be subjected are on the load side of the feeder or branch breakers of the secondary panelboard.

For faults at the indicated location, the transformer's primary, secondary panelboard main, and secondary panelboard feeder circuit breakers sense the through-fault. Ideally, if the three indicated breakers are selectively coordinated, the secondary feeder circuit breaker will operate on and clear the through-fault. Provided the time-current curve of the secondary feeder circuit breaker falls below and to the left of the unadjusted through-fault curve of the transformer, the transformer is protected.

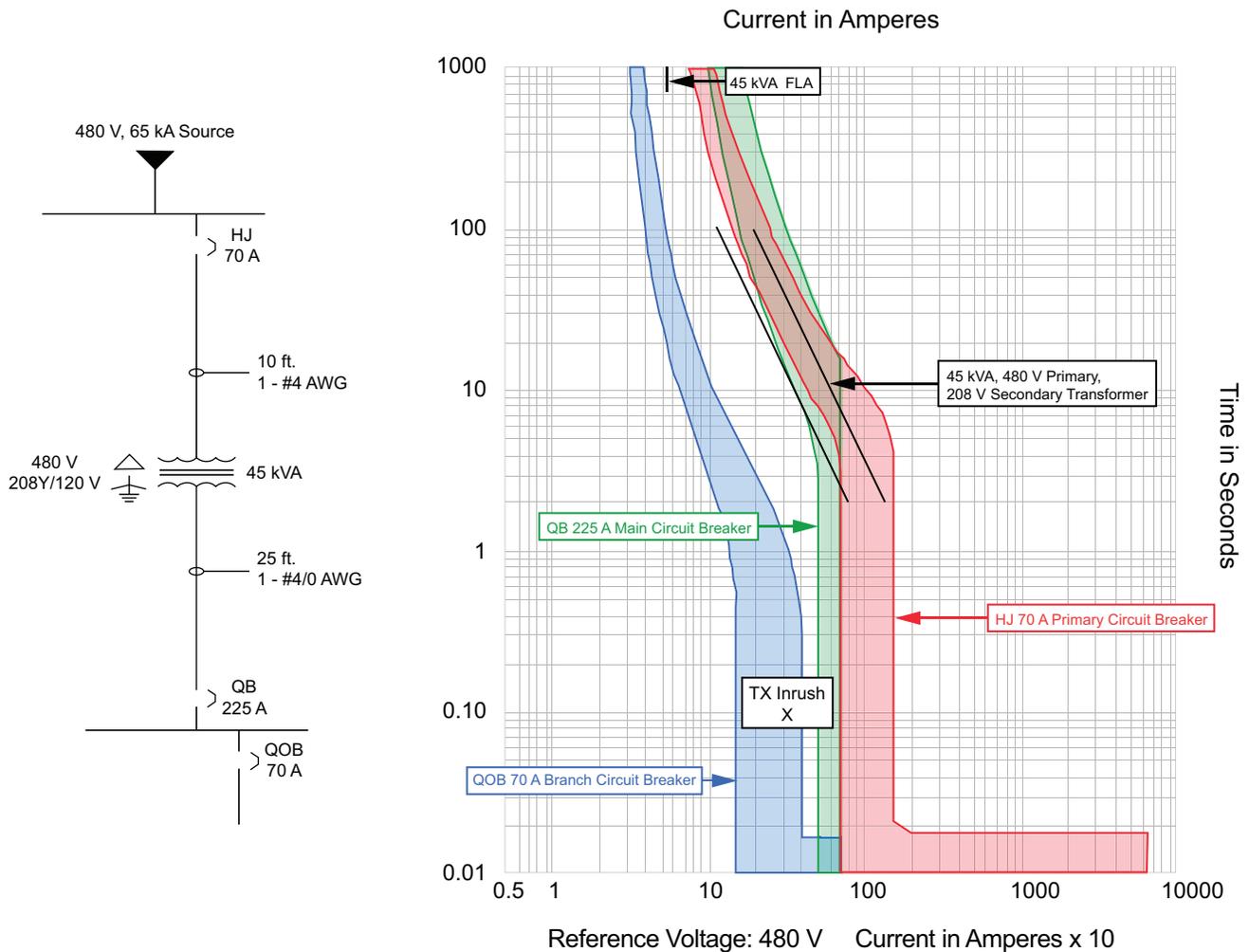
Generally, instead of examining the time-current characteristic of the primary circuit breaker alone against the adjusted through-fault curve, it is recommended that the time-current characteristics of the three devices (indicated by the left-pointing arrows in Figure 6) be viewed as a through-fault protection system, comparing the fastest acting device against the through-fault curve.

Application Example

Figure 7 contains an example of a series circuit consisting of a 70 A primary circuit breaker, a 45 kVA transformer with a 480 V primary and a 208Y/120 V secondary, a 225 A secondary main circuit breaker, and a 70 A branch circuit breaker. The continuous current ratings of the transformer's primary and secondary circuit breakers meet the NEC Article 450.4 requirements. Also shown are the time-current curves of the three circuit breakers and the through-fault curves (unadjusted and adjusted) of the transformer.

Comparing the time-current characteristic of the primary circuit breaker against the transformer's through-fault curves indicates that the circuit breaker will not necessarily interrupt before the through-fault damage thresholds are exceeded. Considering that the most probable through-fault locations over the lifetime of the transformer will be on the load side of the secondary branch circuit breakers (of which the 70 A circuit breaker is the largest) the through-fault protection of the transformer should be evaluated using this device's time-current curve. The total clearing curve of the 70 A circuit breaker falls below and to the left of the unadjusted through-fault curve, indicating that the transformer is protected.

Figure 7: Transformer Through-Fault Protection Example



NOTE: The time-current characteristic curves of the 208 V-applied circuit breakers have been adjusted and plotted at the 480 V reference voltage.

Summary

Power system analysis software allows easy default plotting of transformer through-fault curves for low voltage applications. Understanding the context of the ANSI/IEEE C57.12.59-2001 through-fault guide with the other applicable standards, choosing the proper curves to plot, and exercising engineering judgment in evaluating the overcurrent protective devices are required to correctly determine transformer through-fault protection. An engineering approach was presented in which the primary feeder, secondary main circuit breaker, and largest secondary feeder or branch circuit breakers are viewed as a system providing a transformer's through-fault protection. A typical application was offered, showing this system approach provides practical transformer protection, consistent with industry experience.

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