Transformer-Secondary Faults: Overlooked Aspect of Distribution System Protection

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Unrecognized transformer-secondary faults actually may be the cause of many unexplained equipment failures and system outages. Here is an in-depth probe into the cause of such problems and suggestions for their elimination.

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The importance of distribution-system primary faults, and associated transient recovery voltage (TRV), in the design and application of circuit-interrupting devices is recognized, in varying degrees, by both manufacturers and users. In recent years, much effort has been directed toward standardization and testing, and as a result, TRV has gained widespread recognition as being most important in the successful application of an interrupting device.

What progress has been made, however, in defining the transformer-secondary fault problem and in establishing even minimal test standards? In essence, the answer is little or none. The difficulty of interrupting a transformer-secondary fault with a primary interrupting device should be recognized as a potential source of trouble and perhaps may be the cause of many unexplained equipment failures and system outages.

The incidence of primary outages due to secondary-circuit problems is probably greater than indicated by utility records. Problems such as faults due to transformer failures, transformer shipping damage, and incorrect secondary connections are commonplace on new installations. A large portion of reported primary outages involving primary-protective device operations are ascribed to unknown causes. It is possible that many of these outages are caused by secondary-circuit faults where backup-protective devices operate because of failure of the transformer-protective device to clear. Another large portion of such outages are attributed to lightning—simply because they occurred during a lightning storm. Quite often, direct evidence of lightning damage to the primary circuit would not be found, and the true cause was a secondary-circuit fault.

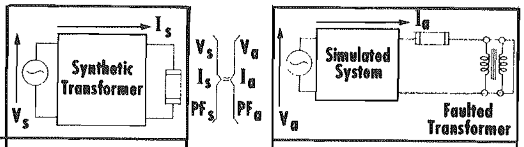
Need Better Testing

Many interrupting-test programs have been and are being conducted to evaluate the performance of interrupting devices. Unfortunately, some of these programs tend to ignore TRV parameters, and consequently yield results that cause misapplication or perhaps acceptance or rejection of the interrupting device under improper conditions. This not only is true for primary-fault testing but particularly for transformer-secondary fault testing to the point of completely ignoring this type of low-current fault.

COMPARISON—PRIMARY FAULTS vs. SECONDARY FAULTS

ITEM	PRIMARY FAULTS	SECONDARY FAULTS
CURRENT	High	Low
RRRV	Low	High
NORMAL OPERATION	Big Blast	Pop
RESULT OF FAILURE	Open arc	Open arc
	Flying shrapnel	Primary fault established
	Line Burn Down	Transformer Damage
	Possible Outage	Possible Outage

SYNTHETIC CIRCUIT vs. FAULTED TRANSFORMER



		Synthetic Circuit		Faulted Transformer	
TRANSFORMER	kVA	50	50	50	50
	kV	7.6	14.4	7.6	14.4
PERFORMANCE	Arcing Time Cycles	1/4	1/4	12	14
	Remarks	Normal Clearing	Normal Clearing	Failed to Clear	Failed to Clear
TRV	f_n Hz	1400	800	17000	11000
	AF	1.4	1.1	1.7	1.5

Also, there is a popular misbelief that if all is well with primary-fault performance, the device must be good for any intermediate or low-fault-current duty. Secondary faults as seen by a primary interrupting device can be a difficult problem. They must not be overlooked in any evaluation program. Realistic interrupting tests should be performed over the entire fault-current spectrum before a design is marketed by the manufacturer *or accepted by the user.*

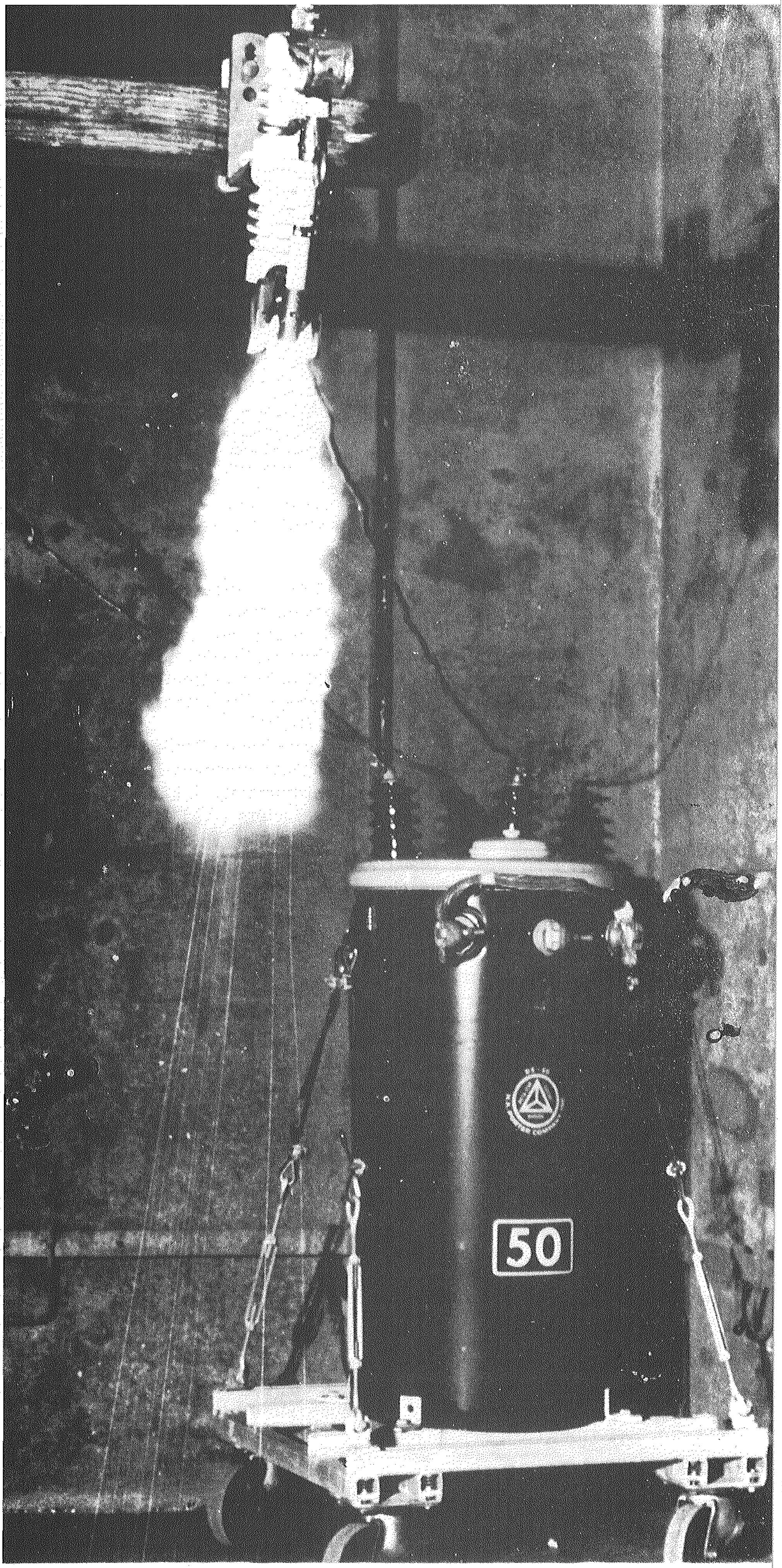
Fault Characteristics

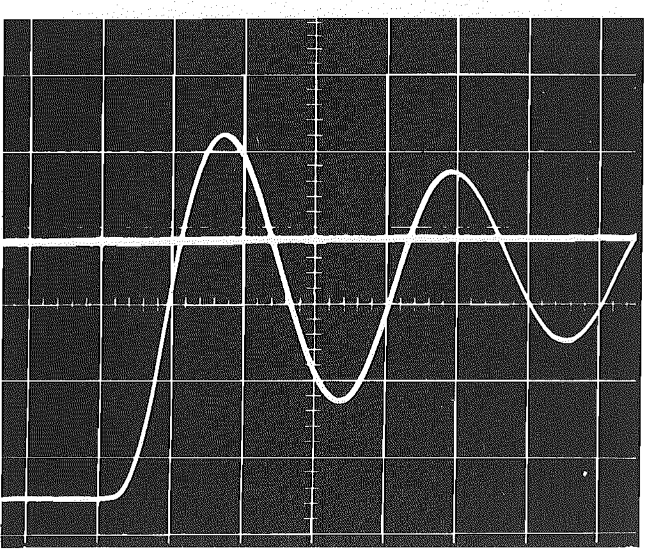
The general situation is that for primary faults the current is high, rates of rise of recovery voltage (RRRV) are relatively low, and either the device clears satisfactorily or it blows up. Secondary faults have a reverse set of conditions such that the current is low, RRRV is high and either the device clears normally or arcing persists for a long period of time.

If the device does not clear, any number of things may happen. The transformer may be damaged, a dropout device may arc during dropout and establish a primary fault as shown on the cover; or a non-dropout device may fail thermally, resulting in an explosion.

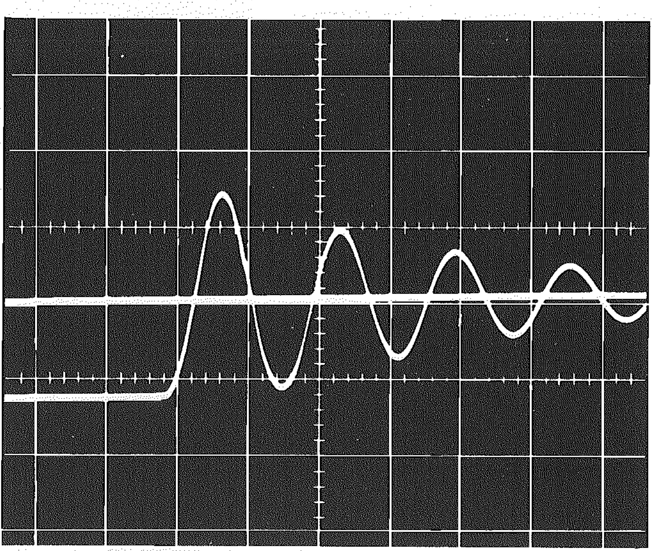
To further validate the premise that distribution transformer-secondary faults can be a pesky interrupting problem, consider the following typical interrupting tests on a 14.4-kv, 50-kva transformer and on a 7.6-kv, 50-kva transformer. The data obtained also dramatically illustrate the influence of RRRV on the performance of a typical open-type distribution cutout in handling a secondary fault.

Fault current on the transformer primary caused by a secondary fault will be approximately 150 amps rms for the 14.4-kv transformer and 300 amps rms for the 7.6-kv transformer. Synthetic laboratory test circuits were devised to yield these approximate current levels at a power factor equivalent to that for the actual transformers—on the order of 50 percent. A typical open-type distribution cutout was used as the interrupting device. Standard 15-kv distribution fuse links were employed.





Three-Phase, 500 KVA, 13200Δ – 208Y/120V Transformer; Three-Phase Secondary Fault; Grounded, Infinite Primary Source; Time Base = 20μsec/div.; fo = 15.6 KHz; AF = 1.4; $t_m = 32\mu$sec



Single-Phase, 37.5 KVA, 2400/4160Y × 7200/12470Y – 120/240V Transformer, 7.2 KV Tap; Secondary Fault; Grounded, Infinite Primary Source Time Base = 20μsec/div.; fo = 30 KHz; AF = 2.0; $t_m = 17\mu$sec

Tests prove that TRV must be considered when performing low-current level interrupting tests.

Interrupting tests indicate that the cutout and fuse-link combination performed admirably with only ½- or 1-cycle arcing time using each synthetic transformer circuit. The next step was to repeat these tests, using the actual transformers as the fault-limiting impedance connected to a simulated source.

Performance of the cutout and fuse link combination under these conditions, however, left much to be desired. Faults on the 14.4-kv, 50-kva transformer were most difficult for the interrupting device to handle, resulting in failure to clear in 50 percent of the tests. Arcing persisted as the cutout dropped open and the fault eventually was cleared by a back-up breaker after 15 cycles.

Performance with the faulted 7.6-kv, 50-kva transformer, as shown on cover, was even more spectacular in that failure to clear resulted in an external flashover of the cutout tube. The photo on p. 87 shows a normal successful operation for a fault on the 7.6-kv, 50-kva transformer.

The obvious comparison, as summarized on page 86, bottom right, is that when using a synthetic test circuit yielding the same voltage, current, and power factor, the interrupting device performed satisfactorily; whereas, when using an actual faulted transformer, the device either performed only marginally or failed completely. The missing ingredient is RRRV.

The synthetic circuits were set up to yield resonant frequencies of approximately 1 kHz and amplitude factors (AF) of about 1.2. Actual frequencies for the faulted transformers were 11 kHz for the 14.4-kv unit, and 17 kHz for the 7.6-kv unit. Amplitude factors were about 1.6. The difference in RRRV for the synthetic and actual circuits is quite extreme and accounts for the difference in performance.

Certainly, for different transformer sizes, for varied current levels, for cutouts and fuse links of a different type, the results may be different, but the basic conclusion is still valid. TRV is important and must be recognized when performing interrupting tests at low current levels—particularly secondary faults on distribution transformers.

Influencing Factors

Factors influencing TRV for secondary faults on distribution transformers, in decreasing importance, are as follows:

(1) Transformer impedance
(2) Transformer capacitance: bushings, winding-to-ground, winding-to-winding
(3) Bus or cable, representing capacitance, connected between transformer and interrupting device.
(4) Transformer- and system-ground connections
(5) System impedance and connections
(6) Secondary circuits involved in fault, if any

The characteristics of the interrupting device also could be added, but since only the inherent circuit characteristics are being considered, the interrupting device will be ignored.

Transformer impedence, which is a function of kva size and percent impedance for a given voltage rating, is obviously the most important factor. Not only does it determine the magnitude of fault current but also the value of inductance in the simple expression for resonant frequency shown on page 89, top. Inductance can be calculated directly from percent impedance, from the transformer voltage and power ratings, and from the transformer-impedance power factor. The trend toward designing transformers with lower impedances and leakage reactances will increase natural frequencies. The resultant RRRV across an interrupting device, when clearing a secondary fault, increases in a direct proportion.

Capacitance is the other parameter in the resonant-frequency formula. Transformer capacitance is certainly the most important, but in addition, any capacitance connected between the transformer and an interrupting device adds directly to the effective transformer capacitance and substantially lowers the natural frequency of the circuit. However, if we assume that an interrupting device normally is mounted directly adjacent to the transformer, this factor can be ignored.

Transformer and distribution-system ground connections also influence frequency because of variations in effective transformer capacitance. System impedance plays a minor role in determining both the magnitude of fault current and the nature of the TRV appearing across an interrupting device.

Circuits involved in the fault on the secondary side of the transformer have an influence on both the fault current and the recovery voltage across a primary interrupting device. The severity of the fault as seen by a primary interrupting device is slightly reduced when secondary circuit conductors are included in the fault circuit. The most difficult condition is a fault directly at the secondary terminals of the transformer. The table at the bottom of page 90 summarizes the basic relationships between these various factors.

TRV Measurement

A convenient means for measuring these properties is a technique commonly referred to as "current injection." As the term implies, the procedure is to inject a current into the circuit or system being studied, and measure the response of the circuit to the injected current. Typical current injection records are shown at the top of page 88.

This technique has been widely used both in the laboratory and in the field over a five-year period on a great variety of circuits and devices. Comparative results from current-injection measurements and actual interrupting tests consistently have shown the current-injection method to be valid. It has been demonstrated that, for secondary faults on transformers, current-injection measurements alone are sufficient for determining the TRV appearing across an interrupting device. Because of the nature of the circuit, the transformer can be isolated from

TRV FREQUENCY AS A FUNCTION OF TRANSFORMER RATINGS

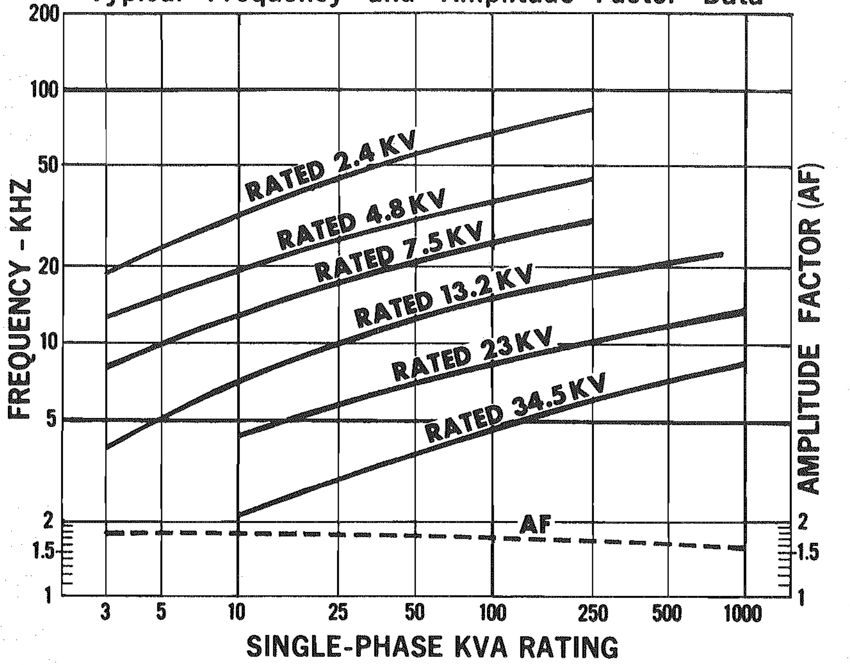
BASIC FORMULA $f_R = \dfrac{1}{2\pi\sqrt{LC}}$

f_R = Resonant frequency
L = Effective inductance
C = Effective capacitance

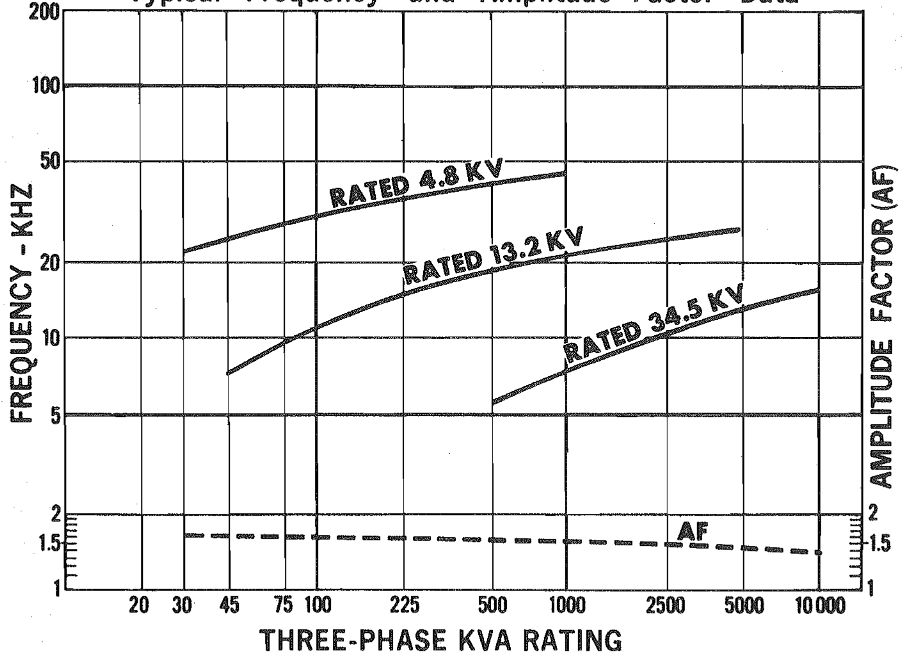
DERIVED FORMULA $f_R = \dfrac{A}{(kV)}\sqrt{\dfrac{(kVA)}{C\,(\%Z)}}$

(kV), (kVA), (%Z) = Transformer nameplate values
C = Effective transformer capacitance
A = Constant

Single-Phase Transformers
Typical Frequency and Amplitude-Factor Data



Three-Phase Transformers
Typical Frequency and Amplitude-Factor Data



RRRV can be as high for a 2-4-kv transformer as for a 34.5-kv unit. Field tests document lab experience.

the distribution system and current-injected. Data obtained can be used to describe fully actual TRV encountered in the field.

A substantial number of distribution transformers have been current-injected. Enough data are available to define the TRV characteristics of most single-phase and three-phase transformers typically used for distribution service. Approximately 200 single-phase transformers have been examined, representing ratings from 2.4 kv through 36.5 kv and from 3 kva through 667 kva. Approximately 50 three-phase transformers were measured varying in rating from 4.16 kv to 34.5 kv and 30 kva to 7500 kva. These transformers represent a cross-section of 15 manufacturers and a wide range of percent impedances.

Typical TRV data from these current-injection measurements are summarized on page 89 for single-phase transformers. Frequency values determine the rate at which the voltage recovers to its crest value across an interrupting device. Amplitude factor data indicate the relative degree of decrement or damping of the transient which directly influences the transient crest voltage as related to normal crest voltage. The average RRRV can be calculated from frequency and the crest voltage as determined by amplitude factor.

Typical results for three-phase transformers are shown on page 89.

A study of the data indicates that frequency is a function of transformer kva rating—a result to be expected since leakage inductance is inversely proportional to kva rating for a given percent impedance. Also, frequency is an inverse function of transformer voltage rating and percent impedance for the same reasons. A simple expression can be readily derived, as shown at top of page 89, using the nominal nameplate ratings to indicate the general relationship. For a given voltage rating and percent impedance, this expression further can be simplified to:

$$f_n = A_1 \sqrt{\frac{(\text{kva})}{C}}$$

A_1 = constant containing (kv) and (%Z)

Capacitance cannot be dropped easily from this expression since it is not solely a function of kva. The current-injection data presented generally follow this relationship.

In a similar fashion, it can be shown that the average RRRV across an interrupting device for a transformer-secondary fault is essentially independent of the transformer voltage rating. Assume the average RRRV is equal to:

$\text{RRRV} = 2f_n\ (\text{AF})\ V_s$

f_n = transformer resonant frequency

(AF) = amplitude factor

V_s = power-frequency recovery voltage

Substituting one of the above expressions and manipulating, the following results:

$$\text{RRRV} = A_2 \sqrt{\frac{(\text{kva})}{C}}$$

assuming amplitude factor is relatively constant and is absorbed into a new constant A_2.

Thus, RRRV can be just as high for a 2.4-kv transformer as for a 34.5-kv transformer for a given kva size. It is recognized that capacitance is a function of voltage, and as a result the expression is oversimplified, but the general idea is evident.

Field and Lab Tests

Field test data on 4.8-, 7.6- and 13.2-kv distribution circuits show that frequency values are essentially equivalent to current-injection values. Recovery voltage frequencies are also independent of system characteristics such as available primary-fault current, effective system capacitance, connected system load, etc. Comparing amplitude factors results in the same general conclusions.

Further exploration of the TRV associated with transformer-secondary faults was conducted in the laboratory. A comparison between lab interrupting-test results and current-injection data shows that the transient appearing across the interrupting device is essentially independent of the lab source circuit used, and is equivalent to the current-injection values for the faulted transformer alone. The general conclusion is that transformer-secondary fault tests can be simulated by a laboratory circuit.

This conclusion does not imply that an accurate representation of the transformer can be eliminated. As discussed previously, a transformer preferably should be used, or a synthetic circuit must be carefully devised to produce not only the same voltage, current, and power factor, but more importantly, the frequency and amplitude factor required. The source or system parameters can generally be ignored as shown by both the field test and lab test data.

Editors Note: Additional information on test procedures and results is available upon request from EL&P or the author.

SUMMARY OF FACTORS INFLUENCING TRV FREQUENCY

Lower transformer impedance = Higher frequency

Higher transformer kVA rating = Higher frequency

Greater system capacitance = Lower frequency

Higher transformer kV rating = Lower frequency

Grounded transformer or system = Lower frequency