AN OVEREXCITATION RELAY
WITH INVERSE TIME CHARACTERISTICS

By

Jim Arthur
ASEA Inc.
San Mateo, CA

John Linders
Consultant
Sarasota, FL

Gunnar Stranne
ASEA Inc.
Yonkers, NY

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Abstract - The desirability for overexcitation protection of transformers which more nearly matches the capability of these components is discussed. A new relay is described which provides this improved protection. The relay incorporates an inverse-time operating characteristic, adjustable over a range adequate for protection of all size transformers. Coordination of overexcitation protection on a system wide basis appears feasible.

INTRODUCTION

Overvoltage operation of transformers, generators and motors can result in overheating, and in extreme cases their destruction in a relatively short time. Sometimes these conditions arise as a result of operating procedures which do not recognize the hazard. In such cases the solution is obvious, although not necessarily easy to implement. In other cases the overvoltage condition is the result of a system upset following a disturbance. In these cases operator intervention cannot be relied upon because: a) there may be no operator, and b) those operators who are available are busy with "more important" tasks. As systems become more fully automated a third possible cause of overvoltage is a malfunction of the automatic regulating equipment, or the regulating equipment may respond to system parameters which can result in overvoltage on specific components.

Overvoltage is a meaningful term only at rated frequency. A low frequency has the same effect on magnetic circuits as high voltage. Thus the preferred expression is overexcitation, and the unit of measurement which incorporates both parameters is volts/hertz (V/Hz). The end use of much of the power generated and distributed by utility systems is for illumination which is not frequency sensitive. As a consequence most voltage regulating control equipment responds to voltage and not to excitation. Historically this has not caused serious system operating problems, because the magnetic components, transformers and machines, were not overly sensitive to overexcitation. Modern designed transformers and machines are more sensitive to overexcitation than earlier equipments. This is the result of more efficient designs, and designs which rely on the improvement in the uniformity of the excitation level of modern systems. Thus, when a system upset that includes overexcitation does occur, transformers and machines may be damaged unless corrective action is promptly taken.

OVEREXCITATION LOSSES

The equivalent circuit of a power transformer, Fig. 1, generally shows shunt branches containing, 1). the magnetizing impedance represented by a pure inductance, 2). the core losses represented by a pure resistance. This equivalent shunt circuit is an accurate representation only at rated frequency and at flux levels up to but not significantly above the design levels. This equivalent circuit cannot be used to calculate overexcitation losses because of the non-linear relations which occur in this region. The present transformer standard, ANSI/IEEE C57.12.00-1980 [1] specifies permissible excitation levels as follows:

"4.1.6 Operation Above Rated Voltage or Below Rated Frequency.

4.1.6.1 Transformers shall be capable of:

(1) Operating continuously above rated voltage or below rated frequency, at maximum rated kVA for any tap, without exceeding limits of observable temperature rise in accordance with 5.11.1 when all of the following conditions prevail:

(a) Secondary voltage and volts per Hertz do not exceed 105 % of rated values
(b) Load power factor is 80 % or higher
(c) Frequency is at least 95 % of rated value

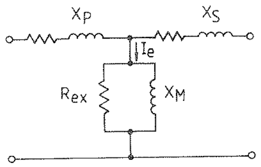

Fig 1. Transformer equivalent circuit, useful only in linear region below saturation.

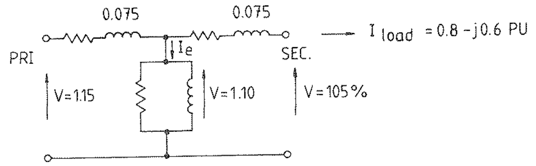

Fig 2. Transformer conditions at 105% voltage and full load, 0.8 PF.
Note: Minor saturation exists and exciting current and losses can not be accurately calculated from constants of fig 1.

(2) Operating continuously above rated voltage or below 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.

4.1.6.2 The maximum continuous transformer operating voltage should not exceed the levels specified in ANSI C84.1-1977

5.11.1 Limits of Observable Temperature Rise

5.11.1.1 Winding Rise. The average winding temperature rise above ambient temperature shall not exceed 65°C when measured by resistance, and the winding hottest spot temperature shall not exceed 80°C.

5.11.1.2 Other Winding Rises. Other winding rises may be recognized for unusual ambient conditions, or for special applications. These are specified in appropriate applications, or in certain product standards.

5.11.1.3 Rise of Metallic Parts, Other than Windings. Metallic parts in contact with current-carrying conductor insulation shall not attain a temperature rise in excess of the winding hottest spot temperature rise. Metallic parts other than those described in the preceding paragraph shall not attain excessive temperature rises at maximum rated load. The temperature rise of the insulating liquid shall not exceed 65°C when measured near the top of the main tank."

The temperature profile within the transformer due to overvoltage will be different from that due to overload. While the Standard recognizes this in general terms, it does not quantify the significance of this different profile, nor of the extremely non-linear effects of serious overexcitation.

The full load kVA, 0.8PF, 105% voltage requirement results in an actual flux level in the transformer core, not significantly different from that at the 110% voltage, no load requirement. For a transformer with 15% impedance, equally divided between primary and secondary windings, and a load of 0.8 + j0.6 pu, the flux level with 105% output voltage will nearly correspond to 1.10 per unit.

The applied primary voltage would be correspondingly higher at 1.15 per unit as shown in Fig. 2. With the flux level at an acceptable value, this higher primary voltage is not detrimental to a transformer fully loaded at 0.8PF. The operation of fully loaded transformers up to 105% output voltage would thus appear to be a conservative practice at rated frequency, especially with transformers having less leakage reactance associated with the output winding.

At these limiting values, one can estimate the losses as follows. Assume a transformer with maximum efficiency of 99% at 75% load. Assume the core losses are equal to the copper losses and are thus 1/2% each. At full load, the losses would be:

$$0.5 + \left[\frac{1.0}{.75}\right]^2 \times 0.5 = 1.39\ \%$$

At no load and 1.1 pu voltage, the losses would be also about 1.39% based on the Standard which calls for no greater temperature rise than under rated load conditions. Thus, in raising the flux level from 100% to 110% the no load losses have increased from 0.5% to 1.39%, i.e., a 10% increase in voltage increased no load losses 280%. Above 110% excitation, losses will increase still more rapidly. At these higher levels the core saturates and some of the flux will enter non-laminated structural components which have large hysteresis and eddy current losses. The excitation current will increase, approaching full load current value at 150% excitation. The temperature rise from all of these losses can damage insulation, weaken mechanical structures and lead to actual transformer failure in a short period of time.

OVEREXCITATION CAPABILITIES

In 1966 McNutt, et al [3] presented a comprehensive analysis of the several components of transformer overexcitation losses. They showed that a rather long period of overexcitation is required for the core laminations to overheat and cause damage. However, unlaminated structural parts can experience runaway heating in a very short time. For example they show that these losses increase 25 fold in going from 110% to 120% excitation. Similarly, conductor loss due to stray flux eddy currents can increase to nearly 200% of full load conductor loss at 130% excitation. They [3] proposed a guide for permissible short time transformer overexcitation capability as shown in Fig. 3. Several other transformer overexcitation capability curves, including the German Standard are shown in Fig. 4. The curves in Figs. 3 and 4 are presented with respect to the rated voltage of each transformer. In the case of a generator - stepup transformer unit, the transformer rating is frequently 5% lower voltage than the generator.

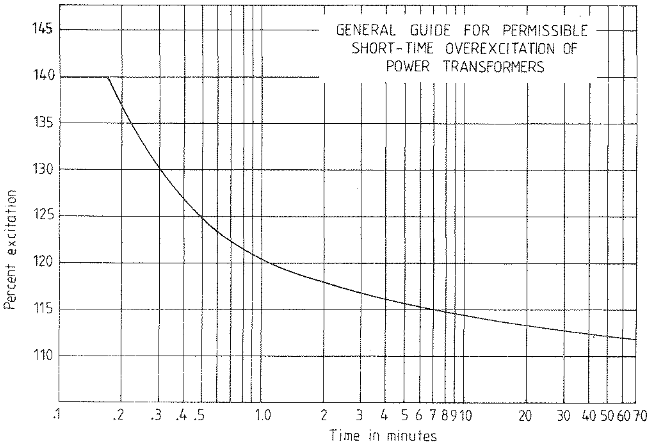

Fig 3. Standard overexcitation capabilities.

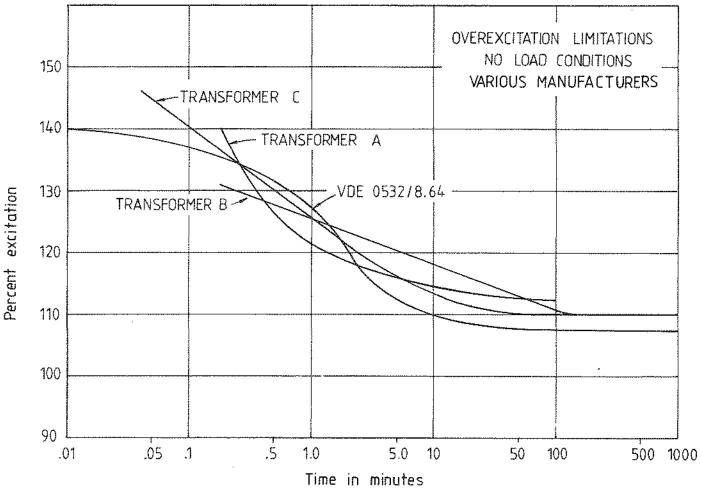

Fig 4. Various overexcitation capabilities.

This must be properly considered when rationalizing the combined overexcitation capability of the unit. And of course the transformer capability is based on its output voltage whereas the unit generator is based on the (generator-output) transformer input voltage.

CAUSES OF OVEREXCITATION

The most likely location for an overexcitation condition is at a generating plant, but most any point on a system could be so affected for one reason or another. Some of the causes of overexcitation are:

1. During generator start-up and shut-down overexcitation will occur at any machine speed if the rated V/Hz ratio is exceeded.
2. Loss of load or load shedding with failure to reduce generator field current accordingly. Maintaining field current in such circumstances has obvious effects. However, generator voltage maintained at the former value can also result in overexcitation of the transformer. This is evident from Fig. 2 where the transformer primary voltage of 1.15 pu is also the secondary voltage under a no load condition. This can be further aggravated if the charging current of a high voltage circuit is also present.
3. Loss of load or load shedding at a transformer substation. Normally L-T-C control action or voltage control capacitor switching will restore voltage to an acceptable level. But if the loss of load is wide spread, the primary supply system voltage may be too high for local corrective action to be fully effective.
4. Islanding
   a). Loss of load or load shedding as noted in items 2 and 3 above may be compounded by low frequency when islanding occurs.
   b). Maintaining voltage, as many regulating systems do during low frequency can also result in overexcitation.
5. Malfunctioning of regulating equipment. Historically operator intervention has provided suitable "backup" to L-T-C's and other automatic regulating devices. Fewer operators, more automatic sequences and more sensitivity of transformers and machines to overexcitation increases the probability of overexcitation damage from malfunctioning regulating equipment.

INVERSE-TIME OVEREXCITATION RELAY PARAMETERS

The basic operating parameter of the described relay is volts/hertz. The relay pickup can be set within the range of 1.5 to 3V/Hz for both alarm and tripping. The operating time is inversely proportional to the degree that the applied V/Hz exceeds the V/Hz setting on the relay. The precise relation approximates a square law and has been chosen based on analysis of the various transformers' overexcitation characteristics such as noted in Figs. 3 and 4. The nominal rating of the relay is 100-120V and 50-60Hz which corresponds to 2V/Hz. The usable frequency range is 2 to 75 Hz and the maximum continuous voltage at any frequency is 180V. The relay has the equivalent of a time dial which permits matching the "thermal time constant" of the device being protected over a wide range of settings. The complete inverse-time operating characteristic is shown in Fig. 5. These curves are the result of an operating equation

$$t = 0.8 + \frac{0.18 \times K}{(M-1)^2} \text{ seconds}$$

where M is the multiple of pickup (V/Hz applied divided by set V/Hz) and K is the set time multiplier.

Fig. 6a shows how these characteristics can match a typical transformer overexcitation capability. In this case the relay is set to pickup at 110% of rated excitation and has a time delay setting of K=3 corresponding to a 3.0 second operating time at 1.45 times pickup (1.60 p.u.). A lesser K setting would provide faster protection and a lower pickup setting more sensitive protection and vice-versa. Thus, the relay characteristic can be adjusted to match substantially any excitation capability curve. Fig. 6b shows how manipulating M and K together can change the effective inverse-time characteristic.

OPERATING PRINCIPLES OF NEW RELAY

There are two basic measurements made in the new relay.

1. Volts per hertz. There are two separate, independently adjustable V/Hz level detectors, one for alarming, the other for tripping.
2. Elapsed time. There are two independent timing circuits.
   a). A fixed time delay, (settable at 0.1 or 3.5 sec.) This is initiated by the alarm level detector. The purpose is to alarm or initiate corrective control action.

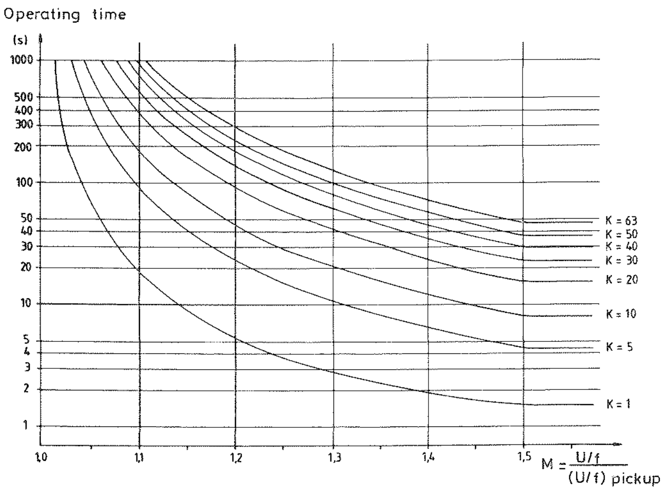

Fig 5. Operating time t as a function of the relationship between the actual excitation and the set starting value, for different time settings K.

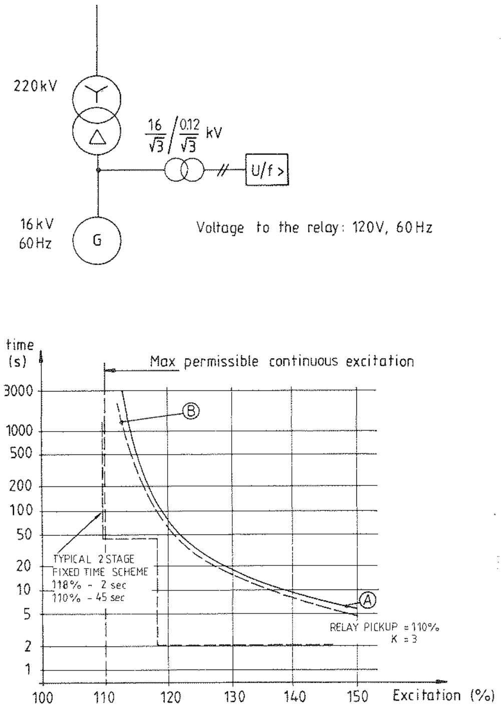

Fig 6a. Ability of RATUB (B) to match transformer capability (A).

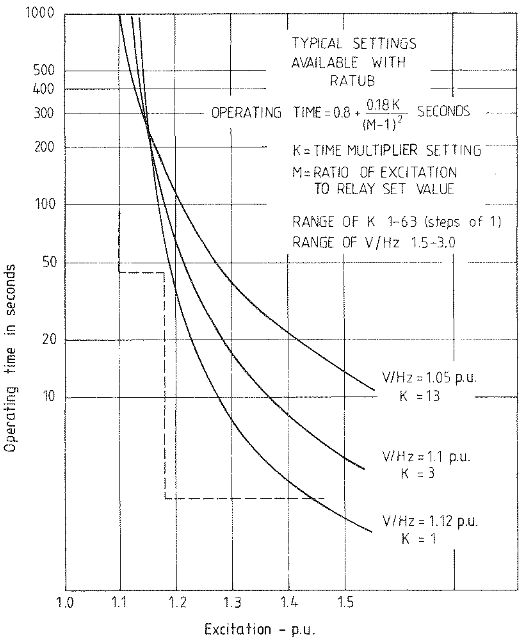

Fig 6b. Typical inverse-time characteristics.

b). A variable time delay which is inversely proportional to the square of the overexcitation level. This is initiated by the level detector for tripping. The time delay of this inverse time curve is adjustable between 1 and 63 seconds at about 1.45 times pickup. In addition, operation of this level detector results in exciting an LED to show that the relay is timing out.

The V/Hz measurement is most easily understood by rearranging the terms:

V/Hz = V/cycle/second = Volt-seconds/cycle

With V in rms in the basic equation, the volt-seconds will also be in rms volt-seconds. However, the transformer flux is proportional to the average voltage over one-half cycle. Thus, the desired measurement for excitation level is:

$V_{avg.} \times \frac{1}{2f}$, where f is system frequency in Hz

This is the area under each half cycle of the voltage wave. Assuming no dc component on a steady state basis, it is immaterial whether the positive or negative half cycle is measured. In the described relay, the positive half cycles are averaged over the half cycle, i.e., integrated over each half cycle period. During the unmeasured half cycles, the measured quantity is transferred to an analog memory for further processing. Figure 7 illustrates how an op-amp, plus control signals can provide this half cycle integration. The control signal is synchronized to the supply such that only positive half cycles are provided to the op-amp input. The op-amp feedback capacitor provides the integration function in a conventional manner. The 1/2 cycle updating control system also controls the integrator output by causing it to reset after transferring this output to the memory capacitor at the end of each half cycle measurement. The memory voltage thus follows the V/Hz signal and is updated each cycle.

The memory voltage is measured by the aforementioned level detectors. The alarm level detector is set by means of a calibrating resistor which controls the cut-off signal level of an op-amp. This is shown in Figure 8. The alarm signal is delayed 0.1 s or 3.5 s to avoid nuisance alarms. This delay is developed in a counter, controlled by the alarm level detector output, which counts the oscillations of the internal oscillator. The counter is set for the desired delay by means of a two position switch on the face plate of the timing module.

The level detector for the time-delay trip function is required to provide an output proportional to the signal level in excess of the set pickup value. This is in contrast to the alarm detector in which the output is required only on a go-no go basis. Compare Figs. 8 and 9. The threshold of the time-delay trip level detector is a fixed value. The voltage applied to this level detector consists of the signal proportional to the V/Hz minus a control voltage. This control voltage, and hence the V/Hz pickup level of the detector, is set by means of a resistor which is adjustable by means of the calibrated knob on the face plate of the level detector module. When this level detector gives an output, it energizes an LED to indicate that the relay is timing out. This output signal also turns on a counter and provides the input to an A/D converter where the signal is converted into a binary number for the remaining time-delay processing. To provide the inverse characteristic, the binary number is first multiplied by itself (squared). This number is then used to multiply the frequency of the internal oscillator so that the output frequency is proportional to the binary number. The individual cycles of the resulting frequency are thereafter processed in a counter which can be set to give an output after the selected number of cycles. This setting is made by the six two position "K" switches. A basic minimum delay of 0.8 seconds is inherent in the counting circuitry. The basics are shown in figure 9b.

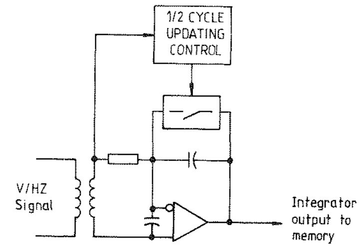

Fig 7. Basics of volt-second integrator.

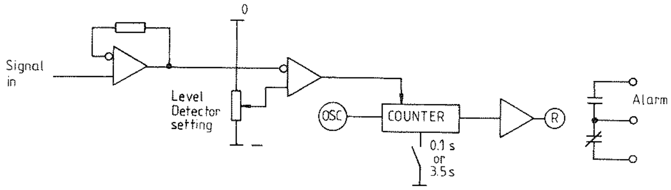

Fig 8. Basics of alarm level detector.

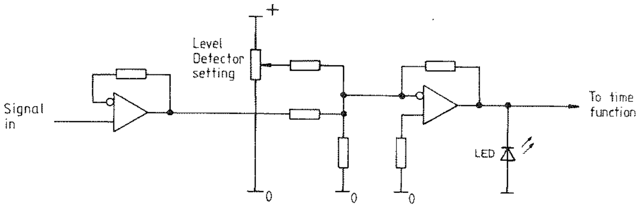

Fig 9a. Basics of inverse time-delay level detector.

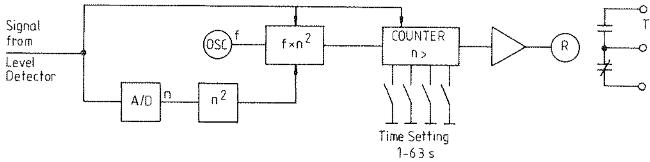

Fig 9b. Basics of digital time delay trip function.

The result is a set of time-delay characteristics as shown in Figure 5. At high levels of overexcitation (eg 1.4 times relay pickup) this K adjustment provides a time delay adjustable in about one second increments from a minimum of under 2 seconds to a maximum of over 80 seconds. The described relay has type designation RATUB and is packaged in the standard COMBIFLEX system for 19" rack or panel mounting. Fig. 10 shows the complete relay consisting of six plug-in modules.

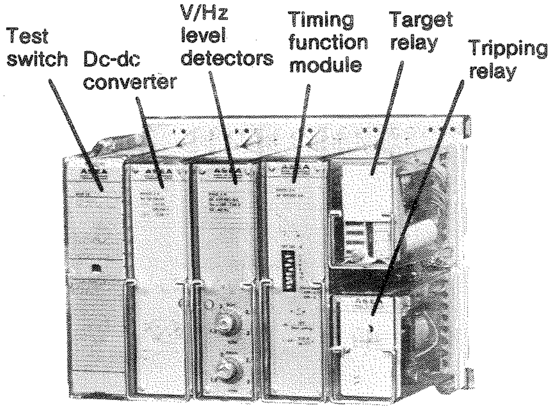

Fig 10. RATUB overexcitation relay.

V/Hz RELAY APPLICATION CONSIDERATIONS

The pickup values of both the time-delay tripping and alarm level detectors are continuously adjustable over a range of 1.5 to 3.0 V/Hz. This, plus the adjustable time-delay characteristic provides a setting flexibility comparable to a conventional time-overcurrent relay. By a suitable choice of pickup and time delay settings, a wide variety of operating time vs. input signal levels can be created, as illustrated in Fig. 6b. Additionally, the alarm function has a separate available output. Since the alarm level can be set independently of the inverse time-delay unit, it can be used to bypass the inverse time delay using either the 0.1 or 3.5 second fixed time delay. Also, the alarm output relay could be used to supervise the time delay tripping, thus permitting the time delay pickup to be set at a lower value with minimum hazard of a nuisance tripping. While the present design provides means only to supervise the time output, it is feasible, if there is a user need, to supervise the starting of the time delay function by means of the "alarm" output signal. The alarm level can also be used with a timer or directly to modify the trip characteristic by "cutting" the inverse-time curve to create a constant, minimum fixed operating time above a certain V/Hz value.

The V/Hz measurement can be made on either the primary or secondary side of the transformer. Either has its application limits with respect to the change in protection due to transformer loading. Transformers with L-T-C's should be monitored on a winding without the tap changing facilities regardless of normal load flow. A transformer with 8% impedance will have about the same primary excitation limit whether unloaded or loaded at 0.8PF. Higher impedance transformers will have the capability of a higher primary voltage when loaded and lower impedance transformers will have a lower primary capability.

Historically, overexcitation protection has been considered an ultimate backup to system malfunctions. That is, it is assumed that the system is incapable of operating in a safe manner due to some malfunction and that a system shut down is acceptable rather than destroying a major component from overexcitation. This philosophy is not questioned in the ultimate. However, this new inverse-time overexcitation relay provides a substantial improvement in the ability to utilize the full V/Hz capability of major components. By using the time made available with this new relay to initiate other system protective or control action, the cause for the overexcitation may sometimes be removed. When this is possible, a major system outage may be avoided, but when it is not possible the new relay still provides proper protection of the major components. Volts per hertz relay coordination in this context means more than the coordination of two or more V/Hz relay settings. It enables coordination of the capabilities of major components with feasible control action throughout the system.

In this context, consideration should also be given harmonic restraint transformer differential relaying to ensure that proper restraint action is obtained during overexcitation events. An undesirable trip could result from transformer differential relays, at light loads, due to the increase in excitation current drawn by overexcited transformers. This excitation current can approach rated transformer load current at 50 to 75 percent overvoltage. Unless proper overexcitation restraint is provided, coordination between the V/Hz relay and the transformer differential relay may be lost.

SUMMARY AND CONCLUSIONS

Overexcitation protection is required for major power system components due to the inability of other protective and regulating devices to detect and prevent excessive overexcitation. Simple overvoltage protection is not sufficient because a decreased frequency has the same excitation effect as an increased voltage and both can occur simultaneously due to a system upset or control malfunction. The inverse-time, V/Hz overexcitation relay has a substantial advantage over a stepped fixed-time V/Hz scheme in that it can be set to match the overexcitation capability of the protected component. This matching protects the component from failure or accelerated aging while providing time for the system control action (or manual intervention) to try to correct the overexcitation.

Coordination of V/Hz overexcitation protection thus has three aspects:

1. Optimum utilization of the protected component's overexcitation capability.
2. Coordination with other protective relays, including other V/Hz relays.
3. Interaction with system control functions.

An overexcitation relay incorporating digital techniques to provide the desired accuracy and range of adjustments has been described and shown to be capable of matching a wide variety of overexcitation capability patterns.

References

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