OVERVOLTAGE CAUSES AND INVERSE VOLTS-PER-HERTZ PROTECTION

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Presented to:
Western Protective Relay Conference
Spokane, Washington
October 20-22, 1987

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INTRODUCTION

Overvoltage on power systems is caused by a variety of sources. Lightning is the most prevalent, but its effect is readily held to acceptable levels through the use of lightning arrestors, often complemented at the machine level by surge protective capacitors. This phenomenon is a short duration one, being over in a few microseconds and having no consequence in the heating of apparatus (other than the surge-diverting equipment).

This paper addresses those longer term overexcitation occurrences which do jeopardize apparatus thermally, and it suggests means by which protection can be provided, whether or not frequency change accompanies the overexcitation.

In this paper, overvoltage refers to instantaneous voltage across circuits or insulation in excess of the normal peak operating voltage to be expected at any point on the power system. Overexcitation is referred to as conditions producing a peak flux density level in the magnetic circuit of apparatus in excess of normal peak operating flux density.

Faraday's Law

The well-known classical equation for induced voltage in a coil is:

$$e = 4.44fANB_M \text{ on } 10^{-8} \qquad (1)$$

which, considering constant cross sectional area, A, and turns, N, reduces to

$$e = K\ f\ B_M \qquad (2)$$

where e is RMS volts applied across the coil, f is frequency in hertz, B_M is flux density in maxwells per unit area and K is a constant, consolidating the remaining elements of the equation.

From this we get:

$$B_M = \frac{e}{Kf} \qquad (3)$$

showing flux density to be dependent not only on voltage, but also on frequency. Volts-per-hertz, then, is a key factor in establishing flux density.

Flux density was described by Steinmetz to be highly influential in eddy current and hysteresis loss, the two major components of iron loss. Loss, of course, creates heat. Since eddy current loss is proportional to the square of flux density and hysteresis loss is proportional to some exponent (such as 1.6) of flux density, it follows that heating is very much dependent on volts-per-hertz.

Causes of Overexcitation

Some of the conditions that are known to cause overvoltage or overexcitation are:

1. Excitation System Failure

Generator regulators, perform their action in a closed loop as figure 1 shows. By sensing generator terminal voltage, they are able to compare this with the preset desired voltage. If the terminal voltage is low, machine excitation is increased. The machine voltage responds and a stable operating voltage is maintained. Failure of the supply network to the regulator or incorrect sensing by the regulator of the machine voltage or runaway in the "boost" direction for any reason causes the generator and perhaps its connected transformers to experience overexcitation. The frequency in this case remains at rated value.

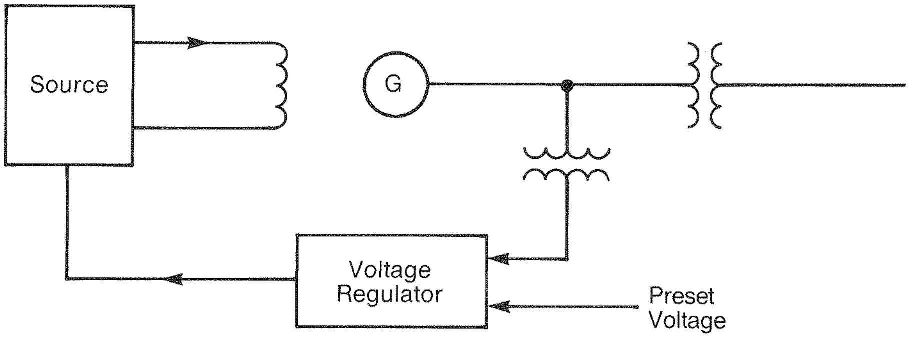

Fig. 1 Excitation System

2. Capacitive Effect

Capacitive current flow through inductive reactance produces voltage rise. Figure 2 represents a long transmission line, open at the end that is remote from generation.

The voltage rise in the equivalent diagram is $I_C X_L$ while the voltage drop caused by I_M, the exciting current of the transformer, is $I_M X_L$. The net voltage rise then is $(I_C - I_M) X_L$. If this can cause the voltage to exceed 110% of the voltage rating of the transformer and is allowed to persist, the transformer will be in jeopardy of failure.

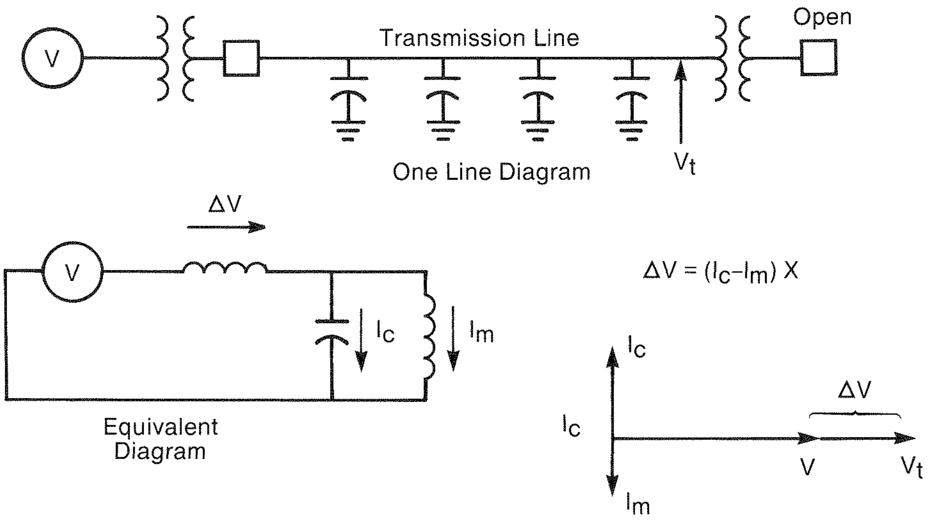

Fig. 2 Transformer Energized Through Line

3. <u>Load Rejection</u>

When a generator is suddenly unloaded by switching as in Figure 3 or a fault as in Figure 4, the difference between power being delivered to the generator shaft and power being taken from the stator terminals appears as P_a "accelerating-power". P_a applied to the generator, the turbine and accessories, causes this rotating mass to increase in angular velocity. Speed increases and frequency increases.

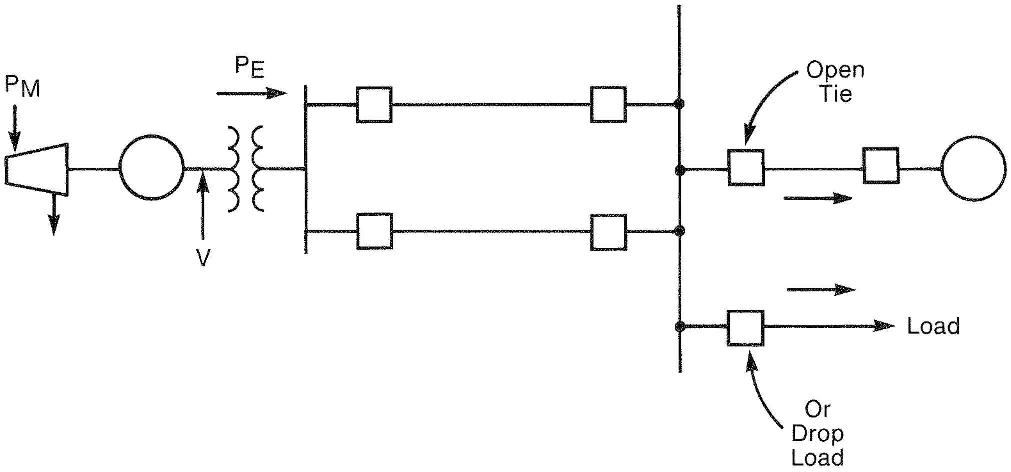

Fig. 3 Acceleration Caused By Switching

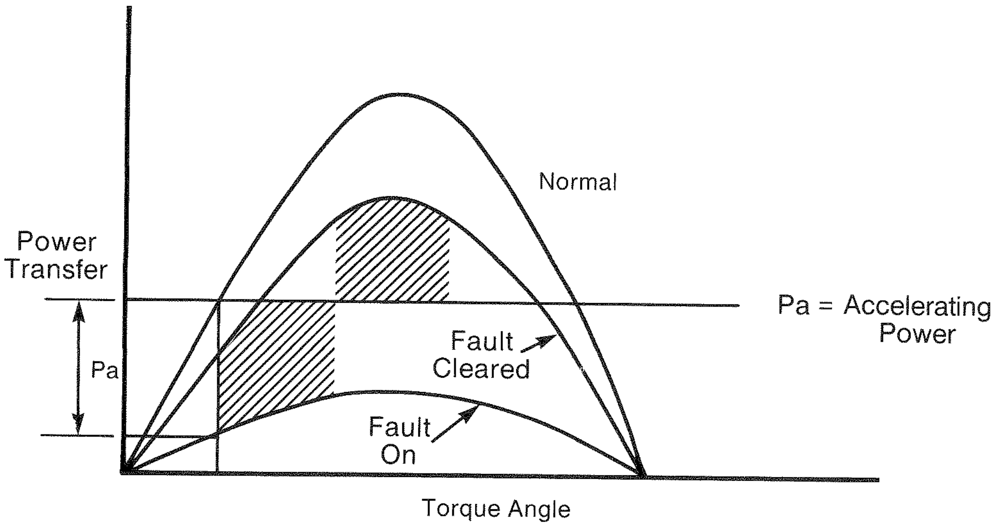

Fig. 4 Acceleration Caused By Fault

If the generator is equipped with a rotating exciter, the effect will be as described in Figure 5. With no change in exciter field current, the exciter voltage increases, raising the generator field current and generator terminal voltage. This is further compounded by the fact that the generated voltage is proportional to speed with a <u>fixed</u> excitation. The combined effect of increased speed and increased field current is that machine voltage increases approximately as the square of frequency, if the regulator is out-of-service or does not respond or there is no manual intervention. A static exciter supplied from the machine terminals would manifest the same behavior because increasing terminal voltage, with speed, would cause the exciter output to increase.

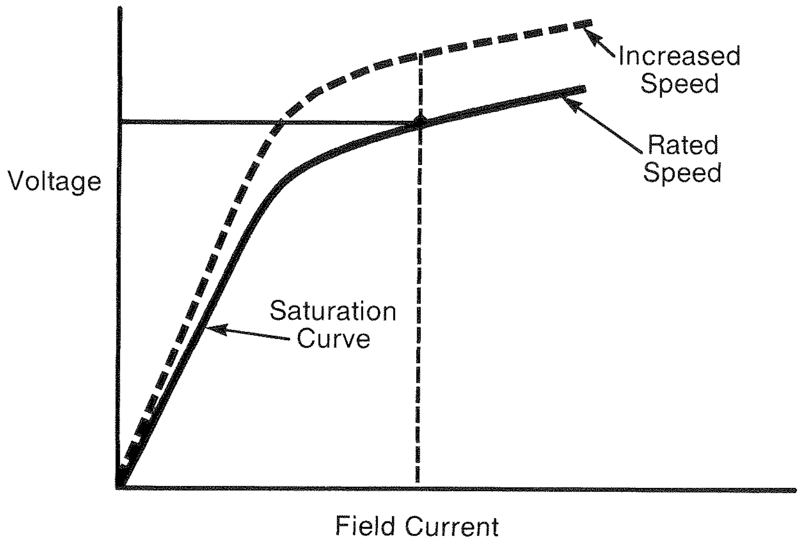

Fig. 5 Effect of Increased Speed

A properly responding, frequency compensated regulator would override these effects, provided of course, it were in service when the load rejection occurred.

4. Coast-down

When a machine is taken off the line, it is generally allowed to coast-down with excitation applied to allow the machine (and unit transformer if used) no load losses to assist in the deceleration process. If the regulator were inadvertently left in service, it would attempt to hold rated voltage as machine speed decreased. This would cause current to be applied beyond the capability of the field winding, potentially damaging the machine. While supervision of voltage level alone will not allow detection of this hazard, supervision of volts-per-hertz will.

5. Start-up

Cross compound turbine generators are synchronized at reduced frequency, and the two machines are brought up to speed together. If the operator is inattentive and leaves the manual excitation at a fixed level as the speed and frequency increase, excessive volts-per-hertz will be applied to the generators and to the unit transformer. This can be detected readily and annunciated by a volts-per-hertz relay.

Overexcitation Limits

In spite of the fact that the basic laws of physics apply equally well to all suppliers of generators and transformers, different construction techniques and use of materials leads to different criteria for establishing overexcitation curve limits The Westinghouse limits are shown in Figure 6.

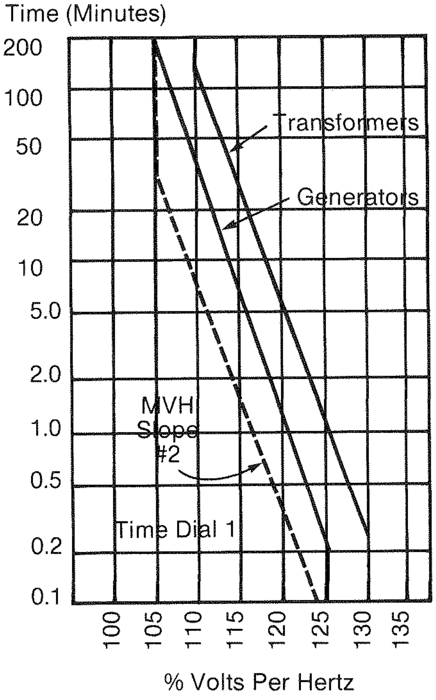

Fig. 6 Transformer and Generator Overexcitation Capability

While the transformer curve appears to be substantially higher than the generator curve, the widespread practice of applying a transformer that has a voltage rating that is 95% of the generator voltage rating in unit generator applications causes the curves to be virtually coincident, allowing a single curve (MVH curve #2, time dial 1) to reasonably protect both.

Other manufacturers have reported characteristic curves differing appreciably from these in times, slopes, and shapes. This complicates the relaying application, but by the designer of the relay using some ingenuity in the choice of basic equations, reasonable coverage of all of the known published shapes has been accomplished. The range of choices available in these curves is shown in Figure 7.

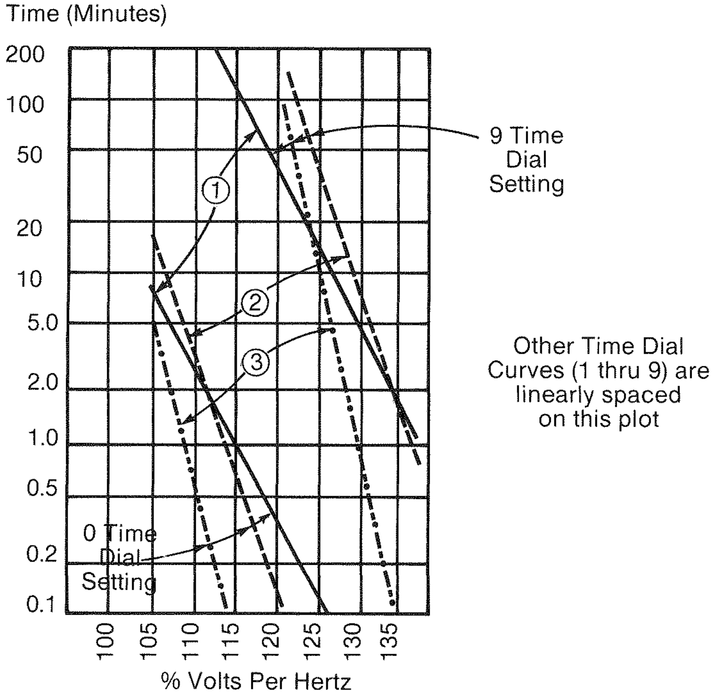

Fig. 7 MVH Relay Characteristics

MVH Relay

The MVH relay is a microprocessor-based inverse volts-per-hertz relay. It allows the selection of three different distinctive shapes, a time dial setting, and a nominal volts-per-hertz level.

1. Operating Principle

The following equation (4) is used to determine the behavior of the MVH relay:

$$t = e^{-\frac{X-K_1}{C}} \quad \text{(minutes)} \qquad (4)$$

where

X = % of V/Hz
K_1 = V/Hz scale factor
C = a slope constant
t = time to trip (minutes)
e = base for natural logarithms

Note: Timing starts when X is above pickup setting (105 to 120%)

Table I shows all values of K1 and C selected in the program.

TABLE I

	K1	C
Curve #1	115 + K x 2.5	4.8858
Curve #2	113.5 + K x 2.5	3.04
Curve #3	108.75 + K x 2.5	2.4429

where K = time dial number (0 to 9)

Three sets of the MVH curves are shown in Figure 7.

By selecting curve # (1 to 3) and the time dial (0 to 9), the microprocessor will select corresponding K_1 and C, and determine the trip time (t) for a given input value of V/Hz % (X).

The microprocessor digitally, alternately, integrates a three phase voltage input with respect to each half cycle in order to determine the ratio of voltage to frequency:

$$\int_0^{T/2} V \sin Wt \, dt = V/\pi f \propto V/f \qquad (5)$$

where f = 1/T = frequency in hertz.

The digital integration performed on each phase is accomplished by sampling the waveform every 768 microseconds. Every zero crossing signal from the waveform marks the end of one integration and start of the next.

After 200 milliseconds, the individual V/Hz computations are averaged and the largest of the three is compared to a pickup value setting. If it exceeds the pickup value, it is input to an inverse time tripping algorithm which obeys equation (4).

The microprocessor calculates the trip time t from equation (4) every 0.2 sec and adds a number of 0.2/t to an accumulator "A". If the number in the accumulator is less than one, the process will be repeated. If the number is equal to or greater than one, a trip signal will be generated to energize the tripping relay.

The flow chart of this process is shown in Fig. 8

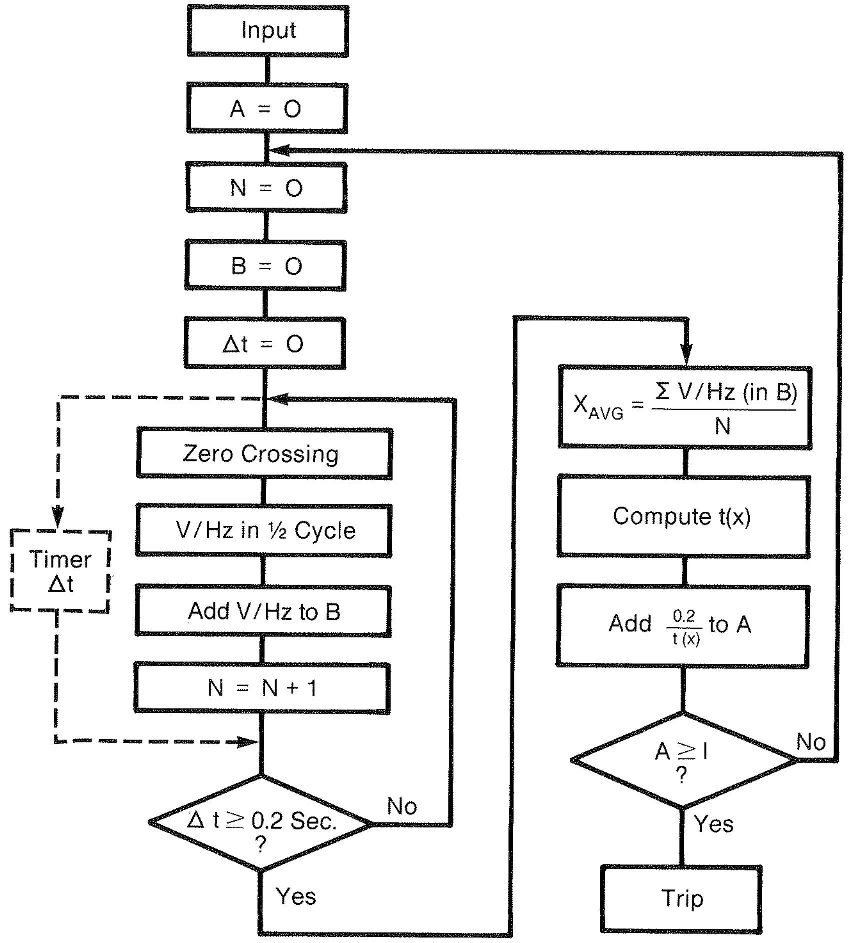

Fig. 8 MVH Flow Chart

Changes in the volts-per-hertz are carefully acknowledged with subsequent additions to accumulator "A" being based on the level to which the change has occurred.

One of the unique capabilities of the MVH relay is its linear rate reset characteristic. The rest time constant is 204 seconds. If any system disturbance causes the value of V/Hz to go above the pickup setting and then the V/Hz is reduced to normal level, it takes 204 seconds to completely reset the system. Actually, the microprocessor reads the number stored in the accumulator "A" just before the reset period has been started and divides this number by 1024, i.e. Delta = Total # in the A/1024. During the reset period, the number in the accumulator will be reduced by the Delta every 0.2 seconds. The accumulator will be completely reset in 204.8 sec, that is 0.2 x 1024. If the overexcitation condition happens again before the system is completely reset, the time to trip will be fast, and it depends on the remaining number in the accumulator.

The MVH relay is equipped with self-check and test features. The dead-man circuit keeps track of the programming routine and the crystal timing. If the programming routing is upset or the timing frequency becomes irregular, the microprocessor will be restarted and the Alarm-2 relay will dropout. The microprocessor also checks all bits in the read-only-memory every 12 minutes. Any defective bit change in the memory will be indicated by the turning off of the Self-Test LED and the dropping out of Alarm-2 relay.

Another feature included in the MVH relay provides a means of blocking tripping of type HU transformer differential relays if the Volts/Hertz exceeds 120% in all 3 phase voltage inputs. Referring to Figure 9, the HU output relay will operate to close contact HUO and open HUC. HUO introduces additional restraint into the special HU differential relay, allowing it to operate if an internal fault should occur during the overvoltage. HUC can be used to hold open the trip circuit of any relay until overvoltage is removed.

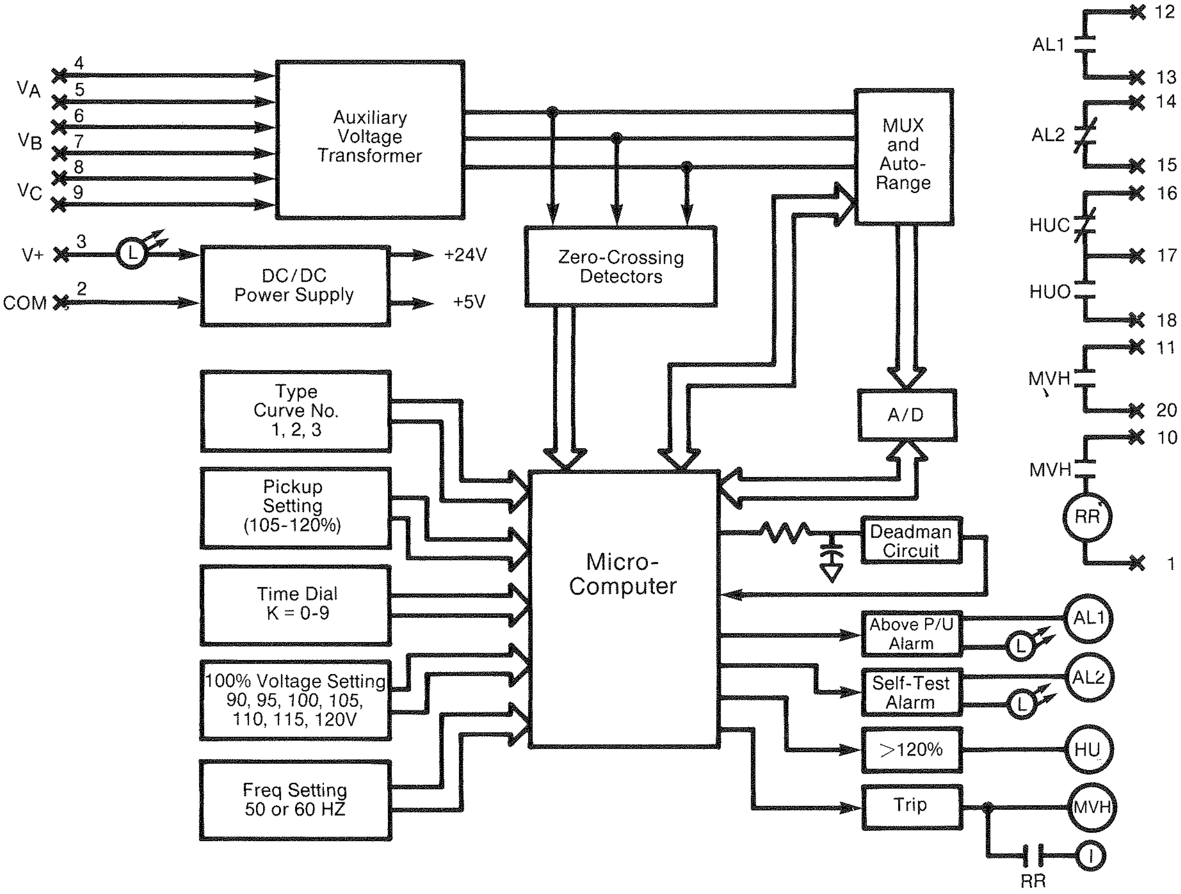

Fig. 9 Type MVH Relay Internal Schematic and Block Diagram

The MVH relay can be set with 100% volts/Hertz corresponding to nominal voltages of 90, 95, 100, 105, 110, 115 and 120 volts at a rated frequency 50 or 60 Hz. The input setting is from 105% to 120% in 1% step (16 settings) with repeatability of 0.5%. This setting allows operation of the relay for volts per hertz in excess of the value chosen.

Though the MVH relay responds to excessive volts-per-hertz, it will, of course, also operate on overvoltage at rated frequency. The relay provides accurate timing between 12.5 and 90 hertz for volts per hertz up to 150%.

Conclusion

There are many ways a transformer or generator can be subjected to overexcitation. To backup other protective or control functions, a device designed to sense excessive volts/hertz should be applied. The MVH relay provides another tool for protecting transformers and generators in a more discriminating and time coordinated way then has been possible previously. The microcomputer serves a function not readily achievable by traditional means.

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