Overexcitation and Overvoltage Protection

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***Abstract*—IEEE standards state that generators shall operate successfully at rated kVA for frequency and voltage levels within specific limits. Deviations in frequency and voltages outside these limits can cause thermal and dielectric distress, which can cause damage within seconds. Monitoring and protection schemes need to be provided for overexcitation and overvoltage deviations.**

I. Introduction

Overexcitation of a generator or any transformers connected to the generator terminals will typically occur whenever the ratio of the voltage to frequency (V/Hz) applied to the terminals of the equipment exceeds design limits. IEEE standards have established the following limits [1] [2] [3]:

- Generators, 1.05 pu at the output terminals (generator base)
- Transformers, 1.05 pu at the output terminals (on the transformer secondary base) at rated load (power factor of 80 percent or higher and frequency at least 95 percent of rated value) or 1.1 pu at no load (at the high-voltage terminals)

These limits apply unless equipment manufacturers state otherwise. When these V/Hz ratios are exceeded, saturation of the magnetic core of the generator or connected transformers can occur, and stray flux will be induced into nonlaminated components. These components are not designed to carry flux, and damage can occur within seconds. It is general practice to provide V/Hz relaying to protect generators and transformers from these excessive magnetic flux density levels. This protection is typically independent of V/Hz control in the excitation system.

Note that overexcitation protection on a generator or its connected transformers is different from field overexcitation protection. Field overexcitation protection, which usually coordinates the overexcitation limiter (OEL) of a synchronous machine, protects the field winding from thermal overload due to field overcurrent.

Excessive overvoltage of a generator will occur when the level of electric field stress exceeds the insulation capability of the generator stator winding, connected transformers, bushings, and surge arrestors. The V/Hz protection cannot be relied upon to detect all overvoltage conditions. If the overvoltage is the result of a proportional increase in frequency, the V/Hz relaying will miss the event because the V/Hz ratio remains constant. It is general practice to provide overvoltage relaying to alarm, or in some cases, trip the generators from these high electric stress levels.

II. Overexcitation Fundamentals

A magnetic field is essential to convert mechanical power to electrical power in a generator. It couples windings together to step-up or step-down voltages. The core of a generator stator or transformer is designed to provide the magnetic flux at a certain limit. The output voltage is proportional to the rate of change of the flux.

Assuming the flux is in the form of:

$$\varphi(\mathrm{t}) = \phi_{\max} \sin(2\pi \mathrm{ft} + \theta) \tag{1}$$

the induced voltage is:

$$\begin{aligned} \mathrm{v(t)} &= \mathrm{N}\frac{\mathrm{d}\phi}{\mathrm{dt}} = 2\pi \mathrm{fN}\varphi_{\max}\cos(2\pi \mathrm{ft} + \theta) \\ &= \sqrt{2}\mathrm{V}\cos(2\pi \mathrm{ft} + \theta) \end{aligned} \tag{2}$$

and the core flux requirement is:

$$\phi_{\max} = \frac{\sqrt{2}\mathrm{V}}{2\pi \mathrm{fN}} \tag{3}$$

The maximum flux in the core is proportional to voltage, inversely proportional to frequency, and can be calculated based on V/Hz.

Relaying for overexcitation, or V/Hz (per-unit voltage divided by per-unit frequency), protects generators and transformers from excessive magnetic flux density levels. High flux density levels result from various operating conditions. At these high levels, the magnetic iron paths designed to carry the normal flux saturate, and flux begins to flow in leakage paths not designed to carry it.

Fig. 1 is an axial cross-section of a turbine generator, showing the main and leakage magnetic fields. Leakage magnetic fields are most damaging at the ends of the core of the generator where the fringing magnetic field can induce high eddy currents in the solid core assembly components and the end-of-core laminations [4] [5]. This results in higher losses and heating in those components. A typical construction for the end of a generator stator core is shown in Fig. 2.

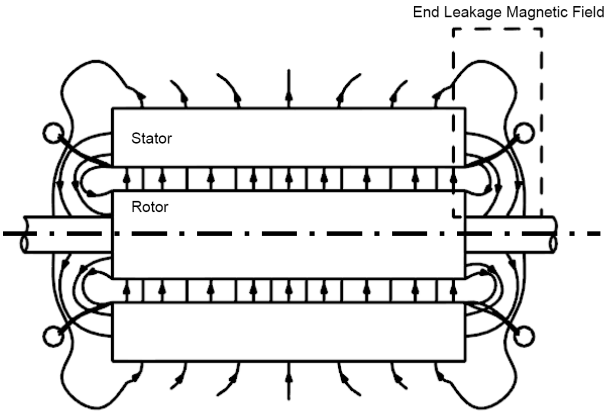

Fig. 1. Axial Cross-Section of Turbine Generator Showing Magnetic Field Paths

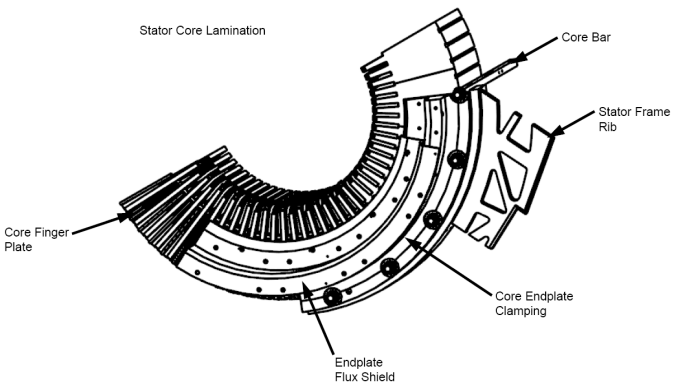

Fig. 2. Typical End Construction of Generator Stator Core

In addition to higher temperatures, eddy currents also cause interlaminar voltages that could further degrade the insulation. At extremely high levels of overexcitation, these induced voltages can be coupled to the stator laminations because of the manner in which the stator cores are designed, assembled, and clamped together. This severe over fluxing can breakdown interlaminar insulation, followed by rapid localized core melting and failure. Fig. 3 shows these current paths. If the thin insulation of the laminations is broken down by high temperatures or voltages, severe iron damage results. These high temperatures and voltages can result in damage within seconds. After this damage occurs, the core is useless. Even normal core magnetic flux density levels will only increase the amount of burning and melting. Equipment downtime will be significant. Damage is more severe than most winding failures, and the repair may require removal of the entire winding and restacking a portion of the core.

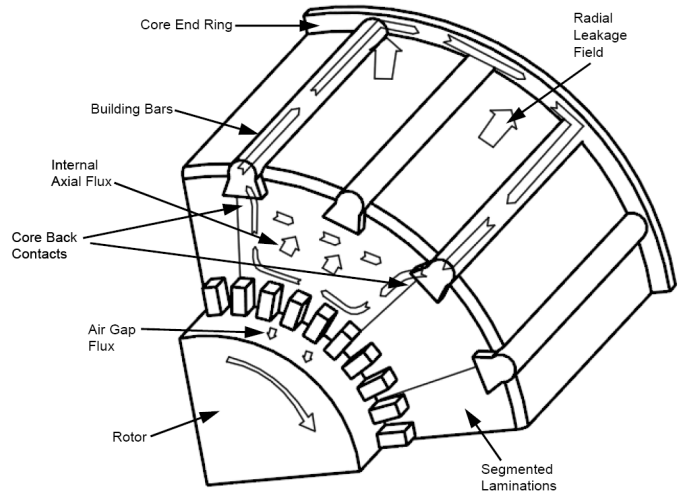

Fig. 3. Leakage Fluxes and Currents at the End of the Core

Damage due to excessive V/Hz operation most frequently occurs when the unit is offline, prior to synchronization. The potential for overexcitation of the generator increases dramatically if operators manually prepare the unit for synchronization, particularly if overexcitation alarm or inhibit circuits are inadequate or voltage transformer (VT) circuits are improperly made up. For example, a large nuclear generator failed when an improperly racked-in VT caused the voltage signal to be far less than the actual machine voltage. This signal was read by the operator manually applying field excitation. The core failed in less than one minute. This situation could also have occurred with an automatic scheme if proper safeguards were not designed into the protective system or if these measures failed.

It is also possible for a unit to experience excessive V/Hz operation while synchronized to the grid. A common belief is that the interconnected power systems in North America are infinite-bus systems and that it is virtually impossible to significantly raise unit voltages above rated operating voltage. This is not true for all units; improper full-boost operation by a faulty voltage regulator has been known to significantly raise local system voltages. Several scenarios may develop that can cause an overexcitation condition when the unit is connected to the system [6] [7]:

- Loss of nearby generation can affect grid voltage and var flow, causing a disturbance that shows itself as a voltage drop. In an attempt to maintain system voltage, the remaining generator excitation systems may attempt to boost terminal voltage to the set point limits of the excitation control while the tripped generation is reconnected. If failure of excitation control occurs during this interval, an overexcitation event takes place.
- A generator may be operating at rated levels to supply a high level of vars to the system. Unit voltage may still remain near rated grid levels because of interconnections. A sudden loss of load or interconnections can cause unit voltage to rise

suddenly. An overexcitation event will occur if the generator excitation control does not respond properly.

- Large capacitive load can activate the leading var limit function in most automatic regulators. When this function is activated, an automatic regulator will increase field current, and the generator voltage is increased. When a generator is isolated on a capacitive load, increasing the generator voltage increases var output of the capacitive load. This action may result in an uncontrolled rise to maximum excitation output and overexcitation of the generator and its connected transformers.
- Self-excitation can occur in generators due to the opening of a remote system breaker when the unit is connected to the system via long transmission lines. If the charging admittance at the generator terminals is greater than the quadrature-axis admittance $1/X_q$, the positive feedback nature of the voltage regulator control action can cause a rapid voltage rise. Self-excitation is normally associated with hydroelectric generators, because the unit may experience overspeed of 200 percent during load rejections [8].

III. Operating Limits on Equipment

Equipment limitations are an important consideration in setting the V/Hz protection for a generating unit. IEEE standards have guidelines on limits for excessive V/Hz and overvoltage of generators and associated unit transformers, including generator step-up (GSU) and unit auxiliary transformers (UATs) [9] [10]. These are summarized in Section I.

When setting overvoltage protection, certain standards govern minimum requirements. Cylindrical-rotor turbine generators must be capable of operation up to 105 percent of rated voltage. Similar variations in voltage are also set for hydroelectric generators [3]. Power transformers are only required to operate up to 110 percent of rated voltage at rated frequency depending on loading levels [2]. The V/Hz capability is measured at the transformer output. For a GSU transformer, the measurement point is at the high-voltage terminals.

Equipment damage due to excessive V/Hz is primarily caused by component overheating, which is dependent on the duration of the event. From the relationships between leakage fields and heating, curves can illustrate the limits on the magnitude and duration of V/Hz events. Manufacturers will generally provide curves for their equipment showing the limits of permissible operation in terms of percent of normal V/Hz versus time. However, manufacturers have difficulty precisely defining damage curves for heating in components that are not normally exposed to excessive stray flux except during an overexcitation event. Therefore, they may instead provide a recommended protection curve. Fig. 4 and Fig. 5 show typical curves for a generator and a power transformer.

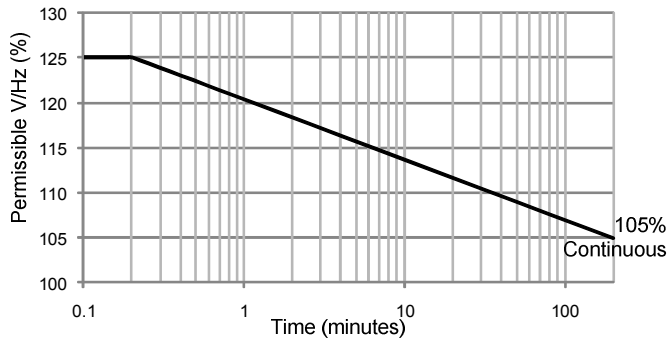

Fig. 4. Typical Limiting Curve for V/Hz Operation for a Generator [11]

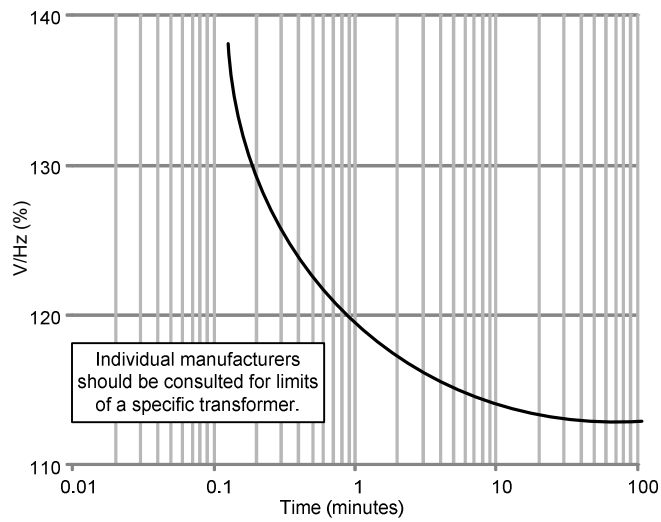

Fig. 5. Typical Limiting Curve for V/Hz Operation for a Power Transformer [10]

In setting the V/Hz protection for a generating unit, it is important that the permissible operating curves for generators and transformers be put on a common voltage base. This is necessary because, in some cases, the voltage rating of a GSU transformer's low-voltage winding is slightly less than the generator's. The resulting turns ratio partially compensates for the voltage drop in the leakage impedance due to load current. The voltage base normally used is the generator terminal voltage, because the VTs typically used for the relay voltage signal are connected to the unit between the generator and UAT and GSU transformers. Note that unless otherwise specified, the curve applies for time intervals of less than 10 minutes [1].

Equipment damage for excessive voltage alone is primarily caused by the breakdown of insulation due to dielectric stress. Overvoltage without overexcitation (V/Hz) can occur when a generator experiences overspeed due to load rejection, severe sudden fault, etc. An overexcitation does not occur in these cases because voltage and frequency increase in the same proportion; therefore, the V/Hz ratio remains constant. Manufacturers will generally provide voltage/time relationships for their equipment showing the limits of permissible operation. Because heat accumulation due to core

overexcitation reduces the dielectric strength of the stator winding insulation, the overvoltage accompanied by overexcitation has a compounding damaging effect to the winding insulation compared to the overvoltage condition alone.

In setting the overvoltage relaying for a generating unit, it is important that the permissible operating limits for generators and transformers be put on a common voltage base for the same reasons described for V/Hz relaying.

IV. Protection Schemes and Characteristics

For V/Hz relaying, two general relay characteristics are used, definite-time and inverse-time. Fig. 6 and Fig. 7 show the basic relay characteristic and zone of protection for each type of relay. For newer microprocessor-based, inverse-time relays, two styles of inverse-time curve settings are available. One relay style allows the user to select specific points on the desired V/Hz-time curve for the user's particular application. The other relay style provides sets of V/Hz-time curves from which the user selects a specific curve, providing a best fit for this application.

Note that the V/Hz curves provided by manufacturers are often based on actual core limits. When such curves are applied at the equipment terminals, they represent a no-load condition. The application of such curves under load may be optimistic. When using V/Hz curves, the applicable conditions for the curve must be known [12].

There are three common protection schemes currently employed for V/Hz relaying in the industry. These schemes are single-level, definite-time; dual-level, definite-time; and inverse-time. One major disadvantage of employing a protection scheme that only utilizes definite-time relays is the tradeoff between equipment protection and operating flexibility. Fig. 8 shows a possible protection scheme using two V/Hz relays in a dual-level, definite-time scheme. Notice the unprotected areas where equipment limits could be exceeded and the areas where the relay characteristics restrict operation below equipment limits.

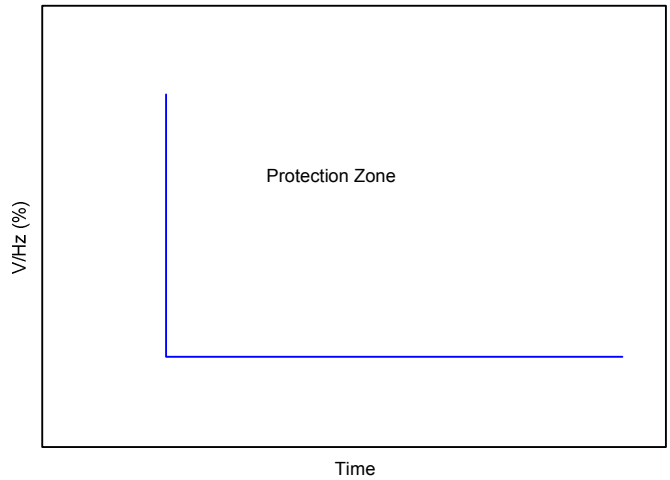

Fig. 6. Typical Definite-Time Relay Characteristic

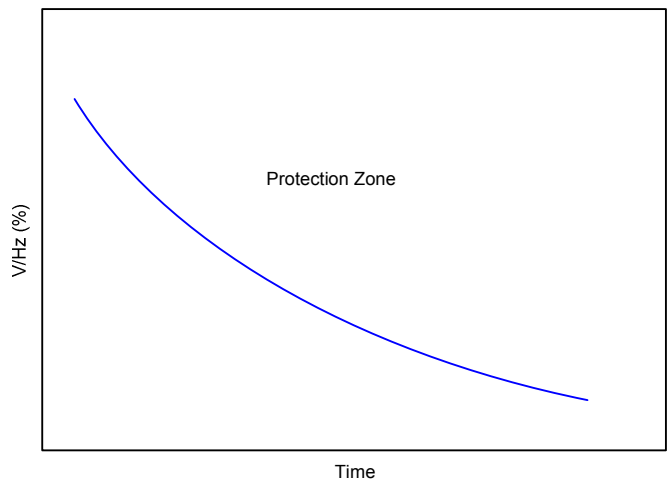

Fig. 7. Typical Inverse-Time Relay Characteristic

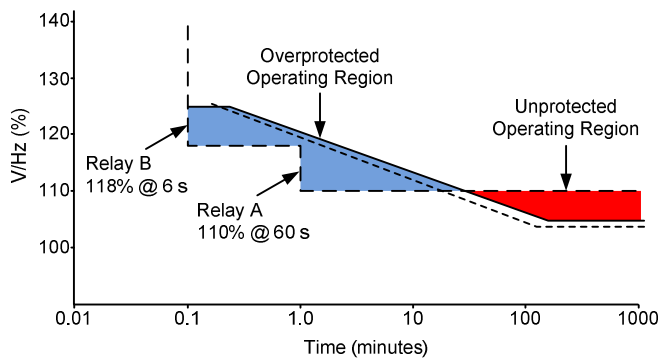

Fig. 8. Typical Relay Characteristic for a Dual-Level, Definite-Time V/Hz Protection

For this reason, inverse-time relays provide the optimal protection and operational flexibility because they coordinate better with the operational limits of the equipment. Fig. 9 shows a typical scheme using both inverse-time and definite-time relays. In the example shown in Fig. 9, the manufacturer recommended protection requires a definite-time element set to trip in 2 seconds above 118 percent V/Hz. The two-second delay allows time for the voltage regulator to correct an extreme overexcitation condition and still protect the unit from damage. The inverse-time element must be set to trip in 45 seconds or less, or to coordinate with the transformer over-excitation curve after placing it on the generator base, whichever is more restrictive. Pickup of the inverse-time element should be coordinated with the V/Hz limiter on the excitation control system. Because continuous operation above 105 percent is not allowed, an alarm element set to pick up at 105 percent with a short delay is also recommended [13].

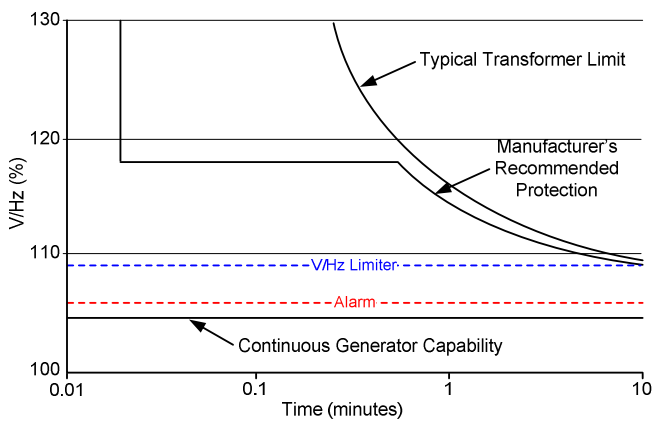

Fig. 9. Optimal Protection and Operational Flexibility is Provided by Using Both Inverse- and Definite-Time Elements

For overvoltage relaying, the pickup should be set above the maximum normal operating voltage, and the relay may have an inverse- or definite-time characteristic to give the regulator a chance to respond to transient conditions before tripping occurs. Additionally, an instantaneous element may be applied for very high overvoltages.

It is important that the overvoltage relaying has a flat frequency response, as frequency excursions can take place during the overvoltage event. This is of particular concern with hydroelectric installations that may have limits on the rate of gate closure imposed by hydraulic pressure in the penstocks. In such cases, these units may experience speed increases in the region of 150 percent during a full load rejection before governor action can reduce the speed.

V. Connection of V/Hz and Overvoltage Relaying

Many V/Hz relays are single-phase devices. Problems arise if the voltage signal for the relays is taken from a single generator VT. A blown fuse or an incomplete circuit connection when racking the VTs back into place can result in no voltage being sensed by the V/Hz relay and, therefore, no protection. For complete and redundant protection, VTs on different phases should be used for the multiple alarm and relay functions. Some of the newer digital relays have alarming capabilities when potential to one or two inputs is lost. For overvoltage relaying, the same issues as V/Hz relaying apply.

VI. Coordination of Protection With Automatic Voltage Regulator

Modern digital excitation systems not only provide field current for a synchronous machine but also include many supplementary controls, such as over- and underexcitation limiters, V/Hz and terminal voltage limiters, and often embed various other protection elements. It is common and recommended practice to have a separate relay at the generator terminal as a backup when the AVR (automatic voltage regulator) is in manual mode or not functional.

It is desirable to have V/Hz and overvoltage protection coordinate with the limiters in the digital excitation system. The limiters keep the generator outputs within the specified design capability. The setting of the V/Hz protection is set slightly above the excitation system V/Hz limit with a time delay to give the excitation system time to automatically adjust the excitation level to fix the core overexcitation problem. The overvoltage protection should be set similarly to coordinate with the terminal voltage limiter in the excitation system.

VII. Tripping Philosophy

Excessive V/Hz operation will result in equipment failure and should be treated as a severe electrical problem. As recommended in the IEEE C37.102, IEEE Guide for AC Generator Protection, the field and main unit breakers should be opened if the unit is synchronized [14]. For units without load rejection capability (unable to quickly ramp down in power and stabilize at a no-load point), the turbine should also be tripped. Prior to synchronization, alarm and inhibit circuits should be provided to prevent an operator from overexciting the generator.

For machines operating offline, the practice is to trip the field breaker only and not trip the turbine. As the problem is with the excitation system, it may be quickly remedied and the unit placed online without going through the full startup process. This is particularly advantageous on steam units with long startup times.

Two tripping schemes should be discouraged: opening only the field breaker on a V/Hz relay operation and sequentially tripping the turbine and then the generator. Some believe that an excessive V/Hz event is only possible with the unit offline and that their protection logic has the V/Hz relay opening only the field breaker for any operating condition. If an event occurs while the unit is synchronized to the grid, the field breaker will open, and the unit must depend on other protective devices to trip.

Sequential tripping of the unit is also not recommended. Sequential tripping implies a scheme whereby the prime mover (usually a turbine) is tripped by a device responding to some disturbance. The generator and field breakers are then

tripped by some other protective device(s), usually including a reverse-power relay, responding to the loss of the prime mover. Time delays inherent in sequential tripping schemes are long enough to result in severe equipment damage.

VIII. Conclusion

V/Hz and overvoltage relaying are applied to generating plants to alarm and trip. Although on the surface they may seem like very similar protections, they are not. A keen understanding of the causes for overexcitation and overvoltage events is necessary for the proper application and setting of this protection. Factors to consider include issues such as generator and transformer capabilities, excitation and governor responses, type of prime mover, and if the unit is online or offline for proper tripping action. These factors have been detailed in this section of the tutorial. To avoid severe damage to the apparatus for overexcitation and overvoltage, this protection should be installed and properly applied.

IX. References

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