THE GENERREX EXCITATION SYSTEM FOR LARGE STEAM TURBINE-GENERATORS

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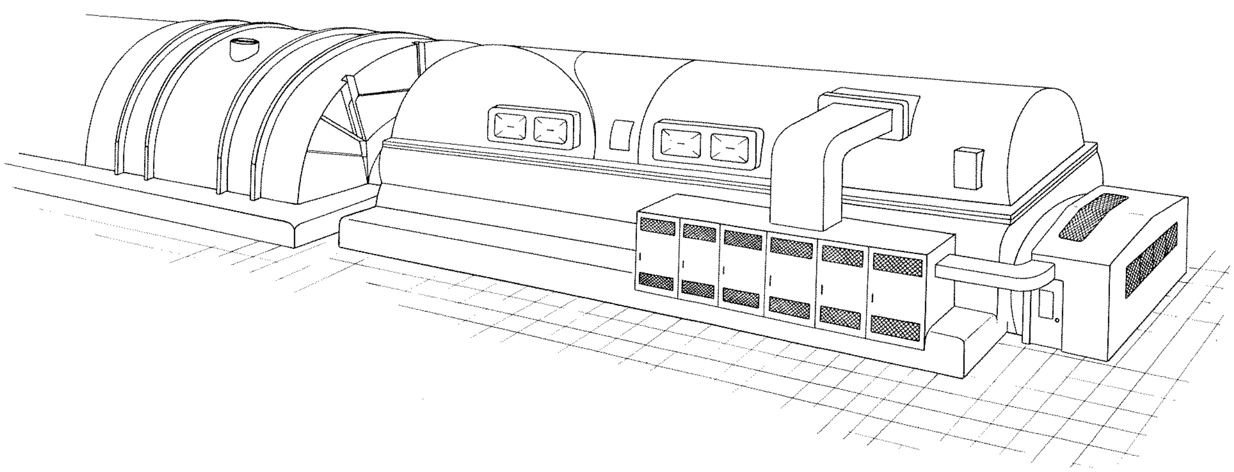

Presented at the

PACIFIC COAST ELECTRIC ASSOCIATION ENGINEERING AND OPERATION CONFERENCE

Culver City, California

March 20-21, 1975

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ABSTRACT

A new concept has been developed combining the excitation system power supply as an integral part of large steam turbine-generators, and utilizing common parts and cooling systems. Excitation power is developed by the flux in the generator air gap and from the current in the generator windings. The result is a self-excited, essentially self-regulating system which also provides for fast field forcing during depressed voltage conditions by the high generator armature current during this period. Rotating parts, common in previous excitation systems, have been eliminated, resulting in simplified station design and easier generator maintenance. Power rectification is obtained with a three-phase, full-wave bridge of silicon diodes with shunt silicon-controlled rectifiers (thyristors) providing fast system voltage response. Integral test panels and redundant features permit on-line maintenance, and a new control panel displays immediate excitation system operating status for the operator.

Through the utilization of all static components the GENERREX system aims for a high degree of reliability and for sustained generator availability. The physical arrangement of the excitation components provides a compact design for ease of access for inspection and maintenance of the main generator. The system features advanced modular design, solid state control components, and unit cell type power rectifiers. The GENERREX system contributes to better system and generator performance by providing:

1. Improved system dynamic stability
2. Improved system transient stability
3. Improved control of generator terminal voltage

A prototype GENERREX excitation system has been manufactured for The Montana Power Company Colstrip 1 generator, rated 377 MVA, 22 KV, 3600 rpm. Factory running tests were successfully completed on the generator and GENERREX excitation system in May, 1974.

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DESCRIPTION OF SYSTEM

The arrangement of components for the GENERREX excitation system may be observed with the aid of Figures 1, 2 and 3. Figure 1 is a simplified one-line schematic of the generator and excitation system; Figure 2 is a profile view of a large 1800 rpm generator with axial and transverse domes, illustrating an outside view of a generator with the GENERREX system; and Figure 3 is a photograph of the prototype equipment during the factory test with a view of the GENERREX system power components mounted on top of the generator frame, with the dome removed. The major parts of the excitation system are:

1. The exciter ac power supply components located within the generator casing and in an excitation dome integrally attached to the top of the generator frame
2. The exciter cubicle, located on one side of the generator frame, containing the power rectifiers and select control components
3. Ac busway connecting the excitation bushings in the generator dome to the rectifier cubicles, and a dc busway connecting the rectifier cubicles to the collector housing
4. The two-section control cubicle housing the voltage regulators, limit and protective circuits, located in a remote clean location such as the relay room
5. The generator collector housing with collector and brush holder rigging.
6. The control panel mounted in the control room

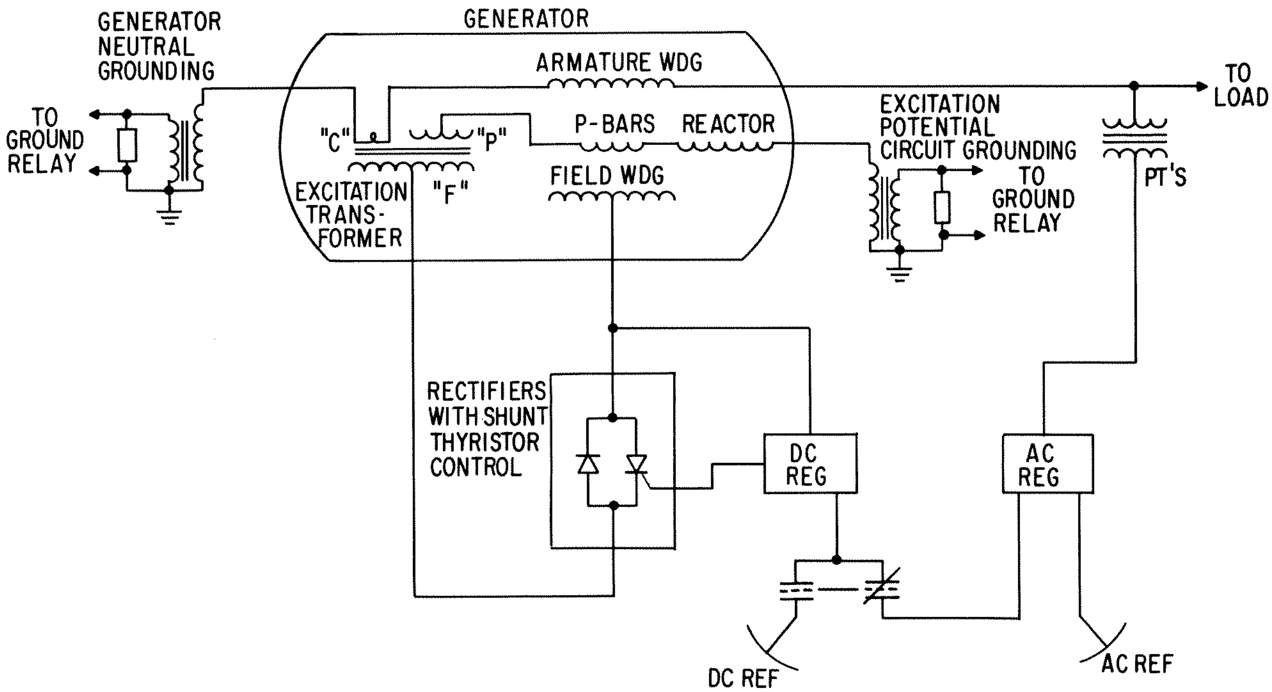

Figure 1. GENERREX excitation system — simplified one-line schematic

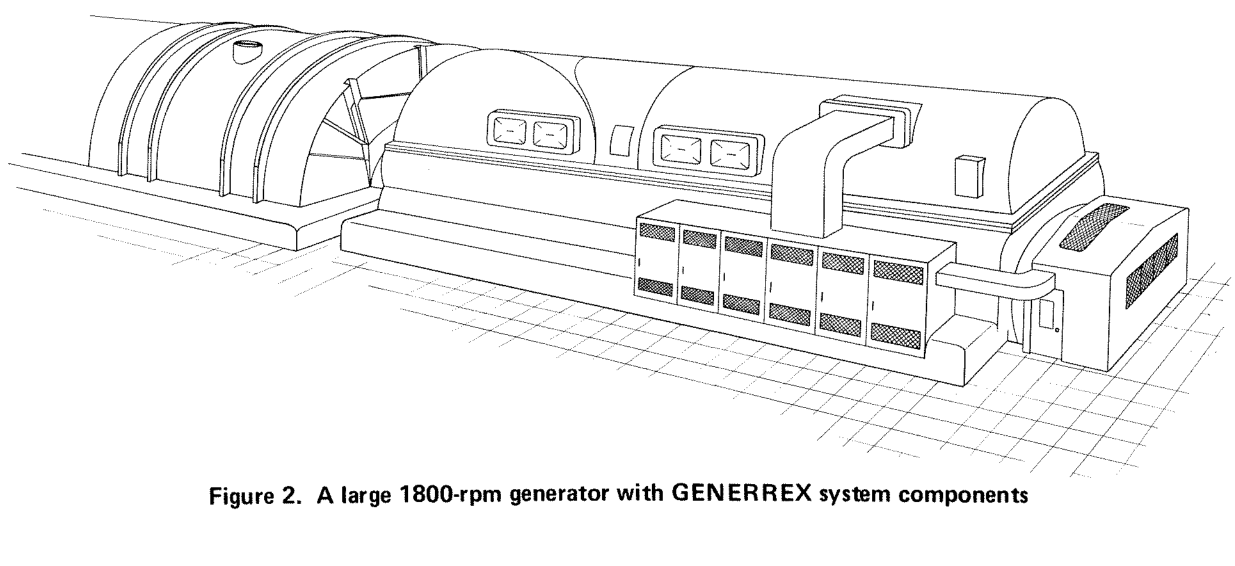

Figure 2. A large 1800-rpm generator with GENERREX system components

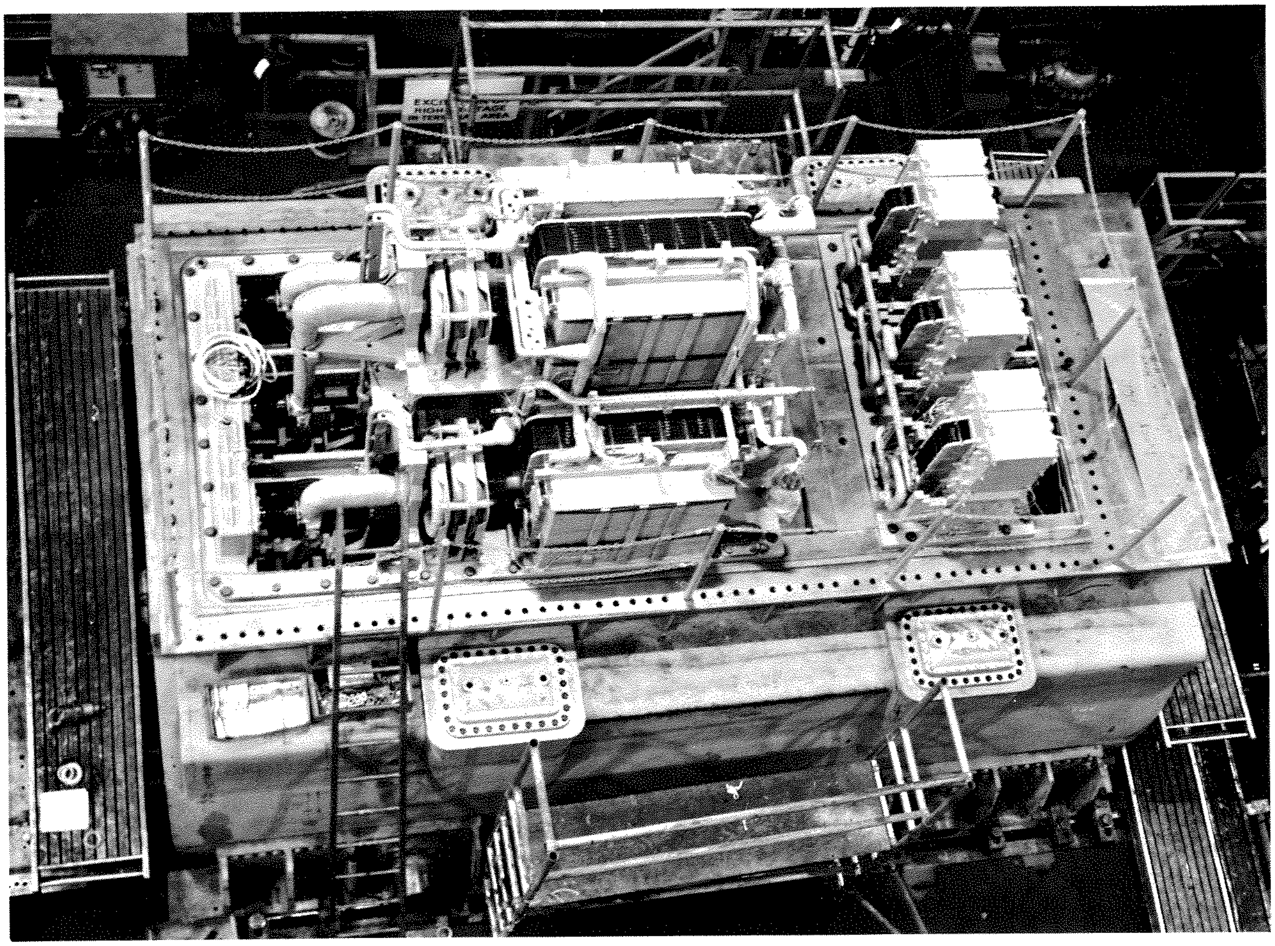

Figure 3. Prototype GENERREX system on test, illustrating the excitation power component assembly on top of the generator

THE EXCITER POWER SUPPLY

The main turbine-generator excitation power is provided by both a voltage and a current source from within the main generator stator. The voltage source is a set of three-phase windings mounted in three generator stator winding slots. The windings may be either water-cooled or externally gas-cooled by the generator hydrogen gas system.

The current source is achieved by bringing the three generator stator leads that normally constitute the neutral of the generator to the excitation dome on top of the generator. Each of the stator winding neutral leads passes through a window of a single-phase excitation transformer. The neutral of the generator is formed by connecting the three windings after passing through the transformers.

The Excitation Potential Circuit

The excitation potential circuit comprises four major segments:

1. The excitation potential windings in the stator core, which are called "P" bars
2. The windings on the excitation transformers, connected to the "P" bars, which are called transformer potential windings
3. The reactors, one in each phase of the potential winding circuit
4. The connection busses – on the generator collector end, connecting the "P" bars to the excitation transformer potential windings; on the generator coupling end, connecting the "P" bars to the reactors mounted on top of the generator

The excitation potential winding consists of three transposed bars, called "P" bars, assembled on top of, and supported from the wedges in three armature winding slots located 120° apart. The method of assembly and a

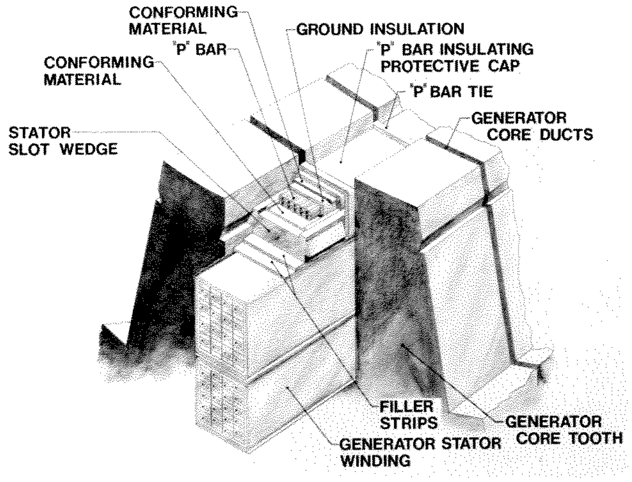

Figure 4. Cross-section of generator armature slot with armature bars and GENERREX system "P" bar

cross-section of the bars is illustrated in Figure 4. To insure that the small protrusion of the bars into the air gap does not permit damage to the bars from installing or removing the generator rotor, the "P" bars are not located in the bottom region of the core where the air gap shim is assembled for rotor removal.

Similar design specifications and manufacturing methods used for the main high-voltage stator winding are applied to the "P" bars and the connection busses. The bars in the generator end winding region are supported from the main armature bar end windings and supports.

In the prototype design, the "P" bars are direct water-cooled in the core and end portions of the generator. The remainder of the winding is indirect gas-cooled. When water-cooled, the individual bars consist of transposed strands using a mix of solid and hollow strands. The water cooling is integral with the water cooling for the main armature windings. The potential windings of the transformers, which connect to the "P" bars, are hydrogen-cooled transposed coils.

One set of terminations of the transformer potential windings forms a neutral point. The "P" bars at the other end of the generator are connected to the linear reactors and, from the reactors, a second neutral is formed. One of the two neutrals is brought outside of the excitation dome to a grounding transformer with secondary resistor. This location and arrangement of the reactors minimizes fault currents which may result from a fault between two or three potential windings, although this possibility is exceedingly remote.

The Excitation Transformers

The three single-phase ac transformers are mounted on a base assembly. Each transformer is constructed with laminations similar to those used for the main generator stator and with three windings: a current winding (the generator stator winding neutral lead), a potential winding, and an output winding which is connected to the rectifier.

The potential winding and output windings of the transformers are made with stranded, transposed conductors. The current windings for the excitation transformers, formed by the generator stator winding neutral lead connections in the excitation dome, are hollow, insulated conductors, hydrogen-cooled, for most generator ratings, with the hydrogen pumped through the conductors by the generator fans. The "C" windings pass through the window in each transformer forming a one-turn winding. The generator neutral tie is made inside the excitation dome, and a neutral connection is brought out of the dome through a gas-tight bushing where a connection to a neutral grounding transformer may be made.

Provision for normal metering and relaying practices is made by mounting the usual complement of bushing type current transformers on the stator winding neutral leads in the excitation dome.

The output, or "F", windings on the transformers are transposed, hydrogen-cooled coils and are connected to three gas-tight bushings which extend out one side of the excitation dome suitable for the ac bus connection to the exciter cubicle.

The excitation transformers, complete with "P", "C", and "F" windings, and with the generator neutral tie, neutral bushing type current transformers, and extensions of the "P" and "C" windings to the connections in the generator frame, are shipped as an assembled unit on a base plate ready to be bolted to supports on the top of the generator frame.

Linear Reactors

Three single-phase linear reactors are applied, one in each phase of the potential circuit. The reactors are of shell type construction with two separate core halves, assembled with the same type of laminations as the excitation transformer. The core is bonded to produce a sound mechanical design coordinated with the clamping and bolting of the core assembly. The coil design is similar to the transformer coils. The reactors are mounted and shipped on a base plate which bolts to the top of the generator frame.

The reactors serve two major functions: contribution to the desired compounding characteristics of the excitation system and reduction of fault currents for faults in the excitation system and generator.

Dome

The excitation transformers and reactors are contained in an excitation dome which is bolted to the top of the generator frame and becomes an integral part of the frame. Two types of domes are provided: (1) a single dome extending either the partial length of the generator or, for large ratings, the entire length or (2) a twin-dome design consisting of an axial and a transverse dome as illustrated in Figure 2. For both the single-dome design and the twin-dome design, the excitation components are arranged in the same manner on top of the generator frame. Observing Figure 3, at the generator collector end, the stator winding neutrals enter the dome area from the generator connection rings. An assembly of current transformers, generally three per phase, is located in front of the assembly of excitation transformers. After passing through the current transformers, the generator leads pass through the excitation transformers and form a neutral. The assembly of three reactors is located at the coupling end of the generator.

A single dome is always supplied with generators equipped with vertical coolers. A single dome or twin dome is applied to generators equipped with horizontal coolers. The two twin-section horizontal coolers are placed on top of the generator frame, towards the center, between the generator neutral connections and the reactors. This arrangement is consistent whether a large single dome is applied or twin domes. At least two dome hatches are provided, one towards the generator collector end and one towards the coupling end, to permit entrance into the dome areas. On twin-dome designs generally three hatches are provided, two in the axial dome, and one in the transverse dome.

The domes are bolted to the generator frame and are sealed by use of a pumping groove filled with a sealing compound between the bolted surfaces, and with a back-up dam also filled with sealant.

Neutral Grounding Transformers

A generator with the GENERREX excitation system is supplied with two protective equipments for fault detection in the ac circuits: one for the generator stator windings; one for the excitation system. Grounding transformers and resistors are applied. Whenever possible, provisions are made for mounting the generator grounding transformer with resistor and the excitation potential circuit grounding transformer with resistor on a pad on top of the frame.

The grounding transformers are enclosed by ventilated, sheet metal lagging which is constructed to blend with the excitation dome structure. A bolted door is provided for access to the grounding transformers.

For a few generator ratings it will not be possible to mount the grounding transformers and resistors on top of the generator. The transformers and resistors may then be arranged inside a special compartment in the exciter cubicle.

If the generator neutral grounding transformers and resistors are mounted separate from the generator, provisions are available to provide a neutral connection to a grounding bushing on the excitation dome.

Transformer secondary resistors are mounted in close proximity to the transformer. Grounding relays may be mounted in the exciter cubicle.

RECTIFIERS AND ASSOCIATED COMPONENTS

An exciter cubicle, which contains the rectifiers, transducers, and associated equipment, is located on a support frame on one side of the generator, as seen in Figure 2. The cubicle is a general purpose, indoor, ventilated design. For outdoor applications, a coordinated weatherproof enclosure is added to the design.

An ac bus connects from the ac bushings in the excitation dome to the top of the exciter cubicle. A dc bus connects from one end of the exciter cubicle to the collector housing. Water piping for the rectifiers and all electrical connections to the exciter cubicle are brought out through the bottom of the exciter cubicle through conduits in the foundation.

The power rectifier sections of the exciter cubicle contain water-cooled power rectifier bridges. Deionized cooling water from the generator stator liquid cooling system is used for cooling the power rectifiers. Each bridge consists of a full-wave, three-phase diode rectifier with shunt thyristors as shown in Figure 5. The diodes and thyristors are of the unit cell type — that is, they are cooled

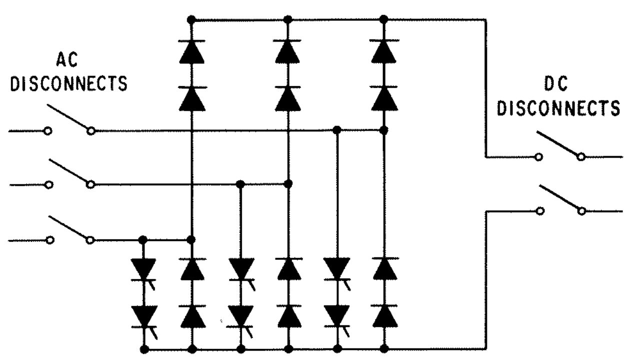

Figure 5. Power rectifier bridge with diodes and shunt thyristors

on each side through pressure contact with water-cooled heat sinks. A five-pole disconnect switch permits isolation of both the ac and dc voltages and currents of each bridge for maintenance under load. The water cooling circuit is individually valved to each rectifier section for similar purposes. Two thermal alarms are provided in each rectifier section, one in each parallel water path, and annunciated on the generator stator water control cabinet annunciator. With one rectifier bridge section removed from service, no reduction results for either generator steady-state or transient capability.

Diode and thyristor condition lamps are mounted in a panel on the door to each rectifier section. These lamps are light-emitting diodes and indicate whether any of the unit cells is inoperative.

Fuses are not needed in the rectifier bridge circuits to protect against high fault currents due to shorted diodes. The high reactance of the line reactor in the potential winding circuit appears as a high reactance in the "F" winding circuit and limits fault currents to low values. Two diodes are provided in each leg to provide ample PIV (peak inverse voltage) capability in the possible event of failure of a cell.

CONTROL CUBICLE

The control cubicle, Figure 6, is a naturally ventilated, free standing design with requirements for front and rear access. This cubicle is designed for installation in a clean, preferably air-conditioned, room such as the station relay room. Only low voltage signals are transmitted to the

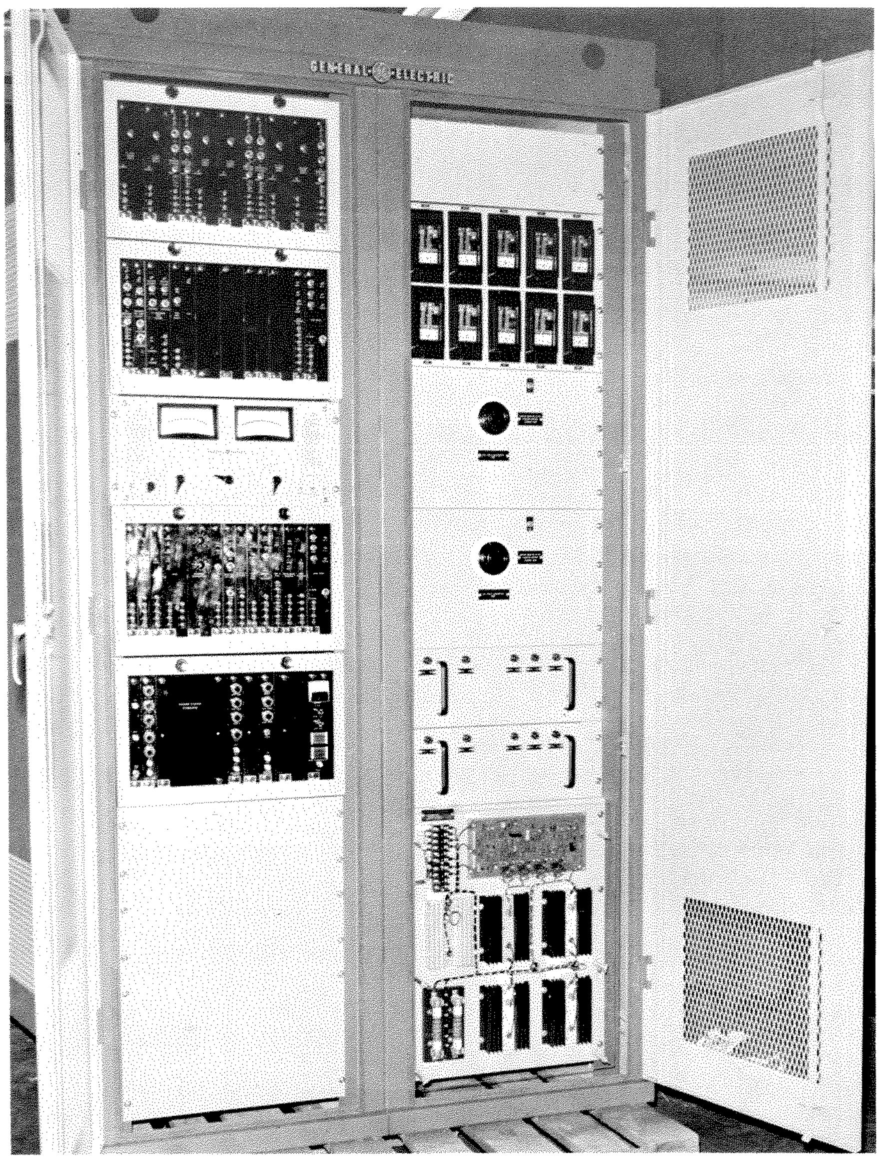

Figure 6. GENERREX system control cubicle

regulator cubicle, and the total heat output from all components is less than 1 KW. The voltage regulator is of modular construction using PC boards (printed circuit boards) and static components. The control circuitry incorporates integrated circuit operational amplifiers and photo-couplers for voltage isolation. A built-in regulator test panel with meters and selector switches provides for on-line checking of most critical circuits.

CONTROL PANEL (WITH MIMIC BUS)

A control panel, shown in Figure 7, is provided for mounting in the control room. This control panel assembly contains switches for regulator mode selection, ac and dc regulator raise and lower, power system stabilizer, field breaker close and trip push-buttons in the case of the prototype unit (or flash field and de-energize field push-buttons for future units), and a field voltmeter, field ammeter, transfer voltmeter, power system stabilizer voltmeter, and an excitation system mimic bus with light-emitting diodes. The mimic bus indicates the control circuitry in operation by the array of light-emitting diodes. If a protective circuit, such as the reactive ampere limit, becomes operative, the light-emitting diode indicating that part of the mimic bus circuit is lighted and also flashes.

Excitation is initiated by means of the field flashing circuit which is automatically energized by closing the field breaker in the case of the prototype unit (or by closing the flash field contact in future units). As standard equipment, this circuit includes a transformer and rectifiers for operation from a 440-volt, three-phase ac input and provides a dc output of 15 percent generator no-load field current for 10 seconds.

COLLECTOR AND HOUSING

A walk-in type collector housing, illustrated in Figure 2, with collector air inlet and outlet ducts located above the floor, and with air inlet filters, is provided as a one-piece housing covering the collector brush holder rigging assembly. Features for attenuation of acoustic transmission are included. The collector housing is designed to be removable with a minimum of disconnects as a single-piece shell. The dc bus from the rectifiers to the collector brush rigging penetrates the collector housing in a readily removable section. Except for lighting and temperature detector wiring, which are provided with quick-disconnects, and a ground connection, no other wiring or piping is attached to the collector housing.

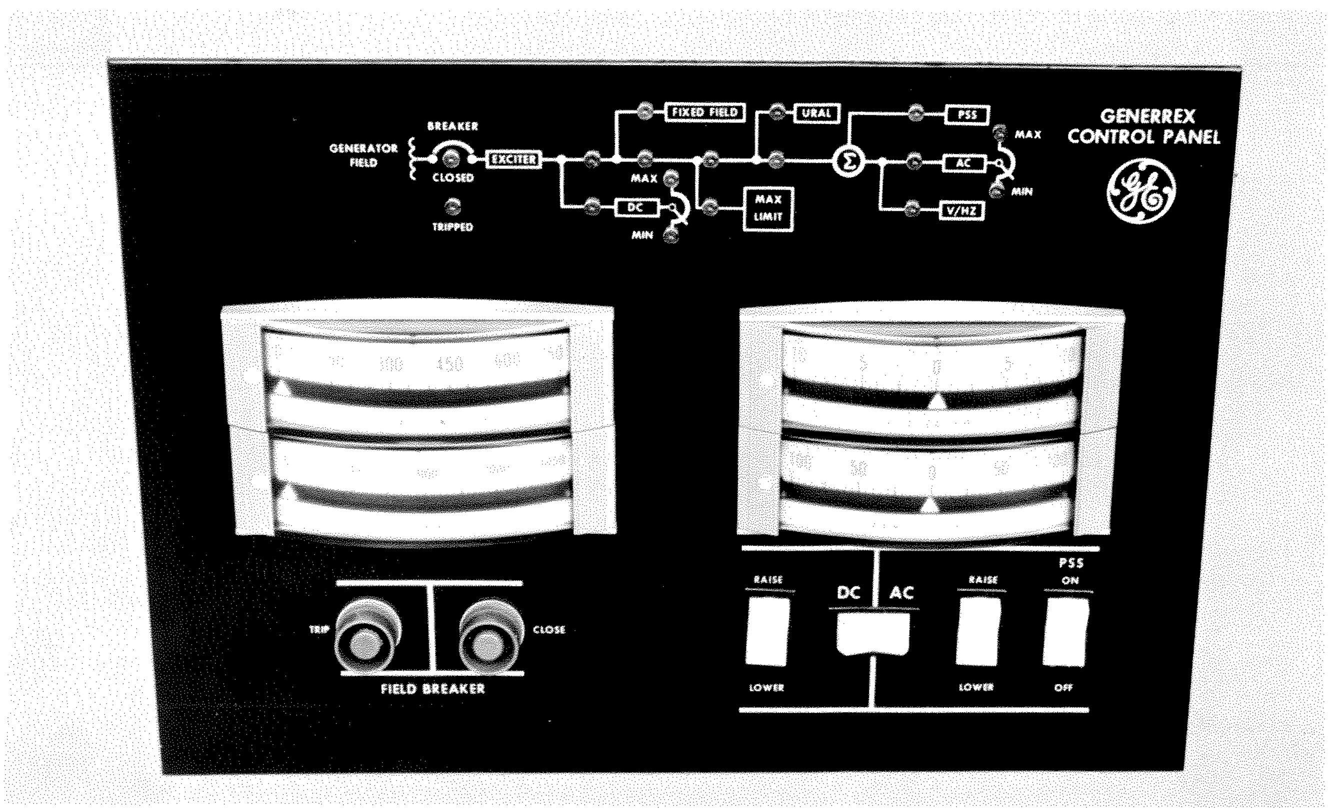

Figure 7. GENERREX system control panel

The collector brush holder rigging assembly is mounted on a base with removable-type brushes and constant pressure type brush springs. Large 3600-rpm generators have a steady bearing mounted on the collector base outboard of the collector rings, while 1800-rpm generators do not require a steady bearing. The brushes are contained in magazines which can be readily and easily removed for brush replacement while the machine is under load.

RELAYS, REGULATING AND PROTECTIVE CIRCUITS, AND ACCESSORIES

The control system is designed to provide automatic regulation, and to incorporate protective relaying and protective circuits. Protective circuits generally accomplish protection by limiting or regulating a variable to a pre-established value.

Protective Relaying Furnished with the Excitation System

- generator field ground
- generator field overvoltage
- generator volts/hertz overexcitation protection
- exciter output unbalanced voltage
- excitation potential circuit ground

Control, Protective, and Limit Circuits

- automatic generator (ac) voltage regulator
- automatic generator field (dc) voltage regulator
- volts/hertz regulator
- power system stabilizer
- underexcited reactive ampere limit
- maximum excitation limit
- generator field current limit
- de-excitation control
- shaft voltage suppressor

Other Functions (for redundancy and aids to on-line maintenance)

- regulator on-line monitor and test panel
- static switching between redundant power supplies
- static switching for loss of one generator terminal voltage signal
- adjustable impedance compensation
- light-emitting diodes for rectifier and regulator condition
- design for 50°C ambient

These functions are provided by circuitry using well proven components and construction techniques. The control system is all solid state with the exception of relays for interfacing with the external plant, such as plant battery, circuit breakers, flashing circuit, and main (plant) control room. Integrated circuit operational amplifiers, photo-couplers, transistors, diodes, resistors, and capacitors comprising these circuits are mounted on plug-in PC boards. All critical circuits on the PC boards have redundant connectors. PC board components requiring adjustment during installation are mounted on face plates so as to be readily available. The PC board face plates also contain light-emitting diodes to indicate board status, jacks to make internal board voltages available for trouble-shooting or testing, and switches to permit testing of protective circuits while on-line.

Protection — De-excitation

For the prototype unit, de-excitation is accomplished by a main generator field breaker and by the simultaneous firing of the thyristors in all three phases of the rectifier bridges. Both means of de-excitation respond to the same signal, such as an excitation trip condition. The firing of the thyristors full-on (advanced firing), essentially short-circuits the exciter output to zero voltage in milliseconds time and provides a path for the generator field current to decay through the rectifier bridge acting as a short-circuit across the generator field.

Redundant circuitry is provided to insure positive de-excitation. Future generators with GENERREX excitation systems may incorporate a means other than the main field breaker to provide the redundant feature.

THEORY OF OPERATION

Figure 8(a) illustrates the conventional single-phase representation for a three-phase synchronous generator. The corresponding phasor diagram relating voltages and currents is shown in Figure 8(b) where:

$$E_i = E_g + jX_{ad} I_a \quad (1)$$

$$E_g = V_T + jX_\ell I_a \quad (2)$$

and where

V_T – generator terminal voltage
X_ℓ – generator leakage reactance
X_{ad} – generator magnetizing reactance
I_a – generator armature current
E_g – induced generator air gap voltage
E_i – induced generator internal voltage
I_f – generator field current

Since the induced generator internal voltage is directly proportional to field current, equation (1) together with equation (2) define the amount of field current which the exciter must supply to the generator, for any generator load current and power factor, to maintain a desired terminal voltage V_T.

Figure 9(a) illustrates a simplified equivalent circuit for the excitation system components shown in Figure 1. In Figure 9(a):

V_P – P bar voltage referred to the transformer secondary
X_P – reactor reactance referred to the transformer secondary
I_P – P bar current referred to the transformer secondary
R_{Fac} – equivalent ac resistance of the generator field
I_{Fac} – field current referred to the ac side of the rectifier
I_{SCR} – thyristor current referred to the ac side of the rectifier
I_R – total ac current into the rectifier circuit
I_a – generator armature current referred to the transformer secondary

The compounding effect of V_P and I_a can be combined into a single equivalent voltage source, V_{TH}, and an equivalent source impedance X_P, by means of Thevenin's theorem, shown in Figure 9(b) where:

$$V_{TH} = V_P + jX_P I_a \quad (3)$$

Since the P bar voltage, V_P, is proportional to the generator air gap voltage, E_g, and if the reactance of the reactor, X_P, is selected proportional to the generator reactance X_{ad}, a similarity between equations (3) and (1) is noted. The phasor diagram in Figure 9(c) which represents equation (3) is also seen to be similar to the phasor diagram in Figure 8(b).

Examination of equations (1) and (3) reveals that:

1. The required generator field current can be expressed as a function of induced generator air gap voltage E_g, the generator armature current I_a, and the generator magnetizing reactance X_{ad}.

2. The excitation voltage supplied to the exciter rectifier is a function of the P bar voltage, V_P, the generator armature current, I_a, and the reactance X_P.

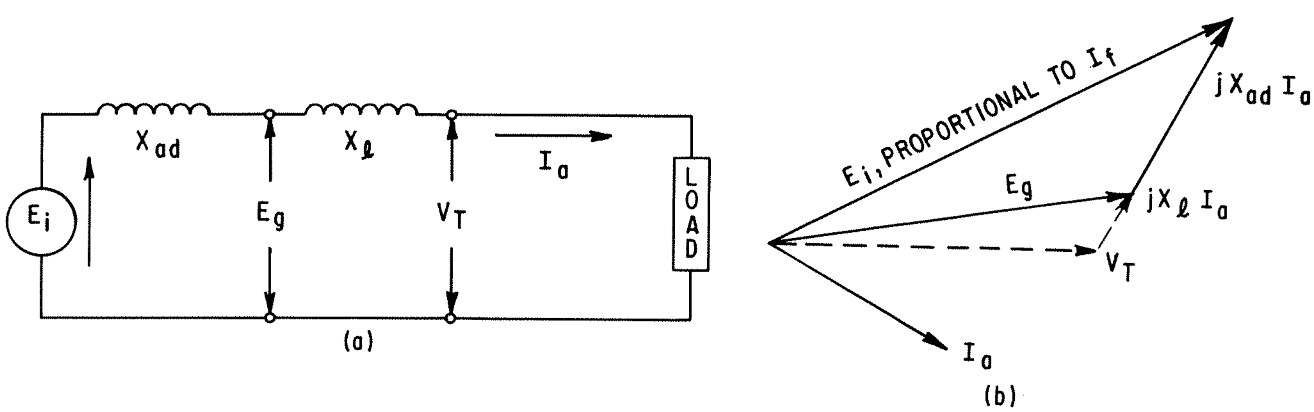

Figure 8. Simplified generator equivalent circuit with phasor diagram

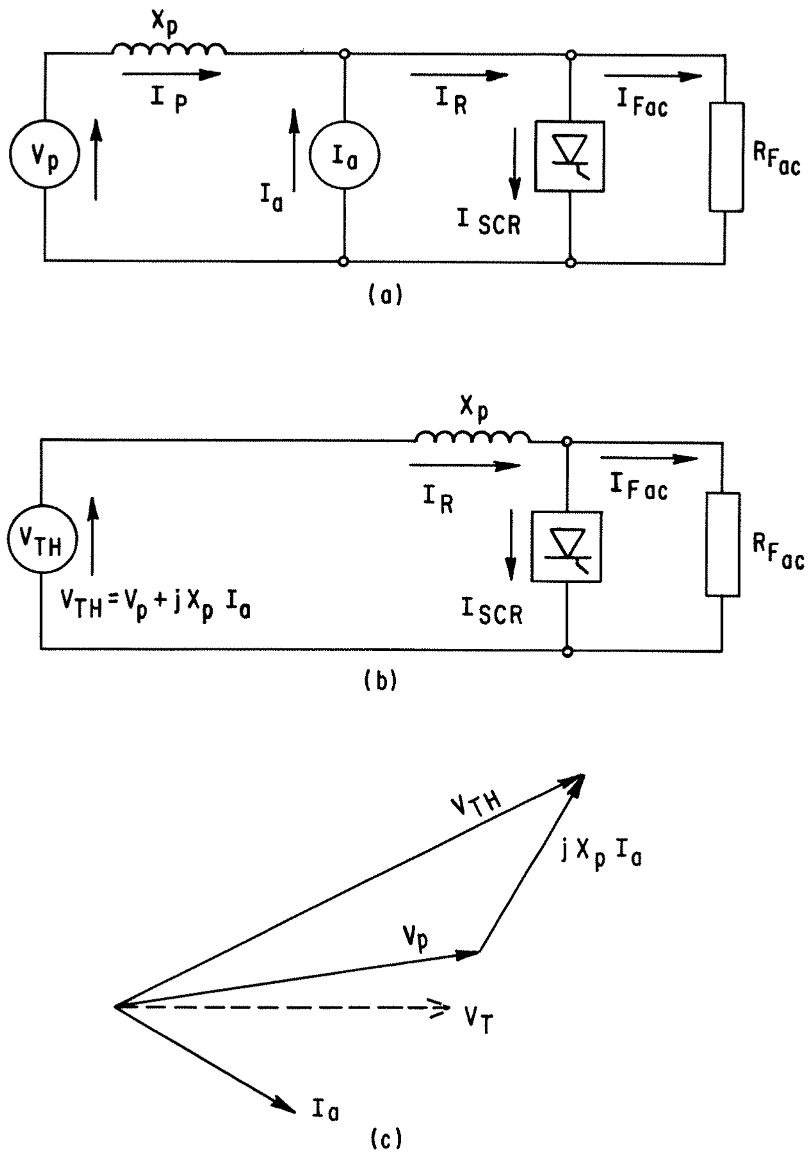

Figure 9. Simplified equivalent circuit of GENERREX excitation system, with phasor diagram

3. If the reactance X_P is designed to be proportional to X_{ad}, then the excitation transformer will produce a voltage which is directly proportional to the field voltage required by the generator at any load and power factor. In Figure 9(b) this voltage is shown as V_{TH}, and the Thevenin equivalent source impedance X_P is shown as part of the rectifier bridge where it behaves as commutating reactance.

4. As illustrated in Figure 10, the system is normally designed so that the excitation transformer output voltage produces more than the required field voltage by a predetermined amount desired for field forcing for small generator terminal voltage variations. Under normal operating conditions the excess available field voltage is reduced to the required value by the controlled firing of the thyristors.

Field voltage can also be rapidly decreased to zero by phasing the thyristors fully on. The design also insures sufficient excitation transformer output voltage to satisfy any load or terminal condition including open-circuit, short-circuit, and any single or three-phase combination of terminal conditions.

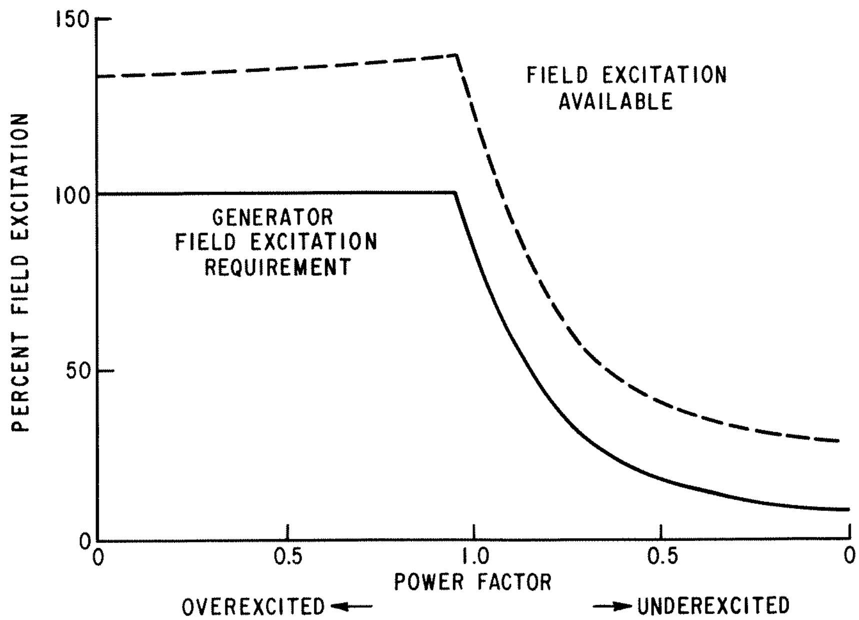

Figure 10. GENERREX system steady-state performance

PERFORMANCE AND TEST RESULTS

The GENERREX excitation system is a high initial response excitation system as defined by IEEE standards.[1]

Under steady-state conditions, the difference between the available and the required excitation is obtained by the voltage regulator by control of the shunt thyristors in the rectifier bridges. Ceiling voltage is immediately available (in cycles) by retarding the firing of the thyristors. Zero voltage is immediately available (in cycles) by firing the thyristors full on. Voltages from zero to ceiling are available by control of the firing angle.

Under fault conditions the sudden increase in fault current, which also flows through the excitation transformer "C" windings, produces the required exciter ceiling voltage and provides for field forcing when system voltage is depressed.

A successful set of factory tests was conducted on The Montana Power Company Colstrip Unit 1, rated 377 MVA, with the prototype GENERREX excitation system.

A series of tests was conducted with the generator stator winding connected either open-circuit or short-circuit. Included were thermal measurements of all excitation system components including the new dome structure, frequency response tests of the control system and the generator, generator terminal voltage and current change steps to analyze the response of the excitation system and generator, de-excitation tests, saturation tests on components such as the excitation transformers to confirm ceiling voltage capability, overall machine ventilation surveys, and acceleration and deceleration runs to measure mechanical response.

Figure 11 illustrates a key excitation system test result — a change in exciter output voltage which is applied to the generator field, and the change in generator terminal voltage, with the generator under no-load conditions. A signal was applied at the voltage regulator input, calling for a change of 10 percent in generator terminal voltage. Figure 11(a) illustrates a fast change in exciter output voltage to a ceiling value. This ceiling condition is achieved by the action of the shunt thyristors which are combined with the silicon diodes comprising the rectifier portion of the excitation system. The exciter ceiling voltage applied to the generator field was achieved well within 0.100 seconds (six cycles) which is required by the definition of a "high initial response" excitation system by official IEEE definitions.[1]

The 10 percent generator terminal voltage change illustrated in Figure 11(b) was accomplished in less than one second. This illustrates the results of the action of a fast, aggressive excitation system.

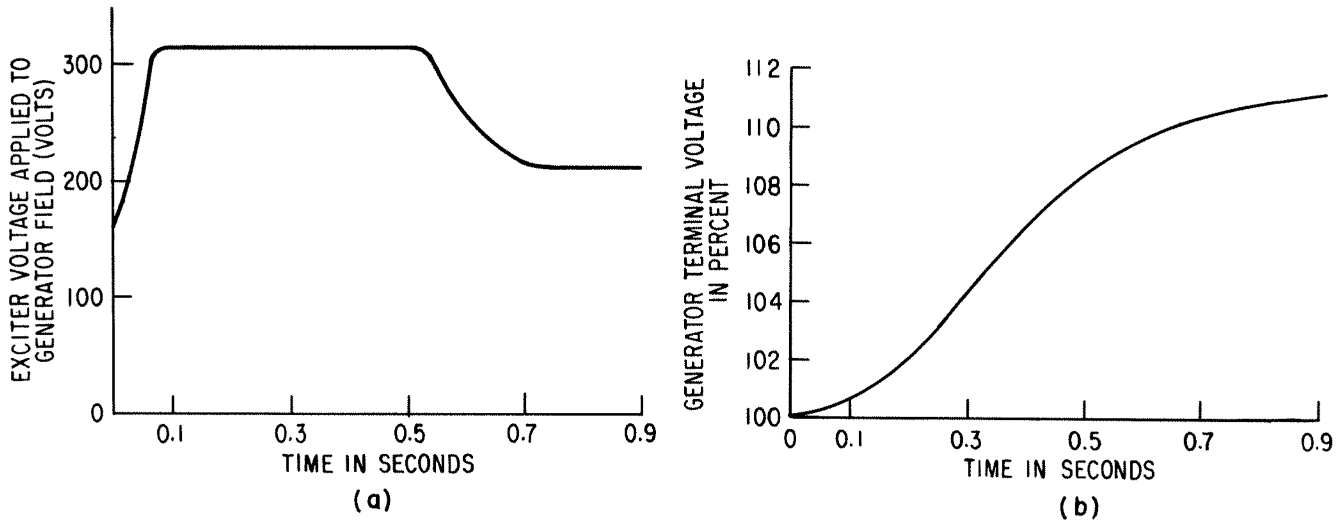

Figure 11. Transient performance of generator with GENERREX excitation system

Although a fast change in exciter output voltage is important, it should be accomplished in a stable manner without undesirable oscillations. The changes both in exciter output voltage, Figure 11(a), and the change in generator terminal voltage, Figure 11(b), indicate a very stable performance of the excitation system, and generator.

Other key performance items were:

1. Low temperature rises for all excitation system components
2. The ceiling voltage test to check the saturation level of the excitation transformers indicated that a higher voltage than required to produce the 3.5 per unit voltage response was obtained
3. Excellent agreement of excitation system and component variables with calculations and previously run tests on models of the excitation system

SUMMARY

Performance and physical features of the GENERREX excitation system include:

Performance features:

- thyristor response
- a compounded power source
- field forcing during depressed generator voltage conditions

Physical features:

- a static power source and static unit cell rectifiers
- an advanced, solid-state, modular control system
- compact station arrangement
- shorter overall unit length
- easier generator rotor removal
- neutral enclosure provided

These features have been verified by design, manufacture, and factory test of a prototype unit.

The GENERREX excitation system is applicable over the full range of generator ratings suitable for electric utility application, including the largest now foreseen for the future.

REFERENCE

1. IEEE Standard 421-1972 "IEEE Standard Criteria and Definitions for Excitation Systems for Synchronous Machines".

LARGE STEAM TURBINE-GENERATOR OPERATIONS
SCHENECTADY, NEW YORK 12345

GENERAL ELECTRIC

7—77 (2500)

PRINTED IN U.S.A.