THYRIPOL®
Static Excitation Systems for the Excitation and Voltage Regulation of Synchronous Machines
Operating Characteristics

- High reliability
- High availability
- Good adaptability
- Minimal maintenance requirements
- High speed of response
- Good regulating properties
- Robust construction

THYRIPOL® is a static excitation system for synchronous generators and synchronous condensers. It is equally suitable for hydroelectric, steam and nuclear power stations and for rotary converters or synchronous condensers in substations.

The excitation of the synchronous machine is controlled directly by a thyristor converter equipped with an electronic voltage regulator, i.e. the converter supplies the excitation current to the rotor of the synchronous machine without any interposed rotary exciters being required.

The following excitation systems are available as standard:

- THYRIPOL®
- THYRIPOL®-L with load-dependent component

The excitation systems can be flexibly adapted to suit the conditions in existing stations, e.g. when such stations are subsequently equipped with static excitation.

This brochure describes the standardized THYRIPOL® excitation system; reference is made to the THYRIPOL® L system with load-dependent component. Further excitation systems specially designed for particular conditions in existing stations are not described here in detail.

The Main Components are:

An excitation transformer (1) which provides power for the excitation converter and has its primary connected to the terminals of the synchronous generator.

A de-excitation device (2) consisting of an a.c. field breaker and field discharge resistors is also part of the THYRIPOL excitation system.

A thyristor rectifier (3) consisting of a fully controlled three-phase bridge or of several such bridges in parallel.

An overvoltage protection device (4) is connected direct to the DC output of the thyristor converter and prevents overvoltages which might otherwise result from negative excitation currents as may be forced by the synchronous machine under fault conditions.

A field-flashing device (5) which initiates excitation build-up, irrespective of the remanent voltage of the synchronous machine, at the time of starting.

An automatic voltage regulator (6) for regulating the voltage at the machine terminals.

An excitation current regulator (7), which is independent of (6), is provided in addition.

Both THYRIPOL® systems are supplied in digital technology.

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**Fig. 1: Block diagram of basic THYRIPOL® excitation system**
**Scope of Equipment**

The standard THYRIPOL® excitation system consists of the following equipment:

1. **Excitation transformer**
   The excitation transformer is a GEAFOL®, dry-type cast-resin rectifier transformer. GEAFOL® transformers avoid the limitations of liquid-filled transformers while retaining their advantages. Three single-phase converter transformers are usually provided where the generator outgoing leads are in isolated phase arrangement.

   An excitation transformer is not required if excitation power is provided by a three-phase main exciter whose voltage can be matched to the excitation voltage of the main machine.

2. **Thyristor rectifier**
   Depending on the output required, this may consist of a single cubicle or of several cubicles lined up in a row and containing the power thyristors (and, if applicable, the silicon diodes), heatsinks, arm fuses, monitoring devices and thyristor firing circuits.

   Top-mounted fans extract the heat loss from the cubicles. The cooling arrangement can be flexibly adapted to the local conditions; air-to-water cooling can for example be provided for the cubicles.

3. **Overvoltage protection, field-flashing circuit and de-excitation device**
   The overvoltage protection is connected to the output terminals of the thyristor converter and protects the thyristors and the rotor of the main machine against critical voltage stressing.

   A field-flashing circuit is only required if the converter is fed from the generator terminals. It consists of a breaker, an uncontrolled rectifier and a matching transformer for connecting the device to the external auxiliary power supply. A field-flashing circuit connected to the power station battery only consists of a breaker and blocking diodes.

   The de-excitation device consists of the field breaker and de-excitation resistor rated to suit the synchronous machine. All of this equipment is accommodated in cubicles.

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**Fig. 2: GEAFOL® dry-type converter transformer**

**Fig. 3: THYRIPOL® excitation system with redundant fans**
4. Regulating and control cubicle

This cubicle accommodates all regulating and control devices. These include the voltage and current transducers, the automatic voltage regulator (AVR) and the excitation current regulator (ECR) (both being suitable for remote adjustment), the thyristor firing circuits, the current-limiting controllers and any additional control devices that may be required. The cubicle also accommodates all power supplies required for the control devices and firing circuits mentioned. Also contained in the same cubicle are the open-loop control, contactors, protective breakers, measuring and auxiliary relays for controlling and monitoring the excitation system and the matching transformers for the connection to the auxiliary power supply.

Routine operation of the control devices is limited to the following functions:

- Controls for the “Higher”/”Lower” adjustment of the reference setters.
- Selector switch for changing over from automatic voltage regulation to manual operation (excitation current regulator) with automatic follow-up and bumpless switching-over facility.

The remaining settings (e.g. current limits, time response, droop, etc.) are optimized by our specialist during commissioning and need not be changed by the operators during normal operation.
**Design Criteria**

The excitation system is designed in accordance with the applicable IEC, VDE and DIN standards. IEEE Std 421 and requirements made in customer specifications may be applicable in addition and generally necessitate the provision of features over and beyond those included in the standard design.

The design is based on the following definitions laid down in VDI/VDE standard 3680, sheet 2:

**Rated-load field voltage** $U_{fN}$

Voltage which must be applied to the field winding with the synchronous machine at normal operating temperature and operating at rated output, rated power factor and rated speed, in order to drive the rated-load field current $I_{fN}$

**Rated current of the excitation system** $I_{EN}$

The excitation current required by the synchronous machine at maximum continuous load governs the design of the excitation system components and is called the rated current of the excitation system.

The following minimum requirement applies: $I_{EN} > 1.05 I_{fN}$

**Ceiling current of the excitation system** $I_p$

The maximum output current of the excitation system is called the ceiling current $I_p$, and is required to be at least 1.4 times the rated-load field current $I_{fN}$ for a minimum time of 5 s.

**Ceiling voltage of the excitation system** $U_p$

This is defined as the maximum output voltage the excitation system is capable of supplying with the thyristor converter at its full positive output voltage setting.

The ceiling voltage depends on the way in which the excitation system is connected, on the states of operation of the synchronous machine and excitation power supply, and on the variation of these states of operation over time.

The design of the excitation system is governed by the nominal ceiling voltage. The supply voltage to the excitation system is assumed to be the rated value of the excitation power supply. In the case of the THYRIPOL® excitation system this means that, with systems connected to the machine terminals, the voltage at the machine terminals is assumed to be at its rated value, that the excitation system is loaded with the rated-load excitation current $I_{EN}$ of the main machine and that, in the case of the THYRIPOL® L excitation system with load-dependent component, the rated current $I_{N}$ is assumed to flow in the stator of the synchronous machine. The machine is further assumed to be at normal operating temperature.

The following factors are taken into account as standard, depending on the excitation system:

THYRIPOL® $\geq 1.6 U_{fN}$

THYRIPOL® L $\geq 1.4 U_{fN}$

**Combined-cycle power plant, Santa Rita, Philippines:** 4 x 298 MVA THYRIPOL® systems.

**Tucurui hydro power plant, Brazil:** 23 x 390 MVA. Siemens is delivering 11 THYRIPOL® systems

**Bugok, combined-cycle power plant, South Korea:** 3 THYRIPOL® systems, 2 x 205 MVA and 1 x 207 MVA
Mode of Operation

Thyristor rectifier

The connection of the thyristor depends on the output and on the phase control limits required. The connection offering the largest phase control range and hence adopted as standard for most applications is the fully controlled three-phase bridge connection. As indicated in Fig. 6a, the maximum negative excitation voltage $U_{fu}$ is approximately 80% of the ceiling voltage $U_p$ owing to the necessary safety margin to the inverter stability limit and because of the commutation time.

This connection allows the excitation current $I_f$ to be reduced to zero in an extremely short period of time. Rapid de-excitation is particularly advantageous on load rejections, since it reduces the power-frequency overvoltages occurring. The curve shown below the diagram gives the variation of the excitation voltage $U_f$ and of the excitation current $I_f$ in response to shifting of the firing angle for full overexcitation at time $t_1$ and for full inverter operation at time $t_2$. At time $t_3$ the excitation voltage collapses to zero since the thyristors permit the current to flow in only one direction. Any required excitation value between the ceiling voltage $U_p$ and the maximum negative excitation voltage $U_{fu}$ can be attained almost instantaneously by means of the gate control equipment.

The maximum rate-of-change of the excitation current depends on the two limiting values and on the time constant in the field circuit of the synchronous machine. The time constant in turn depends on the load condition of the synchronous machine.

Minimum values for the ceiling voltage are specified in the applicable standards, but in practice such minimum values are often exceeded if special requirements have to be met with regard to the control behaviour. The full value of the negative excitation voltage inherently available from a fully controlled three-phase bridge connection is not always needed.

If negative excitation voltage can be dispensed with completely, the half-controlled bridge connection shown in Fig. 6b can be employed.

In this connection the current continues to flow via the bypass diode when the thyristors are in the off-state. The only counter-voltage occurring is therefore the forward voltage of this diode.

The part-controlled three-phase bridge connection shown in Fig. 6c is often employed where the excitation system is required to maintain the excitation current even in the event of a terminal short-circuit of the generator. It consists of a three-phase bridge connection of (uncontrolled) diodes connected in series with a three-phase thyristor bridge of higher voltage. While one of the three-phase bridges is connected (e.g.) to the generator terminals via the converter transformer, the other bridge may be connected either to a constant, independent voltage source such as a three-phase constant-voltage main exciter or, in the case of the THYRIPOL® L excitation system, to a reactor providing a voltage proportional to the stator current of the generator. The excitation voltage then consists of two components, $U_1$ and $U_2$, the latter value corresponding to the rectified, load-dependent voltage component and $U_1$ being adjustable, by appropriate setting of the firing angle, to anywhere between the value belonging to the rectifier firing limit and -80% of this value in inverter operation.

A negative excitation current is only required during significantly under-excited operation of salient-pole type synchronous condensers, if at all. An inverse-parallel connection of two converter bridges may be used for this purpose, but only at a considerably higher cost.

To increase the service reliability, each converter arm contains several thyristors or diodes connected in parallel and provided with separate fuses. Diodes or thyristors that become defective are thus isolated selectively by their HRC fuse to permit operation to continue with the remaining parallel-connected arms. The fuses likewise protect the thyristors and diodes against short-circuits on the DC side.
In order to ensure that the load current exceeds the holding current even if there is an inductance in the load circuit, a gate control current is maintained throughout the pulse length of approximately 12° el.

Fig. 8 shows how the excitation voltage can be varied by adjusting different firing delay angles for a three-phase bridge connection. Special precautions are taken to keep the delay angle within the limits which must be adhered to in order to ensure reliable commutation, i.e. switching of the current from one thyristor arm to the next.

**Thyristor gate control equipment**

Unless a firing pulse is applied to its gate, a thyristor blocks the flow of current in both directions. Current will not start to flow until a voltage of correct polarity is applied (positive to the anode, negative to the cathode) and a pulse is transmitted to the gate electrode (Fig. 7). Once this current has exceeded a relatively low value - the holding current - it continues to flow. The thyristor does not regain its forward blocking ability until the current drops to zero. This may for example result from commutation of the current to another thyristor in the converter connection whose applied voltage is higher. The mean voltage across the load terminals depends on the phase control angle, i.e. the instant within the cycle of the applied AC voltage at which the thyristor is fired.

In the case of the THYRIPOL® excitation system, the load is the field winding of the synchronous machine. The gate control equipment has the task of forming the firing pulses and transmitting them to the thyristor gate electrodes. The timing of the firing pulses is varied as a function of the control command as necessary to produce the required excitation voltage.

The length of the pulses supplied by the gate control set corresponds to 12° el. In the fully controlled three-phase bridge connection, the next-to-conduct thyristor arm always receives its firing pulse after 60° el. Additionally, the pulse is repeated after another 60° el. in order to turn one thyristor arm on the positive bus and one on the negative bus conductive simultaneously during start-up of the converter.

It is important that the parallel-connected thyristors should be fired simultaneously. Adequate firing power must therefore be provided, if necessary by suitable pulse amplifiers.

The envelope of the high-frequency pulse train formed in the gate control set is amplified in separate modules located next to the thyristors to be fired. These modules each contain a pulse transformer which is the most important component because it isolates the gate control circuit from the power circuit.

In order to ensure that the load current exceeds the holding current even if there is an inductance in the load circuit, a gate control current is maintained throughout the pulse length of approximately 12° el.

Fig. 8 shows how the excitation voltage can be varied by adjusting different firing delay angles for a three-phase bridge connection. Special precautions are taken to keep the delay angle within the limits which must be adhered to in order to ensure reliable commutation, i.e. switching of the current from one thyristor arm to the next.
Automatic voltage regulator (AVR)
The voltage across the terminals of the synchronous machine is the ultimate controlled variable. Using the reference setter, its reference value can be varied in operation in a range of ± 10 %. The voltage can moreover be controlled as a function of the reactive current in order to stabilize the reactive power balance among several generators running in parallel. This is done by means of the adjustable quadrature-droop circuit, which can also be used for compensating the voltage drop across the unit transformer.

The reference value thus formed is regulated by the AVR with an accuracy of ± 0.5 % throughout the predetermined rated-load range of the synchronous machine.

Beyond this load range the machine may only be operated for short periods of time. After an adjustable delay the limiting controller then operates and returns the excitation current to the permissible value.

Underexcitation limiter
With several generators or power stations operating in parallel, this device has the purpose of preventing excessive underexcitation of individual generators during low-load periods owing to accidental differences in the settings of the voltage reference setters.

Irrespective of the terminal voltage the excitation is then increased if the preset limiting characteristic is reached.

This limiting characteristic, which is coordinated with the generator protection system, is established by way of comparison between the generator terminal voltage and a value depending upon the stator current and the electrical angle formed between the voltage and current vectors. In this way the equipment can be well adapted to the stability limit for operation in parallel with the system.

Excitation current limiter
This limiting controller operates with some delay and thus permits the system voltage to be supported more massively for a short period of time, followed by reduction of the generator voltage. This means that the limiting controller will only intervene in the event of the system voltage failing to attain the reference value during the maximum ceiling current time of about 5 s, or in the event of the reference value having been raised and the preset output limits of the generator preventing the actual value to be raised accordingly.

The following optional features can be provided in the automatic voltage regulator:

Stator current limiter
During operation at high active power and/or low voltage the stator current of the generator tends to rise beyond its rated value in spite of the action of the excitation current limiter. A decision on whether or not an additional current limiting controller acting on the generator excitation is required as a safeguard against such states of operation must be made in each individual case.

U/f limitation
Generators are not normally sensitive to short-time rises of the flux density - in contrast to large transformers in which high flux densities give rise to local eddy currents which in turn may result in thermal overloading. If a power station is to be kept in operation even in case of substantial system frequency drops, for instance in order to prevent complete break-down of the system, it is good policy to lower the voltage commensurate with the frequency drop by means of a U/f limiting device.

Stabilizing device
This device senses frequency or active-power excursions around the natural frequency of the generator and system and causes a damping influence to be exerted through the voltage regulator and the generator excitation. Provision of such a device is commendable where the steady-state stability is endangered by the presence of long transmission lines in the system and where the natural damping properties of the generator are inadequate.

Reactive power control/ power factor control
This device is particularly advantageous in the case of synchronous condensers provided to prevent fluctuations in the reactive-power requirements of certain load equipments (e.g. rolling mills) from adversely affecting a system. A reactive-power measuring device with non-delayed output senses the reactive power level at the tie point between the load group and the system and counteracts deviations from the reactive power setpoint by direct intervention in the AVR.

Higher level closed-loop and open-loop controls
These include all closed-loop and open-loop control devices capable of influencing the automatic voltage regulator through adjustment of the reference setter. Examples: power factor control at the tie point, common control of several generators, automatic equalization prior to synchronizing, etc.
**Excitation current regulator**

The excitation current regulator permits the synchronous machine to be operated completely independent of the automatic voltage regulator. Every position of its reference setter corresponds to a certain excitation current and ensures that the value set is maintained accurately.

The excitation current is measured by means of a shunt in the DC circuit and a shunt transducer for galvanic isolation. To permit changeover from manual operation to automatic regulation and vice versa without sudden changes in the excitation, the output signals of the manual setter and the automatic voltage regulator are compared and follow-up each other. An additional optional balancing instrument is available and balancing operation carried out prior to changeover also provides a functional check of the device to be brought into operation. In the case of the THYRIPOL® L excitation system with load-dependent component, the excitation voltage is regulated instead of the excitation current.

**Overvoltage protection**

If the field winding of a synchronous machine is connected to controlled or uncontrolled converters, special measures are required to prevent overvoltages. These overvoltages may, for instance, be set up by impressed currents transferred to the field circuit from the AC side of the synchronous machine during disturbances. They may also be caused by switching manipulations in the AC supply circuit of the excitation system.

The Siemens THYRIPOL® excitation system is therefore equipped with overvoltage protection, e.g. in the form of crowbar thyristors which are connected anti-parallel to the field winding of the synchronous machine and are fired by BOD (break-over-diode) elements. They can carry the current for a short period and thereby limit the voltage. On operation of the overvoltage protection, an alarm signal is produced by a monitoring device which also initiates shutdown of the synchronous machine if the duration and magnitude of the current flowing through the overvoltage protection are exceptional.

**De-excitation device**

Various designs are available to meet differing technical requirements. With the THYRIPOL® excitation system, a field breaker is generally provided in the AC circuit to ensure de-excitation of the synchronous machine independent of the gate control circuit of the thyristor rectifier. In special cases a non-linear resistor can be provided instead of the normal (linear) field-discharge resistor. DC field circuit breakers are available optionally.

In addition to operation of the de-excitation breaker combination, the thyristor converter is driven into the inverter range (Fig. 9).

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*Fig. 9: De-excitation with field switch and field-discharge resistor, overvolt protection*

*Fig. 10: Alternative circuit combinations for feeding the THYRIPOL excitation system*
Feeding of the excitation device

In standard applications and especially in cases where the protection system can be matched to the special conditions prevailing in the event of a short-line fault, the THYRIPOL® excitation system is fed from the main machine terminals. No circuit-breakers are required between the excitation power source and the converter, but a field-flashing device connected to the station auxiliary system or station battery is in this case required to ensure excitation build-up in the synchronous machine (Fig. 11). The field-flashing device consists of a small matching transformer and an uncontrolled rectifier, which can be connected to the field winding of the main machine parallel to the converter. The field-flashing device may alternatively draw from the station battery via a contactor and blocking diodes.

The control equipment and thyristor firing circuits are fed from redundant units which establish two supply channels. During starting and in case of a system fault the supply voltage comes from the channel connected to the station battery. This ensures that the thyristors can be fired when at least 20 % of the generator terminal voltage and 90 % of the rated speed have been attained. When the full generator terminal voltage is available after successful clearing of a system fault or completion of the excitation build-up, the other channel takes over the supply of the controls and gate firing circuits.

Additional provision of a series connected, uncontrolled rectifier fed from a series reactor (THYRIPOL® L) or connection of the excitation system to a three-phase constant-voltage main exciter offers the advantage that the short-circuit current reaches the continuous short-circuit level even in the event of a generator terminal short-circuit. If a main exciter is provided, it is a three-phase constant-voltage synchronous generator. In the case of hydro-electric machines, it is generally provided with a voltage regulator to limit the voltage at runaway speed.

The transient reactances of this machine are selected so that the commutation times remain short even at maximum load. The voltage of the auxiliary generator is selected to suit the required ceiling voltage. An exciter with power-frequency output is chosen in order to be able to provide normal gate control circuits for the converter and to permit testing of the excitation system – under the necessary safety precautions – with the main machine shut down and power for testing being provided by the station auxiliary system. The constant-voltage exciter supplies the thyristor converter direct without an interposed breaker. A breaker is not required if the exciter is equipped with a reliable de-excitation device which is capable of reducing the output voltage to the residual voltage level.

The regulator power supply units and the converter cubicle fans are likewise fed from the exciter machine via a transformer.

When the machine is started up, the excitation of the three-phase main exciter is built up automatically from remanence. The thyristor firing circuits are not enabled until all supply voltages are available and the speed of the synchronous machine has reached at least 90 % of the rated value.

Depending on the manner in which the excitation system is connected, various supplements can be provided to permit switchover or reconnection of the three-phase side of the converter to an independent power source for any one or several of the following purposes:

- To excite the generator with its terminals short-circuited, e.g. for assessing the short-circuit characteristics
- To excite the generator during start-up when using a static starting converter
- To provide excitation during electrical braking

Alternatively, auxiliary converters temporarily connected in parallel on the DC side of the main converter can be used for the same purposes.

Monitoring and signaling devices

The monitoring, signaling and protective circuits are fed in the normal manner from the auxiliary systems provided in the power station. The circuits are so designed, however, that the excitation system remains unaffected in the event of any one of the auxiliary supply voltages for these circuits failing.

An appropriately designed monitoring and signaling system provides the operating personnel with information on the states of operation of the equipment and on the cause of alarm and fault signals. Group alarm signals are formed for transmission to higher-level control stations.

**Fig. 11: Connection of the excitation system for feeding from the generator terminals**
Excitation Systems

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The information in this document contains general descriptions of the technical options available which do not always have to be present in individual cases. The required features should therefore be specified in each individual case at the time of closing the contract.