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# Excitation Systems in Synchronous Machines

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# ABSTRACT


The goal of this seminar paper is to review different excitation system configurations in synchronous machines, analyzing their performance and suitability for different situations. Synchronous machines are crucial components of electrical power systems, functioning as generators or motors. Their performance depends mostly on excitation systems. Excitation systems supply direct current (DC) to the field winding, essential for energy conversion.

Certain machines use slip rings and brushes, while larger machines use advanced methods. Modern systems, like static and brushless exciters, eliminate these problems by avoiding sliding contacts. Static excitation draws power from alternator's output, using transformers and rectifiers.

Brushless systems use a rectifier model and a permanent magnet generator. Excitation systems regulate alternator output voltage and protect against faults. They maintain stability by quickly adjusting field current in response to disturbances. The response time is one of the most crucial characteristics of an excitation system. This paper analyzes the operation of various excitation system models, discussing their regulation methods and potential for improved performance.

Understanding different types of excitation systems and their function is crucial for anyone involved in the design, operation, and maintenance of any electrical power system.



**Keywords:** excitation system, synchronous machine, synchronous generator, DC excitation, static excitation, brushless excitation, slip rings, brushes, rotor, stator, system efficiency, power system.

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[Reference:] Sahdev, S. K. (2018). "Electrical machines". University Printing House, Cambridge CB2 8BS, United Kingdom: Cambridge University Press

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[Reference:] Hangzhou Grand Technology. "Slip Ring Brushes: A Detailed Overview." Yuhang District, Hangzhou, 311100, China. Retrieved from https://www.grandslipring.com/slip-ring-brushes/#12. Accessed: May 31, 2024

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[Reference:] Shah, Chinmay & Wies, Richard & Hansen, Timothy & Tonkoski, Reinaldo & Shirazi, Mariko & Cicilio, Phylicia. (2022). High-Fidelity Model of Stand-Alone Diesel Electric Generator With Hybrid Turbine-Governor Configuration for Microgrid Studies. IEEE Access. PP. 1-1. 10.1109/ACCESS.2022.3211300.

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[Reference:] "Static Excitation System – Working Principle." (2017). Electrical Concepts. Retrieved from https://electricalbaba.com/static-excitation-system-working-principle/. Accessed: May 31, 2024

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[Reference:] Synchronous Machine Excitation System Vision Dynamical Analysis Manual. (2016.) 16-065 CW. Arnhem, The Netherlands.

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[Reference:] Sahdev, S. K. (2018). "Electrical machines". University Printing House, Cambridge CB2 8BS, United Kingdom: Cambridge University Press

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[Reference:] "Difference between Current Transformer and Potential Transformer." Retrieved from https://www.macroplasttransformers.com/blog/difference-between-current-transformer-and-potential-transformer/. Macroplast - Keyword India Network. Accessed: June 2, 2024.

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[Reference:] NEPLAN Smarter Tools. "Standard Dynamic Excitation Systems in NEPLAN Power System Analysis Tool." Retrieved from https://www.neplan.ch/wp-content/uploads/2015/08/Nep_EXCITERS1.pdf. Accessed: June 2, 2024.

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[Reference:] Rebollo, Emilio & Blánquez, Francisco & Platero, Carlos & Blazquez, Francisco & Redondo, Marte. (2015). Improved high-speed de-excitation system for brushless synchronous machines tested on a 20 MVA hydro-generator. IET Electric Power Applications. 9. 10.1049/iet-epa.2014.0313.

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[Reference:] Yamashita, K., & Nishikata, S. (2016). A simulation model of a self-excited three-phase synchronous generator for wind turbine generators. 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 1363-1368.

## LIST OF ABBREVATIONS

| | |
|---|---|
| **DC** | Direct Current |
| **AC** | Alternating Current |
| **EMF** | Electromotive Force |
| **P-Q** | Power-Quality |
| **AVR** | Automatic Voltage Regulator |
| **PSS** | Power System Stabilizer |
| **P** | Proportional |
| **PI** | Proportional-Integral |
| **PID** | Proportional-Integral-Derivative |
| **CT** | Current Transformer |
| **PT** | Potential Transformer |
| **HV** | High Voltage |
| **LV** | Low Voltage |
| **PMG** | Permanent Magnet Generator |
| **MVA** | MegaVolt Ampere |
| **HVDC** | High-Voltage Direct Current |
| **HSBDS** | High-Speed Brushless Discharge System |

# 1. INTRODUCTION

Synchronous machines are fundamental elements of modern electrical power systems, primarily used for generating and converting electrical energy. These machines operate at a constant speed, which is directly related to the frequency of the electrical power system and the number of poles in the machine. A synchronous generator, often referred to as an alternator, converts mechanical energy from a prime mover, such as a steam turbine or hydro turbine, into electrical energy.

A crucial aspect of the operation of synchronous machines is the excitation system. The excitation system supplies the necessary direct current (DC) to the field windings of the machine, establishing the magnetic field required for generation or conversion process. This magnetic field interacts with the rotating magnetic field of the stator, enabling the machine to perform its electromechanical energy conversion efficiently.

The primary goal of using excitation systems in synchronous machines is to regulate and control the machine's voltage output and improve the stability and performance of the power system. Different excitation methods, including DC exciters, static excitation systems, and brushless excitation systems, have been developed to meet these objectives. Each system has its advantages and applications, adjusted to the requirements of different power systems and machine sizes.

Excitation systems also play an important role in protecting the machine and the power system from faults and disturbances. By quickly responding to changes in the system and adjusting the field current accordingly, excitation systems help maintain the desired voltage levels and ensure the reliable operation of synchronous machines. Advanced excitation systems incorporate control and protection functions, improving the overall efficiency and stability of the power grid.

## 2. OVERVIEW OF SYNCHRONOUS MACHINES

Synchronous machines generate alternating (AC) currents and voltages and are primarily used in electrical power systems, although they also serve as motors. These machines are characterized by their ability to operate at a constant speed, making them essential for stable power generation and transmission. In the following subsections, we will explore the different types of synchronous machines and their operating principle.

### 2.1. Types of Synchronous Machines

Synchronous machines can be categorized based on their prime movers and rotor designs. According to the prime mover, they include turbogenerators (driven by steam or gas turbines), hydrogenerators (driven by water turbines), and diesel generators.

By rotor design, they are divided into machines with cylindrical rotors, typically used for high speed applications, and machines with salient pole rotors, suitable for lower speed applications. The salient poles of the magnet stick out of the rotor surface. Additionally, the rotors with salient poles typically incorporate four or more poles. They are used when the turbine speed is low.

In synchronous machine, the rotor acts as a large electromagnet. The cylindrical rotor has nonsalient poles, which means that they do not stick out of the rotor surface. They are used when the turbine speed is high. Cylindrical and salient configurations are shown in Figure 1. The figure represents the section of the rotor and stator (armature) inside of the synchronous machine. [1]

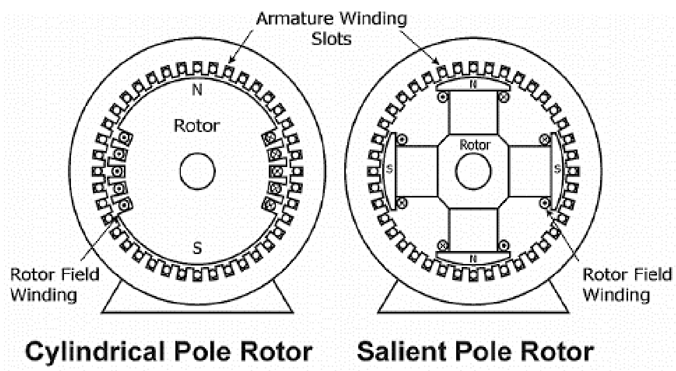


**FIGURE 1.** Cylindrical and Salient Pole Rotor Types

## 2.2. Operating Principle

Discussing synchronous machines, we already know that the two main parts of these machines are: stator and rotor. In stator windings, with the armature reaction, come the magnetic losses. It is known that the magnetic field is best enclossed through a magnet, and the worst through air. In there, the losses are the largest. Reactance is used to represents these losses. When it comes to the rotor, the terms of excitation and rotor magnetic field are associated with it. For the synchronous generator precisely, the goal is to convert the mechanical energy into electrical energy.

Operating principle of synchronous generator begins by understanding that if the stator of the synchronous machines has three-phase windings, the three phases are each separated by exactly 120°. This is because they will not induce the electromotive force (EMF) at the same time, shown in Figure 2. For one rotor turn, for n number of pole pairs, we have n number of changes of EMF.

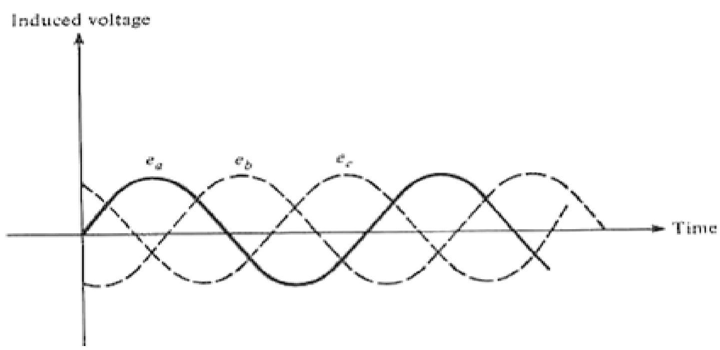


**FIGURE 2.** Three-Phase Voltage produced by the Synchronous Generator

Since pole pair is constant, and we are required to have an agreed frequency, this means that the turning speed of synchronous machines needs to be constant as well. This analogy is formulated in Equation 1. In here, *n* is the rotor turning speed, *f* is the frequency of stator currents, while *p* is the number of pole pairs.

$$n = \frac{60f}{p}$$

**EQUATION 1.** Turning Speed for the Synchronous Machine

The exciting DC will start flowing through the exciting winding. The direction of this current is such that – one pole is North, the next one is South, and so on. The DC supply is also called the exciter. This leads to the forming of the steady rotor magnetic field. The force of excitation is steady, compared to the rotor, and that is why we call this field – steady.

The turbine acts externally and starts turning the rotor mechanically. This creates the rotating magnetic field. This field will intersect the stator windings, creating EMF in those windings. This occurence, alongside many other in electrical machines, is an interpretation of the Faraday's Law.

These windings are called armature windings, and the main voltage is induced in here. Figure 3 includes stator and rotor positions during the operation of synchronous machines, as well as the DC excitation. Armature windings and field windings are shown, as well as 120° phase difference.

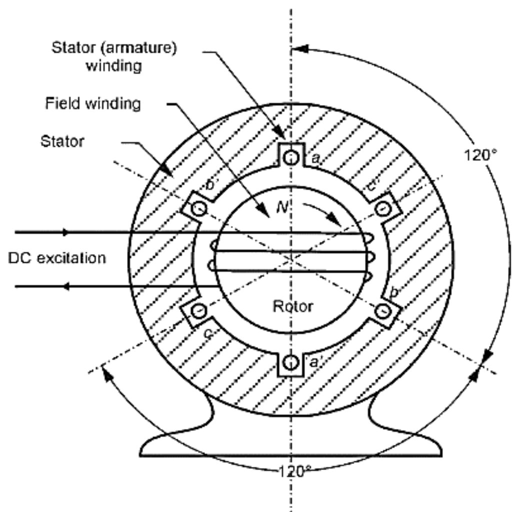


**FIGURE 3.** Components for the Operation of Synchronous Machine

If we load the stator with a three-phase symmetrical load, then we will have three currents flowing through the stator windings, all exactly 120° separated from each other. Axes of these currents will together enclose an angle of electrical 120°, giving an equivalent turning field. This field's speed depends on the current. It needs to have the same speed as the rotor (turbine speed). This is the speed from Equation 1 and it is called the synchronous speed. Because of this, the synchronous machines are called this way. The relative speed of these two fields will, as expected, be zero.

# 3. EXCITATION SYSTEM CONSIDERATIONS

The main functions of excitation systems in synchronous machines are to supply DC to the field winding of a synchronous generator, and to carry out control and protective tasks that are crucial for the efficient and safe operation of the power system.

One of the key components in a power system is the synchronous generator, since it generates electrical energy. In a generator, mechanical energy (typically from a turbine) is converted into electrical energy. This conversion can only occur if the generator is properly excited. The excitation of the generator also determines its output values, such as voltage and reactive power.

## 3.1. Synchronous Generator Operating Point

The excitation of a generator needs to be carefully regulated. This means regulating the generator's output energy, which naturally influences the stability of the entire power system. Figure 4 represents the P-Q diagram of a generator, which represents the range with the defined limits.

Operating point of a generator needs to be within a certain area, determined by several limits [2]:

▪ Minimum excitation current (curve a) - the smallest current value needed to excite the generator

▪ Practical stability limit (curve b) - the boundary within which the generator operates stably

▪ Maximum excitation current (curve c) - the highest amount of current for safe excitation

▪ Maximum armature current (curve d) - maximum current the generator armature can handle

▪ Maximum turbine power (line e) - the highest power the turbine driving the generator can produce

▪ Minimum turbine power (line f) - the lowest power output that the turbine can produce

Together, these limits form an area within which the generator must operate to function effectively and safely. This represents synchronous generator stability.

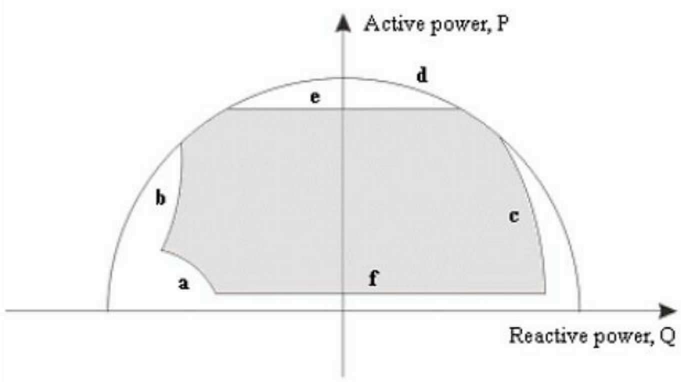


**FIGURE 4.** P-Q Diagram of a Synchronous Generator

## 3.2. Elements of an Excitation System

Excitation system typically includes an automatic voltage regulator (AVR), an exciter, measuring elements, a power system stabilizer (PSS), and a protection unit. [3] The exciter, which can be a separate DC or AC generator, provides electrical power to the field winding.

The generator terminal voltage is rectified and filtered to a DC quantity and compared with a reference by a voltage transducer. Load compensation will be initiated in case if it is desired to hold the voltage at a remote point.

The AVR controls the exciter, maintaining steady-state operation by adjusting the field voltage and current. However, during sudden disturbances, the AVR might affect power swings and/or damping. [4] To counter this, a PSS introduces an additional control signal to stabilize voltage oscillations, improving system stability.

Measuring elements (limiters) monitor various parameters like armature voltage and current, and excitation voltage and current, ensuring the system operates within safe limits. The protection circuitry is put to counter excessive physical values, such as high field voltage and current, preventing potential damage. Together, these components enable the excitation system to effectively manage reactive power flow and improve the overall stability and capacity of the power system. These components are seen in Figure 5, showing each of their individual positions.

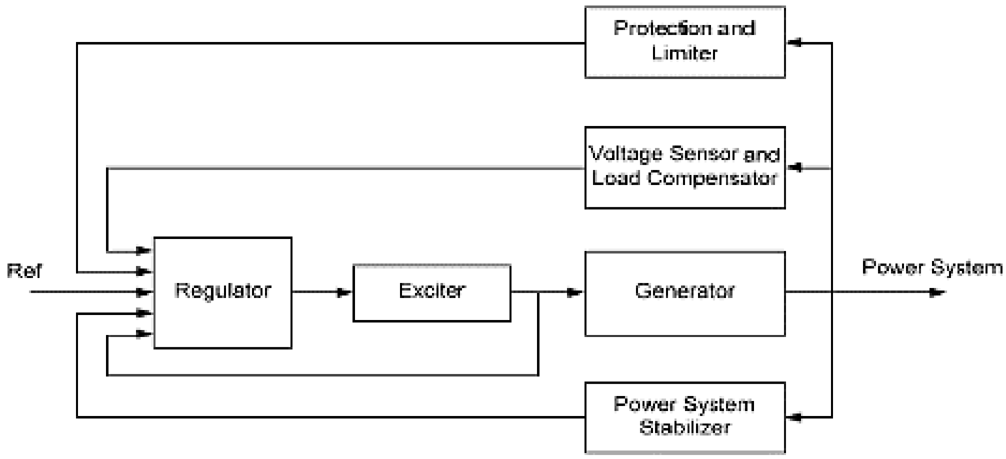


**FIGURE 5.** Excitation System Components

## 3.3. LINEAR VS NONLINEAR REGULATION

Linear regulation is used in excitation systems because it provides simple and effective control during steady-state operations, ensuring stability and reliability under normal conditions. Nonlinear regulation is designed to handle dynamic and unpredictable changes, maintaining the system stability during transitions and disturbances by adapting to different conditions.

### 3.3.1. Linear Regulation

Linear regulation in excitation systems involves using controllers that adjust the system based on a proportional relationship. There are three main aspects to consider: the speed of operation, the autonomy of the system, and the maximum drive security. Speed is crucial for maintaining power system stability, especially during sudden changes in excitation states or in voltage.

Linear controllers, such as proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers, are commonly used. P controller is simple but can diverge in a steady state. The PI controller eliminates steady-state divergence but slows down the system's response.

PID controllers add a derivative element to improve system dynamics and counteract the slowing down from the integral component. These controllers require precise adjustment of each parameter, either through mathematical modeling or experimental methods, in order to create maximum optimal performance at a specific operating point. [5] A diagram of PID controller is common for understanding each of its three components and it is represented in Figure 6.

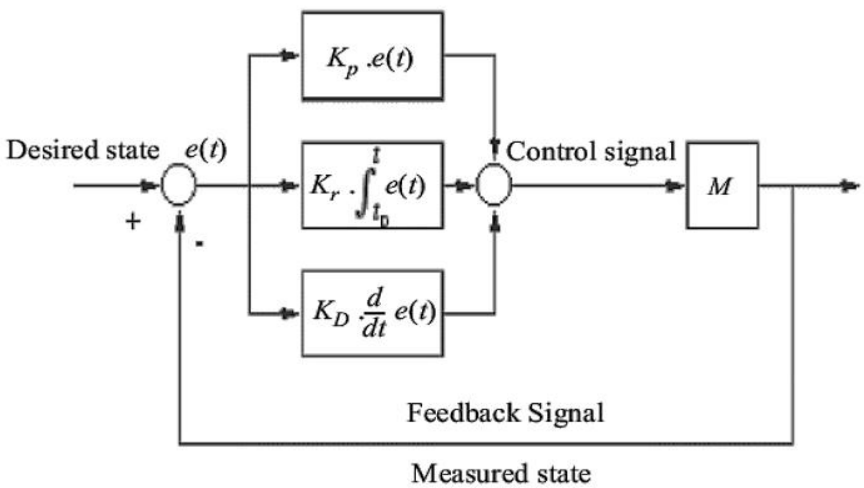


**FIGURE 6.** PID Controller Schematic

### 3.3.2. Nonlinear Regulation

Nonlinear regulation deals with maintaining stability and performance across a wider range of operating conditions, especially during transitions or system faults. Unlike linear controllers, which work well only at steady state, nonlinear ones adapt to dynamic changes and disturbances. Advanced methods are used in nonlinear regulation, with some of them discussed below.

Neural networks can predict system behavior based on historical data, while fuzzy control fixes imprecisions and uncertainties in system response. Adaptive control adjusts system parameters in real-time to adapt to changing conditions. Nonlinear regulation often involves monitoring the load angle of the generator, which indicates its position relative to stability limits. [6] Changes in the load angle can be used as input for power system stabilizers (PSS) to maintain stability.

## 4. TYPES OF EXCITATION SYSTEMS

Excitation systems for synchronous machines are essential for supplying the necessary field current to the rotor winding. There are three main types:

▪ **DC Excitation Systems** - using DC generators to provide field current and often involve slip rings and brushes,

▪ **Static Excitation Systems** – drawing the power from the alternator's output and using thyristor bridges to convert it to DC, eliminating the need for sliding contacts, and

▪ **Brushless Excitation Systems** - using a rotating rectifier and a permanent magnet generator to provide DC power without slip rings and brushes.

Additionally, the term AC Excitation Systems refers to the source of the excitation power rather than a type of excitation system. These systems use an AC generator and a rectifier to provide the necessary DC current for the field winding. They are closely related to Brushless Excitation, as well as the Static Excitation System. Additionally, they can incorporate rotating thyristors.

Each system has its unique advantages. Because of that, different excitation systems are designed for and used to satisfy specific applications and different machine sizes. In the following sections, all of the individual excitation systems will be disccused.

### 4.1. DC EXCITATION SYSTEM

DC Exciters are a traditional method which involves three machines:

▪ **The Pilot Exciter**,

▪ **The Main Exciter**, and

▪ **The Main Three-Phase Alternator**.

These three machines are all mechanically coupled and driven by the same shaft. [7]

The entire excitation system circuit diagram, with these three machines, is illustrated in Figure 7.

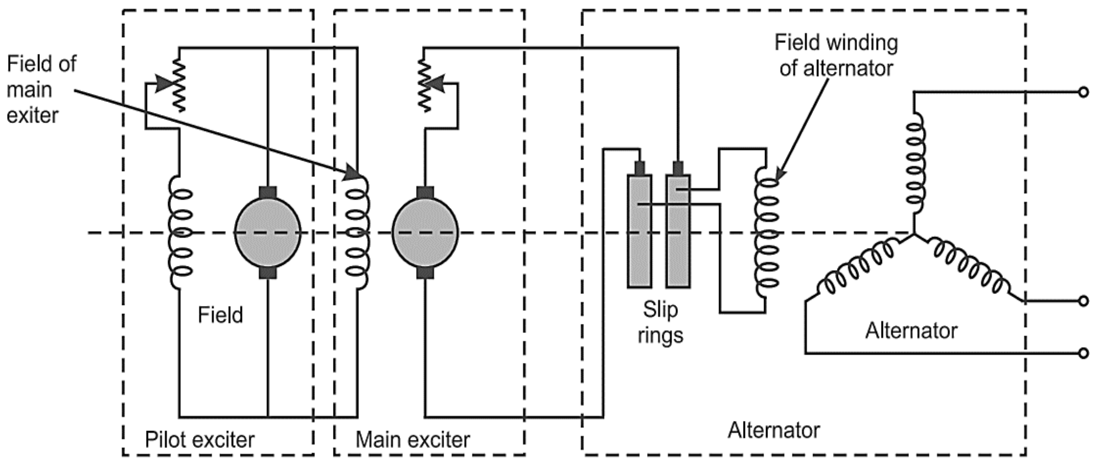


**FIGURE 7.** DC Excitation System Circuit Diagram

Firstly, the pilot exciter is a DC shunt generator. It has its field winding connected in parallel with the armature (shown in Figure 7 by the small coil labeled "Field"). The output of the pilot exciter feeds the field winding of the main exciter.

The field winding of the main exciter is powered by the pilot exciter. This generator provides the necessary current to the field winding of the main alternator. A motor or shaft of a generator can drive the exciter. It can be either self-excited or separately excited. [8] When separately excited, the exciter field current is supplied through a pilot exciter - comprising of a DC shunt generator.

The output from the main exciter is delivered to the field winding of the alternator through brushes and slip rings. Slip Rings are metal rings that are insulated from the rotating shaft. They are crucial for transferring the DC current to the rotor's field winding.

Brushes are conductive materials that maintain electrical contact with the slip rings, allowing current to flow into the rotating part of the alternator.

The field winding of the main three-phase alternator is excited by the current supplied from the main exciter. The connection includes slip rings and brushes which transfer the DC current to the rotating field winding. The alternator then generates a three-phase AC output.

### 4.1.1. Operating Principle

When explaining the operation of a DC excitation system, we understand that the pilot exciter is the starting point. After it, the main exciter and the alternator from Figure 7 come into play.

The pilot exciter, driven by the same shaft as the main exciter and alternator, generates DC output which is fed into the field winding of the main exciter.

The main exciter then generates a larger DC output that is supplied to the field winding of the alternator via slip rings and brushes. These components are shown in Figure 8. The slip rings are metal rings that completely encircle the shaft. However, they are insulated from it.

The slip ring assembly consists of a rotating rotor attached to the equipment's shaft and a stator fixed to the housing unit. Metal conductive rings on either part form electrical paths. Brushes, made of carbon or metal, establish electrical contact between these rings, allowing the current to flow from the stationary parts to the rotating parts of the alternator.

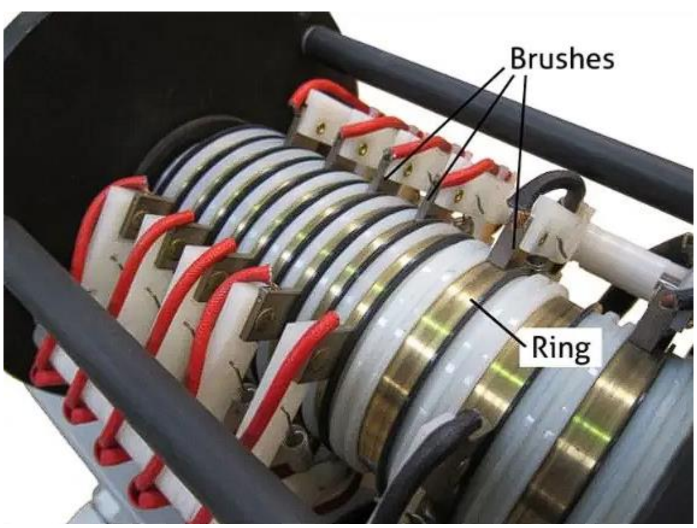


**FIGURE 8.** A View of Slip Rings and Brushes

### 4.1.2. DC Exciter Models

In recent years, DC exciters are suppressed by the other two types of excitation systems (brushless and static). There is roughly 20 excitation system models that are overall used in the entire world. However, DC Exciters have four of their models which are still used in certain applications. [9]

These four models are:

▪ **DC1A** – used for self-excited shunt fields with a voltage regulator in buck-boost mode

▪ **DC2A** - similar to DC1A but with different voltage regulator output limits

▪ **DC3A** - represents older systems with DC commutators and noncontinuous voltage regulators

▪ **DC4B** - newer model that differs from DC1A by incorporating a PID controller

The DC4B Model of an excitation control system is shown in Figure 9. This model includes a closed-loop system, which means we have a feedback loop. Voltage regulator feeds the Field Excitation. In case of saturation, our actual output differs from the desired output and we feed that output to the input for correction. Damping filter helps with adjusting the output to get desired one.

Overall, these four models are practical models, used in real life for different situations.

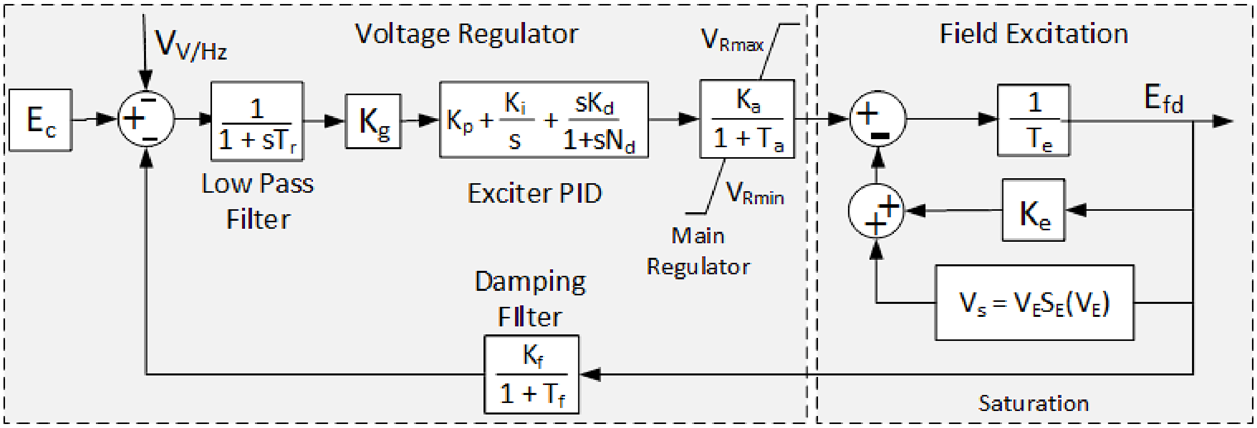


**FIGURE 9.** DC4B Excitation System Control Model

### 4.1.3. Advantages and Disadvantages

As mentioned in section 4.1.2, DC Exciters are nowadays used a lot less due to the development of the brushless and static excitation systems. There are couple of reasons for that. However, it is essential to firstly understand where it is advantageous to use these systems.

Firstly, DC Exciters have a straightforward operation and are suitible for small and medium sized synchronous machines. DC exciters mostly provide good control stability, which is crucial for maintaining the desired voltage output in synchronous generators.

This stability is beneficial for the sensitive electronic equipment. Additionally, DC excitation systems offer a cost-effective solution. The design of its components has lower initial costs, and, because of that, it is beneficial to the small and medium sized machines, as already mentioned.

Although suitable for smaller implementations, disadvantages of DC Exciters become apparent in larger machines, in which the other excitation systems are more preferred. As the size of the generator increases, many problems rise.

For larger machines, DC Excitation systems suffer from cooling and maintenance issues. These problems are associated with slip rings and brushes. Larger devices have higher currents, leading to increased heat generation in slip rings and brushes. This increases the wear of these components, meaning it decreases the overall efficiency of the entire machine.

Additionally, these components can wear out over time and they require regular maintenance. While suitable for small to medium size machines, DC excitation systems may not be as scalable or efficient in larger applications. The maintenance issues associated with larger machines outweigh the benefits of simplicity and reliability, leading to use of alternative excitation systems.

## 4.2. STATIC EXCITATION SYSTEM

Static Excitation System involves drawing the excitation energy for the main alternator field from the output of the main three-phase alternator itself.

Its design is a lot more complex compared to the DC Excitation System, and the following components are implemented inside of this system:

- **Three-Phase Alternator**
- **Step-Down Transformer (IR)**
- **Thyristor Bridge Rectifier**
- **Regulator**
- **Potential Transformer (PT) and Current Transformer (CT)**
- **Battery Bank**
- **Field Discharge Resistor**
- **Brushes and Slip Rings**
- **Field Winding**

The circuit diagram in Figure 10 contains all of these components, with careful considerations of each component needed, in order to understand this complex design.

Three-Phase Alternator is the main component generating AC electrical energy. It consists of a rotor (field winding) and a stator (armature winding). The Step-Down Transformer lowers the high voltage produced by the alternator to a value for rectification. Thyristor Bridge Rectifier will converts the stepped-down AC voltage into a controlled DC voltage. Thyristors, acting as switches, allow current flow in only one direction. Voltages and currents are transformed to an appropriate level and rectifiers (controlled or uncontrolled) provide the necessary DC to the field winding. [10]

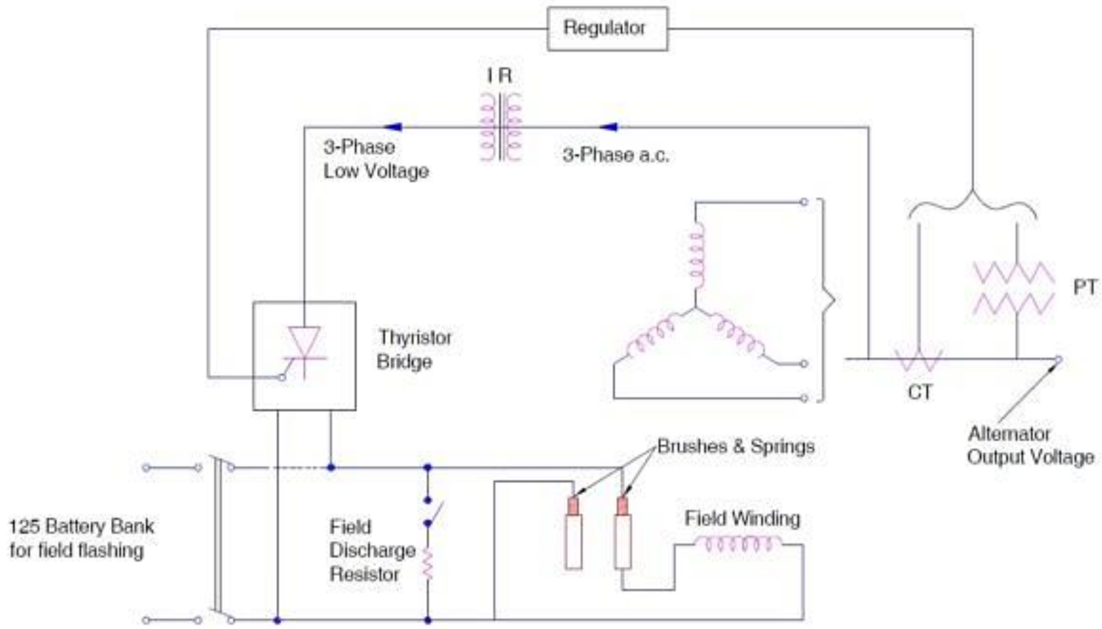


**FIGURE 10.** Static Excitation System Circuit Diagram

The regulator controls the firing angle of the thyristors in the rectifier, regulating the output DC voltage. It receives feedback signals from the alternator to adjust the excitation level as needed.

Potential and Current Transformers measure alternator output voltage and current, respectively. Their feedback signals are crucial so the regulator can maintain the desired voltage level.

During startup, the battery bank provides initial excitation to the alternator's field winding. It ensures that the alternator begins generating power even when not connected to an external source. Field Discharge Resistor provides a safe path for discharging the current in the field winding when the excitation is off or in case of fault. It prevents damage to the system and ensures safe operation.

Brushes and Slip Rings are present in static excitation systems as well. These components conduct the transfer of DC excitation current to the rotating (field) winding of the alternator. Excitation is provided to the field winding placed on the rotor, with slip rings and carbon brushes used. [11]

Field Winding is located on the rotor of the alternator, and it generates the magnetic field necessary for power generation when energized.

### 4.2.1. Operating Principle

By observing Figure 10, we understand that, firstly, the field winding is energized by the battery bank to establish an initial magnetic field. This brings the alternator up to its rated speed.

As the alternator reaches its operating speed, the output voltage begins to build up. Feedback from Potential and Current Transfomers allows the regulator to monitor the alternator's voltage and current levels. Once the output voltage of the alternator reaches a sufficient level, the field winding is disconnected from the battery bank.

The thyristor bridge rectifier, controlled by the regulator, takes over the excitation process, providing the necessary DC voltage to the field winding. With the thyristor bridge rectifier supplying excitation, the system enters steady-state operation. The regulator works constantly to adjust the firing angle of the thyristors based on feedback signals from the Potential and Current Transformers. This maintains the desired output voltage level. Overall, this feedback loop ensures a stable and efficient operation of the synchronous generator, under different load conditions.

### 4.2.2. Static Excitation System Models

Static excitation systems have seven different models used across the world. Rectifiers supply the power to the field winding, which can be either controlled or uncontrolled. While most of these systems can generate negative excitation voltage, only a few are capable of producing negative excitation current. The ability to produce negative excitation current is a great advantage because it allows for fast deexcitation, which is crucial in the event of a fault in the generator. [12]

The models of the Static Excitation are the following ones:

▪ **ST1A** - excitation power supplied from transformer at generator terminals or bus

▪ **ST2A** - generator current and voltage as a power source

▪ **ST3A** - field voltage control loop, as well as various controlled-rectifier designs

▪ **ST4B** - ST3A variation with PI controller

▪ **ST5B** - ST1A variation with additional overexcitation and underexcitation limits

▪ **ST6B** - PI voltage regulator with inner field voltage regulation

▪ **ST7B -** static potential source system with configurable PI/PID controller is shown in Figure 11. It is potential/source controlled with both High Voltage (HV) and Low Voltage (LV) gates. By nature, these models are PI, but a phase compensator can introduce a derivative (D) function.

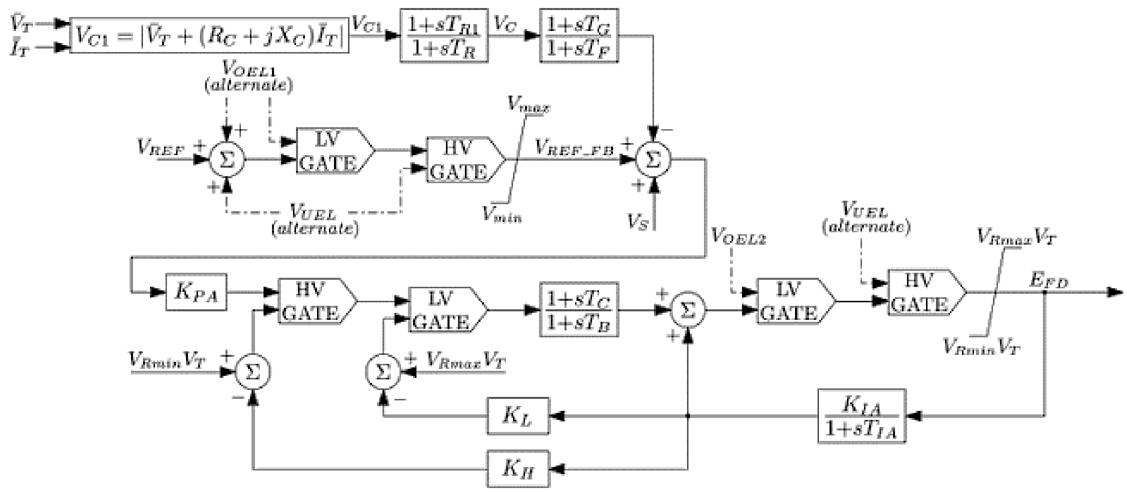


**FIGURE 11.** ST7B Static Excitation System Control Model

### 4.2.3. Advantages and Disadvantages

As this entire Section 4.2 suggests, the Static Excitation System is more complex compared to the DC Excitation System. However, it offers multiple benefits that outweigh the complex design.

Static excitation systems are often used in large power plants where precise and fast control of the generator output is crucial. This is because the power plants operate under varying load conditions.

In industrial applications, in need of a stable and reliable power supply, these systems maintain consistent voltage levels. Static Excitation Systems are used in marine and aviation generators.

In here, the compact size and low maintenance are crucial. Additionally, in aircrafts and marine vehicles, it is essential to lower the fuel consumption as much as possible.

One of the most significant advantages of static excitation systems is their fast response time. The response time is of approximately 20 milliseconds. There is no separate rotating exciter, which means the system is free from friction and windage losses in the exciter.

These systems can quickly stabilize the generator's output, making them highly effective in maintaining voltage stability during load changes or disturbances. In a power plant experiencing sudden load fluctuations, the static exciter can immediately adjust the excitation current.

Static excitation systems do not have the need for mechanical components such as exciter windage. This reduction in mechanical parts leads to lower maintenance requirements. A smaller number of components that can wear out or fail are used. This leads to higher reliability and lower operational costs. The excitation voltage in static excitation systems is directly proportional to the alternator speed. This characteristic improves the overall performance and efficiency of the system. Additionally, the Static Excitation System has the ability to reverse the field voltage, meaning that in case of a fault, generator returns to its regular operation in less than 3 seconds. [13]

However, Static Excitation Systems have certain disadvantages. Complex design and drawing the energy directly from the alternator itself leads to appearance of certain constraints.

Static excitation systems involve complex electronic components such as thyristors and voltage regulators. These components can be expensive and they require advanced control mechanisms, which can increase the overall system cost and complexity. In smaller machine setups, with limited budgets, the need for advanced maintenance will result in this system not getting implemented.

Since the excitation power is drawn from the main alternator, any issues with the alternator directly affect the excitation system. This means that any faults or disturbance in the alternator leads to problems with the excitation system as well, compromising the entire power generation process. For example, in a power plant, if the main alternator experiences a failure, the static excitation system would also be compromised, leading to a potential power outage.

## 4.3. BRUSHLESS EXCITATION SYSTEM

The brushless excitation system efficiently controls the excitation of a synchronous generator using silicon rectifiers and thyristor bridges, eliminating the need for slip rings and brushes, while ensuring a quick response time. The following components are implemented in this system type:

▪ **Permanent Magnet Generator (PMG) – Pilot Exciter**

▪ **Main Exciter**

▪ **Thyristor Bridge**

▪ **Regulator**

▪ **Shunt, Potential and Current Transformers**

▪ **Base Adjustment and Regulator On-Off .**

Together, these components make the brushless excitation system, whose circuit is shown in Figure 12. Based on this, the operating principle and every system component are understood.

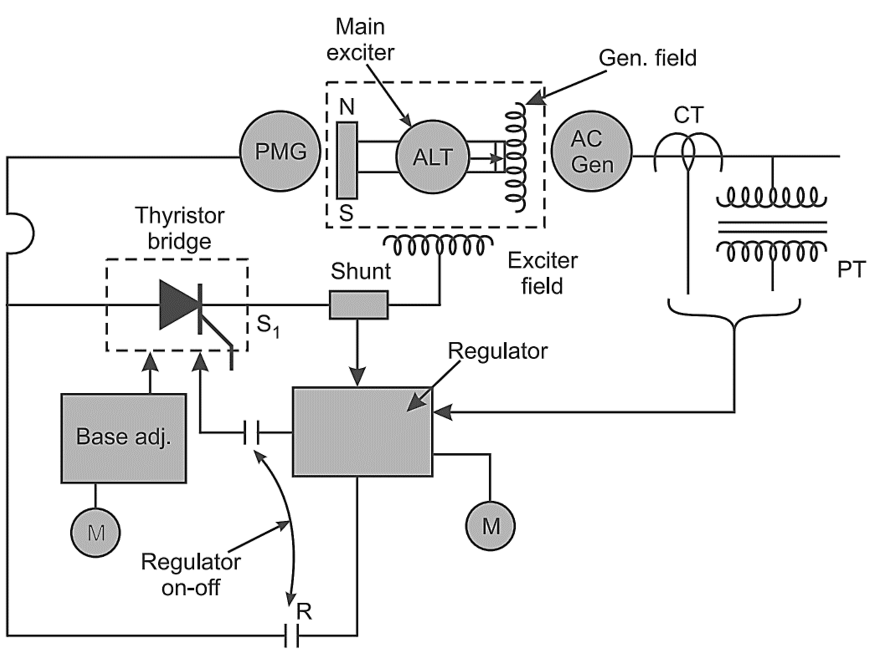


**FIGURE 12.** Brushless Excitation System Circuit Diagram

Firstly, the Permanent Magnet Generator functions as a Pilot Exciter and will generate AC voltage from rotating permanent magnets and stationary three-phase armature. This is the input power for the excitation system. After that, the Main Exciter comes into play. It consists of a stationary field and a rotating armature, and produces an AC output from a rectified PMG voltage. [7]

The Step-Down Transformer will lower this AC value, so it can be operated on by the thyristor. The Thyristor Bridge rectifies AC output of main exciter into a DC output. It supplies DC power to main alternator field winding. Regulator controls excitation system based on the feedback received from the generator. Thyristor gating circuits are adjusted to maintain voltage stability.

Potential and Current Transformers constantly provide feedback to the regulator, regarding generator parameters. They are called Instrument Transformers and are presented in Figure 13.


**FIGURE 13.** Potential & Current Transformers

#### 4.3.1. Operating Principle

From Figure 12, the operational principle is observed, and it can be seen that the operation begins with the Permanent Magnet Generator. It is the source for the AC voltage.

The PMG will generate an AC voltage as it is driven by the generator shaft. This AC voltage is then converted into DC using a three-phase full-wave phase-controlled thyristor bridge rectifier.

The DC power is then fed into the stationary field of the main exciter, which, in turn, produces AC voltage in its rotating armature. The AC output from the main exciter is rectified by silicon rectifiers to provide DC power to the main alternator's field winding, eliminating the need for traditional slip rings and brushes.

A crucial component of this system is the regulator, which continuously monitors the generator's output voltage and adjusts the excitation level accordingly. This ensures stable voltage levels, even during changing loading conditions. The regulator receives feedback signals from shunt, Potential and Current Transformers to maintain precise control.

Additionally, the regulator can fine tune the excitation level through a buck-boost control signal, ensuring optimal generator performance. The exciter’s armature current is directly related to the generator’s field current, which is strongly linked to the power system dynamics. The brushless excitation system offers efficient and precise control over the excitation, with a fast response time being below 0.1 seconds, ensuring a stable operation under different loading conditions. [14]

### 4.3.2. Brushless Excitation System Models

As already discussed, these systems incorporate an AC Permanent Magnet Generator, as well as a rectifier to produce DC. These rectifiers can be either of rotating or stationary type. This is the largest group of models in excitation systems. [9] It includes the following models:

- **AC1A** - excitation with non-controlled rectifier
- **AC2A**: - additional compensation for exciter time and field current
- **AC3A** - self-excitation system with additional nonlinearity
- **AC4A** - thyristor bridge in exciter output circuit
- **AC5A** - simplified brushless excitation systems model
- **AC7B** – having advanced control circuitry and a PID controller

▪ **AC8B** - PID controller with defined proportional, integral, and differential gains

▪ **AC6A** - field-controlled alternator-rectifier excitation with electronic regulators, depicted in Figure 14. Voltage regulator gain, time constants, limits, minimum and maximum regulator output, exciter saturation functions and many more are values which need to be standardized. [15]

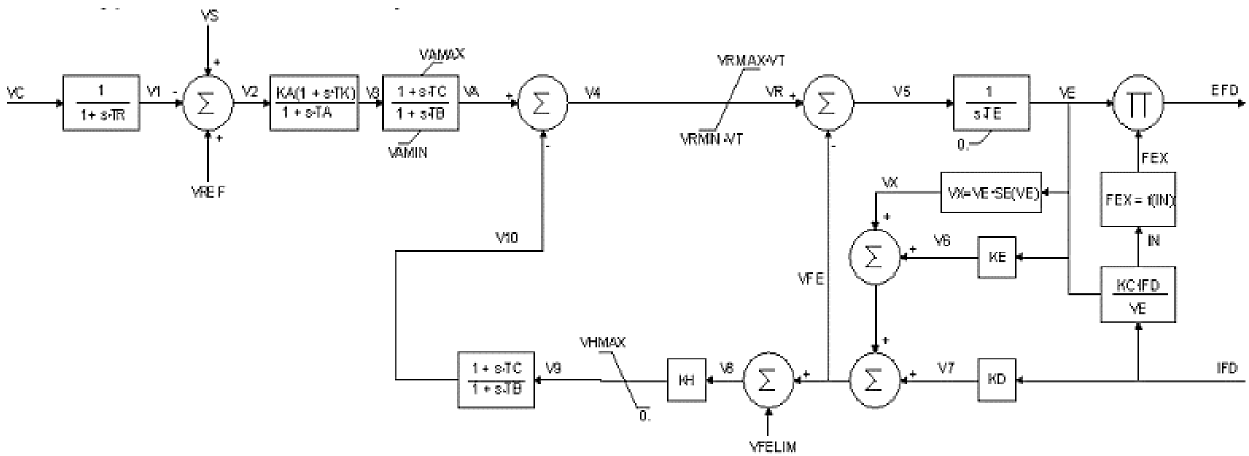


**FIGURE 14.** AC6A Brushless Excitation System Control Model

### 4.3.3. Advantages and Disadvantages

Brushless Excitation Systems offer many advantages that are similar to ones in Static Excitation Systems. However, being without brushes and slip rings offers additional benefits.

Without brushes and slip rings, there is no need to deal with the wear and tear of these components, which are common points of failure in systems which incorporate them. By removing the risk of sparking that brushes can cause, brushless systems will have much better operational safety, especially in environments with flammable materials.

Since there are no brushes, it means that there are fewer components that require regular inspection and replacement, reducing the overall need for maintenance. This leads to lower maintenance costs and fewer shutdowns for repairs, which is crucial in any industrial application.

Industrial applications, for example manufacturing plants, require a stable and reliable power supply, in order for them to maintain power production efficiency and avoid costly downtime.

Modifying the upper limit of voltage regulator, with values that allow the overvoltage to reach values of up to 40%, can improve the response time of the excitation system significantly. Using solid-state components like thyristors reduces the probability of mechanical failures and increases the overall reliability of the system. With fewer moving parts, the chances of mechanical breakdown are significantly reduced, leading to increased functioning times and reliability. [16]

Brushless systems quickly adjust to changes in the load, maintaining stable generator output and ensuring consistent power quality. In power plants, fast response to load changes is crucial to avoid blackouts and ensure that there is a continuous power supply present. Power plants demand high reliability and quick response to load changes, making brushless excitation systems ideal.

Modern solid-state components allow for a more compact and integrated design, saving valuable space. In aerospace applications, where space and weight are crucial, the compact nature of brushless excitation systems is a significant advantage. Weight and space of a vehicle need to come with as much reliability as possible. In marine generators, where maintenance opportunities are limited, the durability and low maintenance requirements are highly beneficial.

However, Brushless Excitation Systems have certain disadvantages. The need for complex circuitry and higher initial investements present certain drawbacks with these excitation systems.

Brushless excitation system of synchronous generators typically has a poor dynamic deexcitation which is a major problem during load rejection. This is mainly due to the diode bridge rectifier. The main control of the deexcitation is done by implementing a PID controller. [17]

The use of advanced control circuitry and thyristor bridge rectifiers adds complexity to the system. Maintenance of this equipment requires skilled employees, which can be a challenge in certain remote or less developed areas of the world.

The advanced components and control systems involved in brushless excitation systems are typically more expensive than those in some other excitation systems. For example, while the higher initial cost can be justified by lower long-term operational costs, it might be a big constrain for smaller machine projects, where the budget will be limited.

# 5. CASE STUDY

Case study is done towards the end of this seminar paper. We have already mentioned the implementation of Excitation Systems in power plants. However, in those cases we naturally referred to nonrenewable electrical energy sources. For this case, we will shift towards the renewable electrical energy systems and observe which excitation systems are the most common.

In **Hydroelectric Generators**, Static and Brushless Excitation Systems are used. The brushless exciter is where rectifiers are directly connected to synchronous machine field, eliminating need for brushes. This system is used for small hydro generators up to 10 MegaVolt Ampere (MVA).

The most used excitation system for hydro generators is the static excitation system, which comes in two types, based on the required speed of generator field suppression. Figure 15 shows the schematic of Hydroelectric Excitation System, supplying electric current to rotor electromagnets.

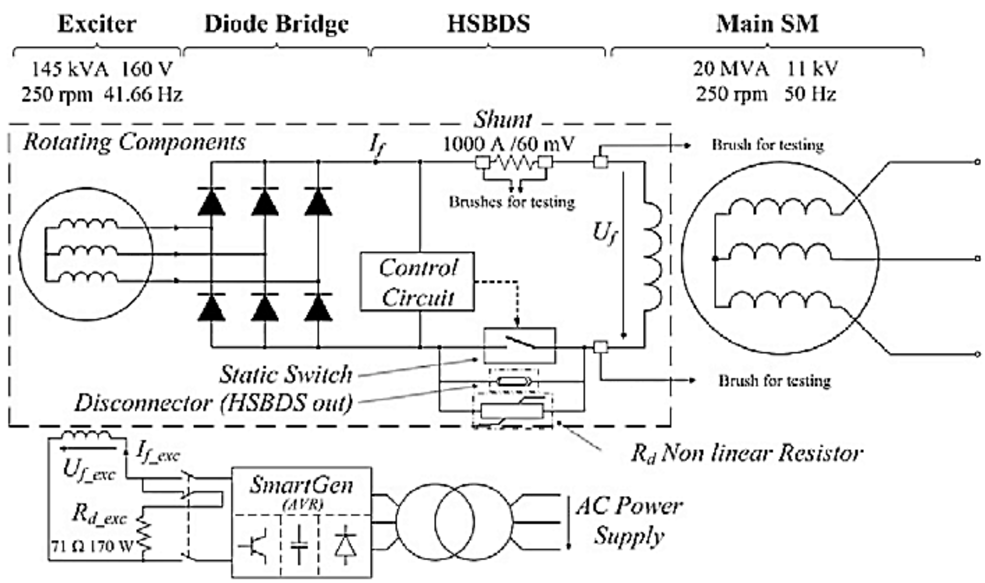


**FIGURE 15.** Hydroelectric Generator Excitation System

The hydro generator excitation system starts with an exciter that converts mechanical energy to AC energy. This AC power is rectified to DC by a diode bridge and then regulated by the High-Speed Brushless Discharge System (HSBDS), which includes a control circuit and static switch.

The regulated DC current energizes the main synchronous machine's field windings, creating the necessary magnetic field for power generation. Additional components like the shunt, non-linear resistor, and auxiliary systems ensure precise control. Brushes are included for testing purposes.

The full inverting bridge type employs six thyristors in a three-phase full-wave bridge rectifier, allowing the reversed DC voltage during full load rejection. On the other hand, the semi-inverting type uses three thyristors and three diodes and does not permit negative field forcing.

For the new generators, excitation systems from generator leads are common, often requiring slip rings for power supply to the field winding. In such systems, field flashing equipment is necessary, obtaining power from machine terminals.

In **Wind Generator Systems**, Static Excitation Systems are used the most as well. They offer fast response times and precise control. These characteristics are crucial to have when dealing with the changing nature of wind energy.

These systems use a current source thyristor inverter for wind farms. It implements synchronous generators like PMG. The model employs transformation for salient pole machines, and it is connected to High-Voltage Direct Current (HVDC) transmission system using a thyristor rectifier.

Figure 16 shows the excitation system of a wind turbine generator, with the components involved in the excitation process and connection to the HVDC transmission system.

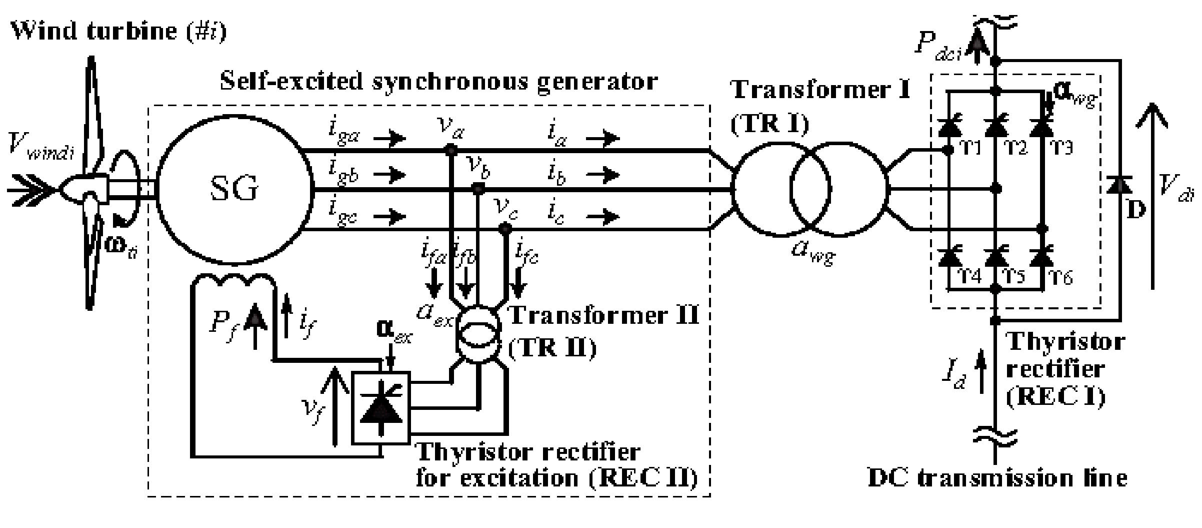


**FIGURE 16.** Wind Generator System

The system includes a self-excited synchronous generator, thyristor rectifiers for excitation (REC I), transformers (TR I and TR II), and the HVDC transmission line. Additionally, it features a diode bridge and a control circuit for managing excitation.

The excitation system uses thyristor rectifiers to convert AC to DC, providing the necessary excitation current to the generator's field winding. This ensures efficient generation and conversion of electrical energy.

The generated power is transformed and rectified before being transmitted through the HVDC transmission line. This setup allows for efficient long distance transmission of electricity generated by wind turbines to the grid.

The control circuit and shunt help regulate the excitation current, maintaining stability and optimal performance of the generator. This is crucial for handling the changing nature of wind energy.

**Solar Generator Systems** often use static excitation systems due to their reliability and efficiency in converting solar energy into electricity. The fast response time of static excitation systems enables them to quickly adjust to changes in sunlight intensity, optimizing power generation. Brushless excitation is used less since these systems are usually of smaller sizes, and, because of that, it is not effective to invest in advanced and expensive equipment from brushless exciters.

Additionally, the compact design of these systems makes them good for solar installations, where the space is crucial. Static excitation systems offer an opportunity to effectively use solar energy and maximize the performance of solar power plants.

# 6. CONCLUSION

Excitation systems are crucial for synchronous machines, ensuring a proper field current supply. Synchronous machines are used to generate AC currents and voltages. They are primarily found in electrical power systems. The mechanical energy from a prime mover is, at the end, converted to electrical energy. The operation of two main synchronous generator parts: rotor and stator, is crucial to understand. Synchronous generators have the unique ability to operate at a constant speed, which makes them perfect for power generation.

The three main excitation systems discussed include: DC, static, and brushless excitation systems, each offering its unique advantages. While DC systems use generators with slip rings and brushes, static systems draw power from the alternator's output, and brushless systems use rotating rectifiers and permanent magnet generators.

Different excitation systems are appropriate for different machine sizes. It is normal that smaller machine projects have lower budgets. Because of that, they settle for the cost-effective solution most of the time. On the other side, larger machine projects have many potential fault points to take into account, and that is why they have to, certainly, invest more money.

Each excitation systems has its models used in modern applications, but the static and brushless excitation system models are by far the most used ones. Excitation systems play a crucial role in regulating voltage output, improving system stability, and protecting against faults. Understanding these systems is essential for designing efficient power systems. Case studies further illustrated the practical implementation of excitation systems, focusing on renewable energy systems, where static and brushless excitation systems are used the most.

## REFERENCES


[1] Glučina, Matko & Anđelić, Nikola & Lorencin, Ivan & Car, Zlatan. (2022). Estimation of Excitation Current of a Synchronous Machine Using Machine Learning Methods. Computers. 12. 1. 10.3390/computers12010001.

[2] D. Jolevski. (2009). “Excitation System of Synchronous Generator,” University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Arhitecture, Split

[3] S. Tesnjak, G. Erceg, R. Erceg, D. Klarin, Z. Komericki. (2000). “Excitation System of Synchronous Turbo G enerator,” in Thermal Power Plant Features in the Meaning of Electric Power System Demands, HEP d.d., Zagreb

[4] J. Machowski, J.W. Bialek, S.Robak, J.R. Bumby. (September 1998). “Excitation control system for use with synchronous generators,” IEE Proc.-Gener. Transm. Distrib., Vol. 145

[5] Bansal, Hari. (2009). Tuning of PID Controllers using Simulink. International Journal of Mathematical Modeling, Simulation and Applications

[6] M. Miskovic, M. Mirosevic, G. Erceg. (2009). “ Load Angle Estimation of a Synchronous Generator Using Dynamical Neural Networks,” Energija, vol. 58, No. 2, pp. 174-191, INSPEC

[7] Sahdev, S. K. (2018). “Electrical machines“. University Printing House, Cambridge CB2 8BS, United Kingdom: Cambridge University Press

[8] Tsegaye, Shewit & Fante, Kinde. (2018). Analysis of Synchronous Machine Excitation Systems: Comparative Study. Energy and Power Engineering. 10. 1492 - 1496. 10.5281/zenodo.1130957.

[9] Jerković Štil, Vedrana & Miklosevic, Kresimir & Špoljarić, Željko. (2018). Excitation System Models of Synchronous Generator

[10] Synchronous Machine Excitation System Vision Dynamical Analysis Manual. (2016.) 16-065 CW. Arnhem, The Netherlands.

[11] "Static Excitation System – Working Principle." (2017). Electrical Concepts. Retrieved from https://electricalbaba.com/static-excitation-system-working-principle/. Accessed: May 31, 2024

[12] IEEE Power Engineering Society. (2006). “IEEE Recomanded Practice for Excitation System Models for Power System Stability studies,” IEE Std. 421-5-2005, IEEE New York, NY, USA

[13] Schmuelling, S., Kreischer, C., & Gołębiowski, M. (2015). "Comparison of Different Methods for Excitation of Synchronous Machines." Maszyny Elektryczne – Zeszyty Problemowe, Nr 3/2015 (107), 89. TU Dortmund University, Chair of Energy Conversion & Rzeszow University of Technology, Faculty of Electrical and Computer Engineering.

[14] Aliprantis, D. C., Sudhoff, S. D., & Kuhn, B. T. (2006). A Brushless Exciter Model Incorporating Multiple Rectifier Modes and Preisach’s Hysteresis Theory. IEEE Transactions on Energy Conversion, 21(1).

[15] NEPLAN Smarter Tools. "Standard Dynamic Excitation Systems in NEPLAN Power System Analysis Tool." Retrieved from https://www.neplan.ch/wp-content/uploads/2015/08/Nep_EXCITERS1.pdf. Accessed: June 2, 2024.

[16] Nicolau, N. (2016). Brushless excitation of synchronous generators: study of models and control optimization. Instituto Superior Técnico, Universidade de Lisboa.

[17] Chouaba, Seif & Barakat, Abdallah. (2019). Advanced Brushless Excitation System with Dynamic De-Excitation Capability. International Review of Electrical Engineering. 14. 10.15866/iree.v14i2.16367.