Automatic Voltage Regulator

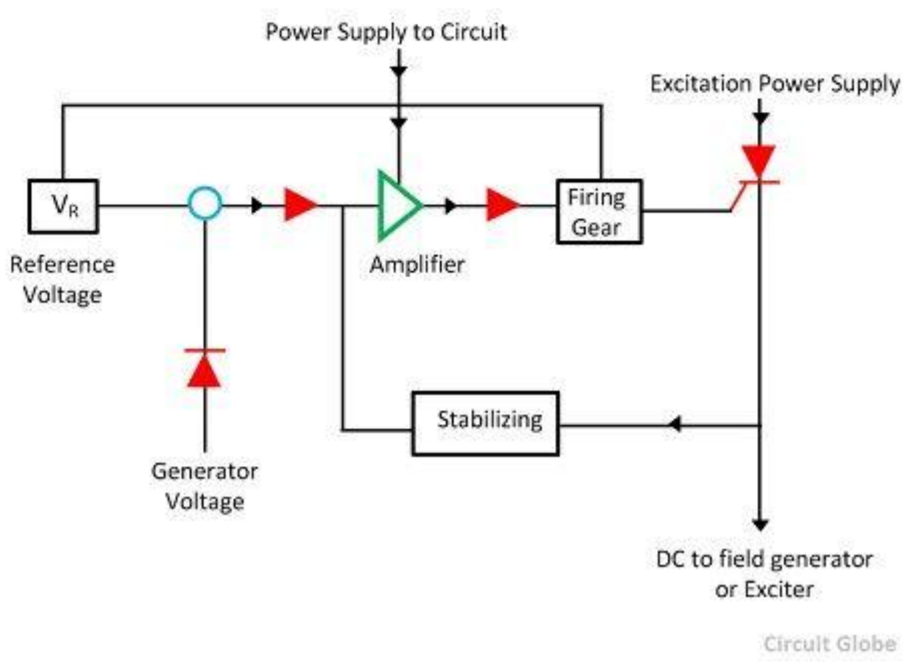
The automatic voltage regulator is used to regulate the voltage. It takes the fluctuate voltage and changes them into a constant voltage. The fluctuation in the voltage mainly occurs due to the variation in load on the supply system. The variation in voltage damages the equipment of the power system.

The variation in the voltage can be controlled by installing the voltage control equipment at several places likes near the transformers, generator, feeders, etc., The voltage regulator is provided in more than one point in the power system for controlling the voltage variations.

In DC supply system the voltage can be controlled by using over compound generators in case of feeders of equal length, but in the case of feeders of different lengths the voltage at the end of each feeder is kept constant using feeder booster. In AC system the voltage can be controlled by using the various methods likes booster transformers, induction regulators, shunt condensers, etc.,

Working Principle of Voltage Regulator

It works on the principle of detection of errors. The output voltage of an AC generator obtained through a potential transformer and then it is rectified, filtered and compared with a reference. The difference between the actual voltage and the reference voltage is known as the **error voltage**. This error voltage is amplified by an amplifier and then supplied to the main exciter or pilot exciter.



Thus, the amplified error signals control the excitation of the main or pilot exciter through a buck or a boost action (i.e. controls the fluctuation of the voltage). Exciter output control leads to the controls of the main alternator terminal voltage.

Application of the Automatic Voltage Regulator

The main functions of an AVR are as follows.

1. It controls the voltage of the system and has the operation of the machine nearer to the steady state stability.
2. It divides the reactive load between the alternators operating in parallel.
3. The automatic voltage regulators reduce the overvoltages which occur because of the sudden loss of load on the system.
4. It increases the excitation of the system under fault conditions so that the maximum synchronising power exists at the time of clearance of the fault.

When there is a sudden change in load in the alternator, there should be a change in the excitation system to provide the same voltage under the new load condition. This can be done by the help of the automatic voltage regulator. The automatic voltage regulator equipment operates in the exciter field and changes the exciter output voltage, and the field current. During the violent fluctuation, the ARV does not give a quick response.

For getting the quick response, the quick acting voltage regulators based on the **overshooting the mark** principle are used. In overshoot mark principle, when the load increase the excitation of the system also increase. Before the voltage increase to the value corresponding to the increased excitation, the regulator reduces the excitation of the proper value.

Excitation System of a Synchronous Machine

The word **Excitation** means the production of flux by passing current in the field winding.The arrangement or the system used for the excitation of the synchronous machine is known as **Excitation System**. To excite the field winding of the rotor of the synchronous machine, direct current is required. Direct current is supplied to the rotor field of the small machine by a DC generator called **Exciter**. A small DC generator called **Pilot Generator**, supplies the current to the Exciter.

The Exciter and the Pilot Exciter both are mounted on the main shaft of the Synchronous generator or motor. The DC output of the main Exciter is given to the field winding of the synchronous machine through brushes and slip rings. The pilot exciter is excluded in smaller machines.

For medium size machines, **AC Exciters** are used in place of DC Exciter. AC Exciters are three phase AC generators. The output of an AC Exciter is rectified and supplied through the brushes, and the slip rings to the rotor winding of the synchronous machine.

For large synchronous generators having few hundred megawatt ratings, the Excitation System requirement becomes very large. The problem of conveying such a large amount of power through the high-speed sliding contacts becomes formidable.

Presently, the large synchronous machines are using **Brushless Excitation System**. A Brushless Exciter is a small direct coupled AC generator with its field circuit on the stator and the armature circuit on the rotor. The three phase output of the AC exciter generator is rectified by solid state rectifiers. The rectified output is connected directly to the field winding, thus eliminating the use of brushes and slip rings.

A Brushless excitation system requires less maintenance due to the absence of brushes and slip rings. The power loss is also reduced. The DC required for the field of the exciter itself is sometimes provided by a small pilot exciter. A pilot exciter is a small AC generator with a permanent magnet mounted on the rotor shaft and the three phase winding on the stator. It provides the field current of the exciter. The exciter supplies the field current of the main machine. Thus, the use of a pilot exciter makes the excitation of the main generator completely independent of external supplies.

Excitation System

Definition: The system which is used for providing the necessary field current to the rotor winding of the synchronous machine, such type of system is called an excitation system. In other words, excitation system is defined as the system which is used for the production of the flux by passing current in the field winding. The main requirement of an excitation system is reliability under all conditions of service, a simplicity of control, ease of maintenance, stability and fast transient response.

The amount of excitation required depends on the load current, load power factor and speed of the machine. The more excitation is required in the system if the load current is large and the speed or power factor of the system is less.

Types of Excitation System

The excitation system is mainly classified into three types. They are

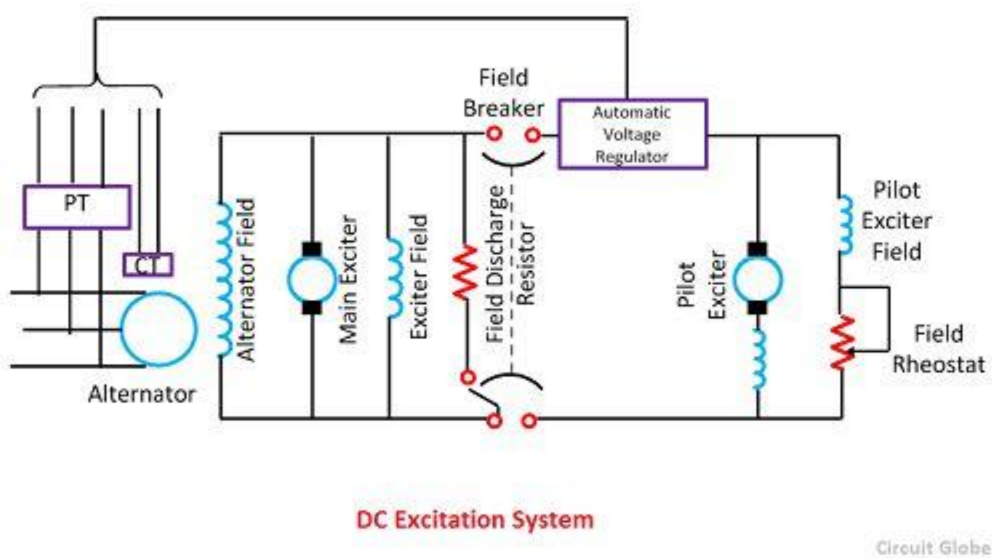
1. DC Excitation System
2. AC Excitation System
   - Rotor Excitation System
   - Brushless Excitation System
3. Static Excitation System

Their types are explained below in details.

1. DC Excitation System

The DC excitation system has two exciters – the main exciter and a pilot exciter. The exciter output is adjusted by an automatic voltage regulator (AVR) for controlling the output terminal voltage of the alternator. The current transformer input to the AVR ensures limiting of the alternator current during a fault.

When the field breaker is open, the field discharge resistor is connected across the field winding so as to dissipate the stored energy in the field winding which is highly inductive.



DC Excitation System

The main and the pilot exciters can be driven either by the main shaft or separately driven by the motor. Direct driven exciters are usually preferred as these preserve the unit system of operation, and the excitation is not excited by external disturbances.

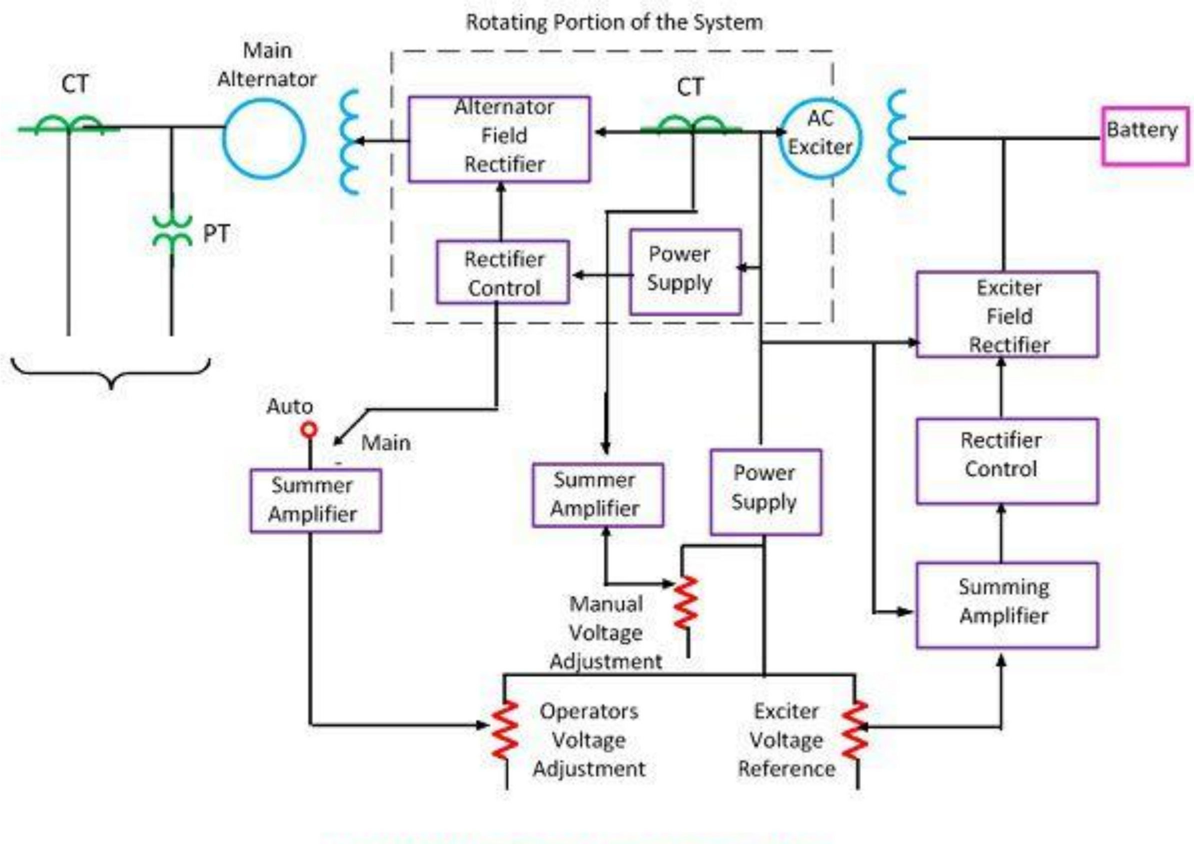
The voltage rating of the main exciter is about 400 V, and its capacity is about 0.5% of the capacity of the alternator. Troubles in the exciters of turbo alternator are quite frequent because of their high speed and as such separate motor driven exciters are provided as standby exciter.

2. AC Excitation System

The AC excitation system consists of an alternator and thyristor rectifier bridge directly connected to the main alternator shaft. The main exciter may either be self-excited or separately excited. The AC excitation system may be broadly classified into two categories which are expalined below in details.

a. Rotating Thyristor Excitation System

The rotor excitation system is shown in the figure below. The rotating portion is being enclosed by the dashed line. This system consists an AC exciter, stationary field and a rotating armature. The output of the exciter is rectified by a full wave thyristor bridge rectifier circuit and is supplied to the main alternator field winding.

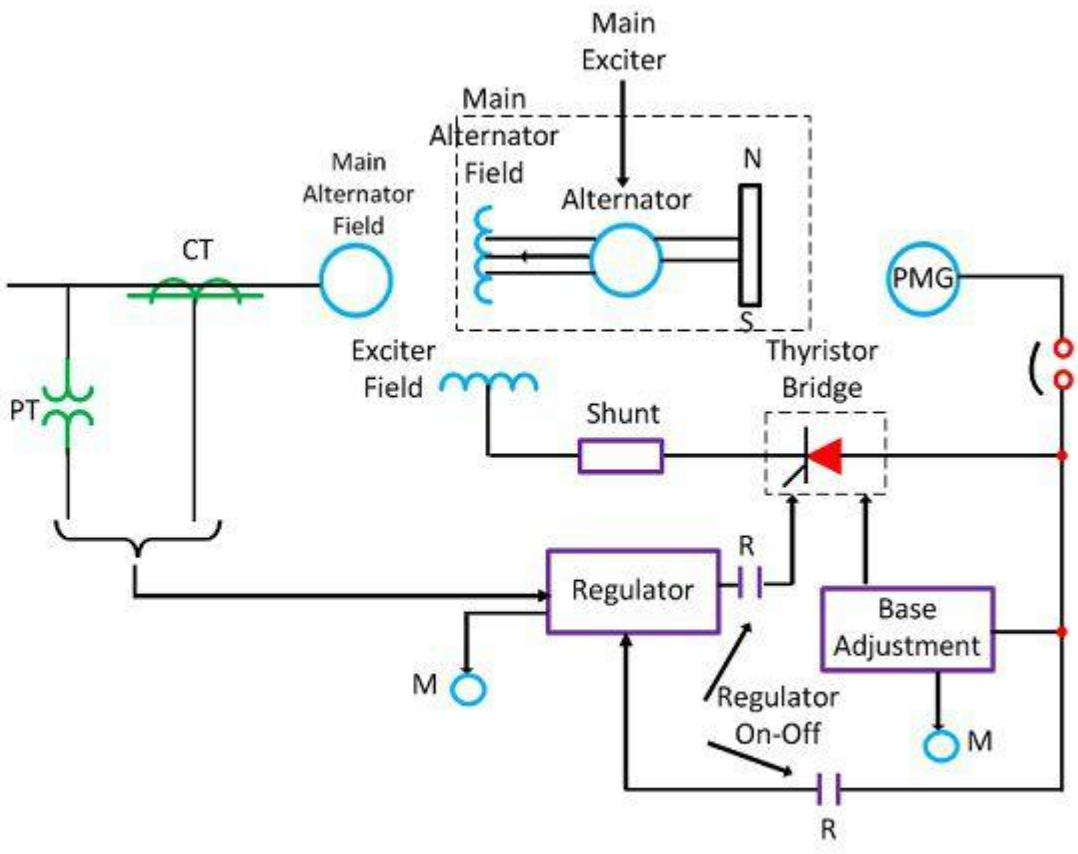


Rotating Thyristor Excitation System

The alternator field winding is also supplied through another rectifier circuit. The exciter voltage can be built up by using it residual flux. The power supply and rectifier control generate the controlled triggering signal. The alternator voltage signal is averaged and compare directly with the operator voltage adjustment in the auto mode of operation. In the manual mode of operation, the excitation current of the alternator is compared with a separate manual voltage adjustment.

b. Brushless Excitation System

This system is shown in the figure below. The rotating portion being enclosed by a dashed line rectangle. The brushless excitation system consists an alternator, rectifier, main exciter and a permanent magnet generator alternator. The main and the pilot exciter are driven by the main shaft. The main exciter has a stationary field and a rotating armature directly connected, through the silicon rectifiers to the field of the main alternators.



Brushless Excitation System

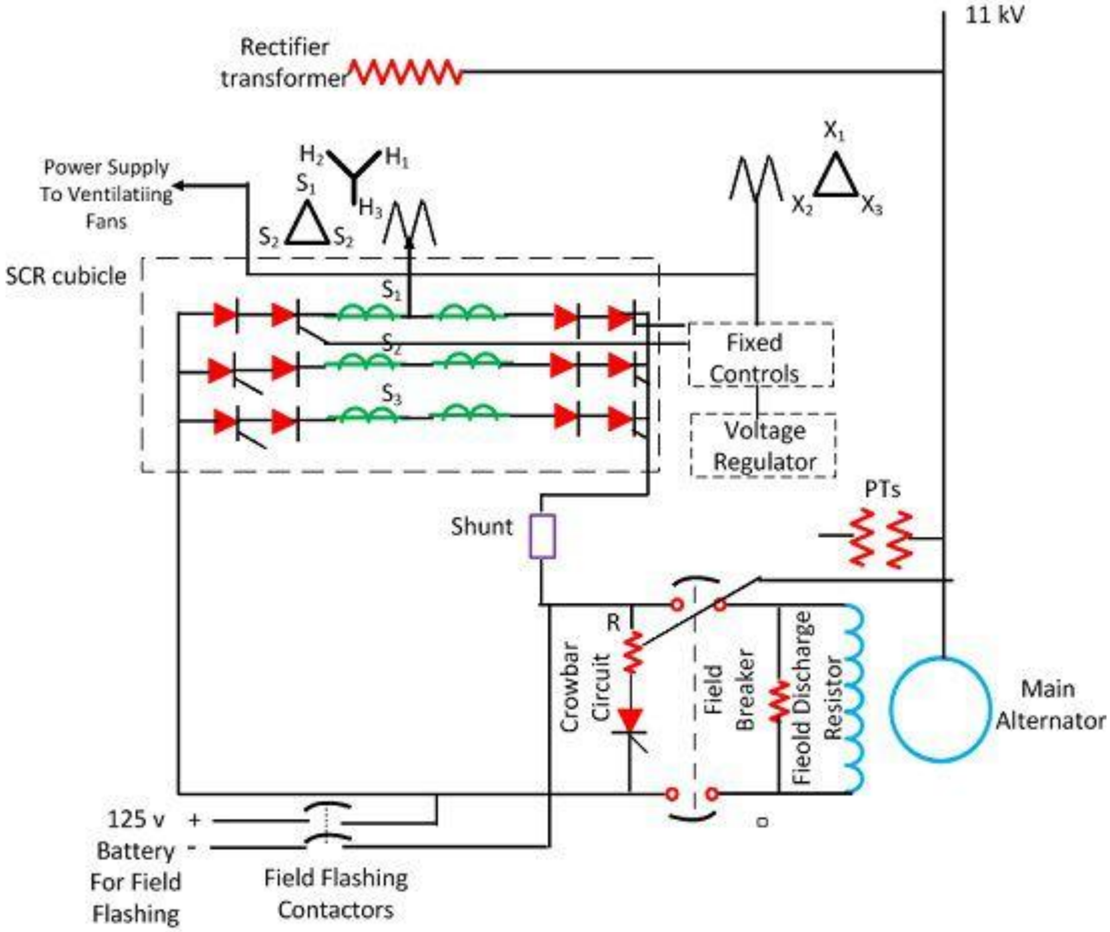
Circuit Globe

The pilot exciter is the shaft driven permanent magnet generator having rotating permanent magnets attached to the shaft and a three phase stationary armature, which feeds the main exciter field through silicon rectifiers, in the field of the main alternator. The pilot exciter is a shaft driven permanent magnetic generator having rotating permanent magnets attached to the shaft and a 3-phase stationary armature, which feeds the main's exciter through 3-phase full wave phase controlled thyristor bridges.

The system eliminates the use of a commutator, collector and brushes have a short time constant and a response time of fewer than 0.1 seconds. The short time constant has the advantage in improved small signal dynamic performance and facilitates the application of supplementary power system stabilising signals.

3. Static Excitation System

In this system, the supply is taken from the alternator itself through a 3-phase star/delta connected step-down transformer. The primary of the transformer is connected to the alternator bus and their secondary supplies power to the rectifier and also feed power to the grid control circuit and other electrical equipment.



Static Excitation Using SCRs

This system has a very small response time and provides excellent dynamic performance. This system reduced the operating cost by eliminating the exciter windage loss and winding maintenance.

Chapter 3

AUTOMATIC VOLTAGE CONTROL

1.1 INTRODUCTION TO EXCITATION SYSTEM

The basic function of an excitation system is to provide necessary direct current to the field winding of the synchronous generator. The excitation system must be able to automatically adjust the field current to maintain the required terminal voltage.

The DC field current is obtained from a separate source called an exciter.

The excitation systems have taken many forms over the years of their evolution. The following are the different types of excitation systems.

1. **DC excitation systems**
2. **AC excitation systems**
3. **Brushless AC excitation systems**
4. **Static excitation systems**

1.2 DC EXCITATION SYSTEMS

In DC excitation system, the field of the main synchronous generator is fed from a DC generator, called exciter. Since the field of the synchronous generator is in the rotor, the required field current is supplied to it through slip rings and brushes. The DC generator is driven from the same turbine shaft as the generator itself. One form of simple DC excitation system is shown in Fig.1.

This type of DC excitation system has slow response. Normally for 10 MVA synchronous generator, the exciter power rating should be 20 to 35 KW for which we require huge the DC generator. For these reasons, DC excitation systems are gradually disappearing.

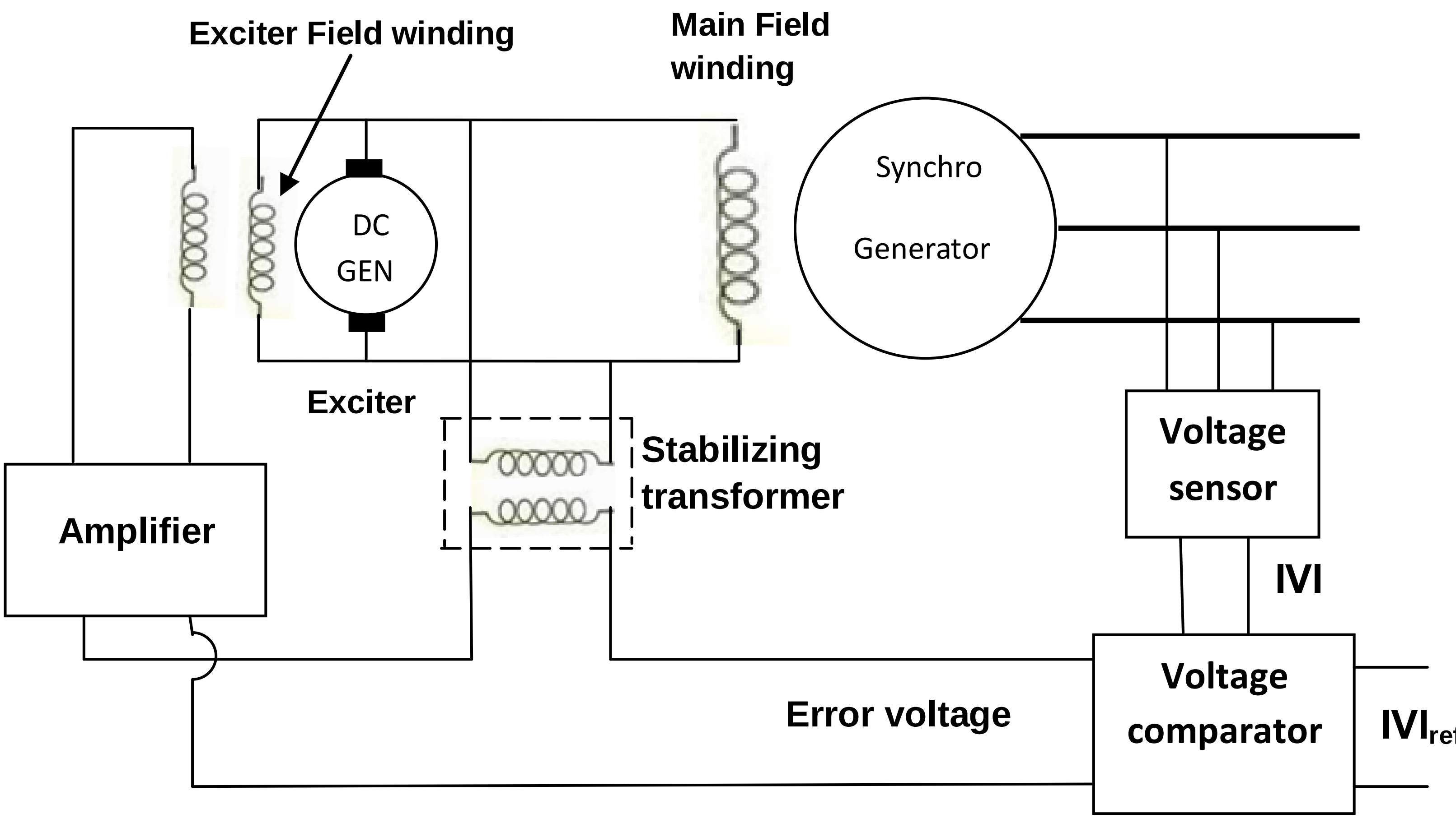


Fig. 1 DC Excitation system

1.3 AC EXCITATION SYSTEMS

In AC excitation system, the DC generator is replaced by an alternator of sufficient rating, so that it can supply the required field current to the field of the main synchronous generator. In this scheme, three phase alternator voltage is rectified and the necessary DC supply is obtained. Generally, two sets of slip rings, one to feed the rotating field of the alternator and the other to supply the rotating field of the synchronous generator, are required. Basic blocks of AC excitation system are shown in Fig. 2.

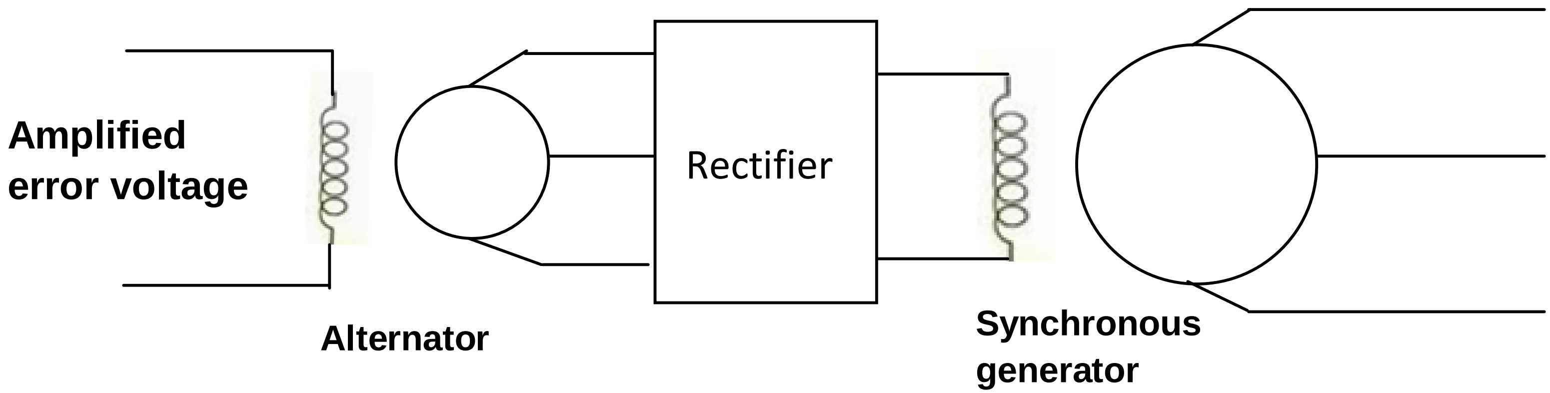


Fig. 2 AC Excitation system

1.4 BRUSHLESS AC EXCITATION SYSTEMS

Old type AC excitation system has been replaced by brushless AC excitation system wherein, inverted alternator (with field at the stator and armature at the rotor) is used as exciter.

A full wave rectifier converts the exciter AC voltage to DC voltage.

The armature of the exciter, the full wave rectifier and the field of the synchronous generator form the rotating components.

The rotating components are mounted on a common shaft. This kind of brushless AC excitation system is shown in Fig. 3.

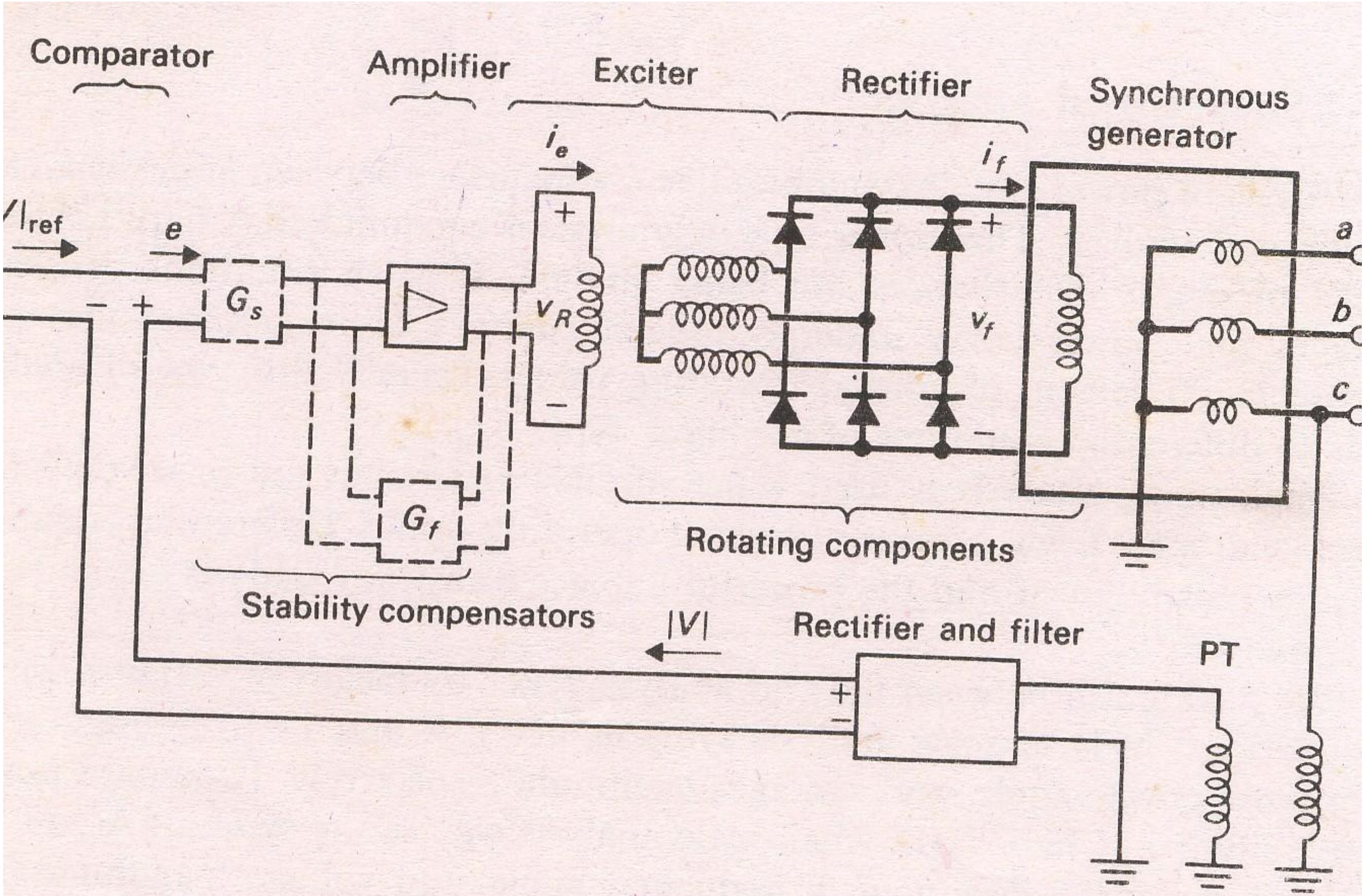


Fig. 3 Brushless AC Excitation system

1.5 STATIC EXCITATION SYSTEMS

In static excitation system, a portion of the AC from each phase of synchronous generator output is fed back to the field windings, as DC excitations, through a system of transformers, rectifiers, and reactors.

An external source of DC is necessary for initial excitation of the field windings.

On engine driven generators, the initial excitation may be obtained from the storage batteries used to start the engine

2.1 INTRODUCTION TO EXCITORS

It is necessary to provide constancy of the alternator terminal voltage during normal small and slow changes in the load. For this purpose the alternators are provided with Automatic Voltage Regulator (AVR). The exciter is the main component in the AVR loop. It delivers DC power to the alternator field. It must have adequate power capacity (in the low MW range for large alternator) and sufficient speed of response (rise time less than 0.1 sec.)

There exists a variety of exciter types. In older power plants, the exciter consisted of a DC generator driven by the main shaft. This arrangement requires the transfer of DC power to the synchronous generator field via slip rings and brushes. Modern exciters tend to be of either brushless or static design. A typical brushless AVR loop is shown in Fig. 3.

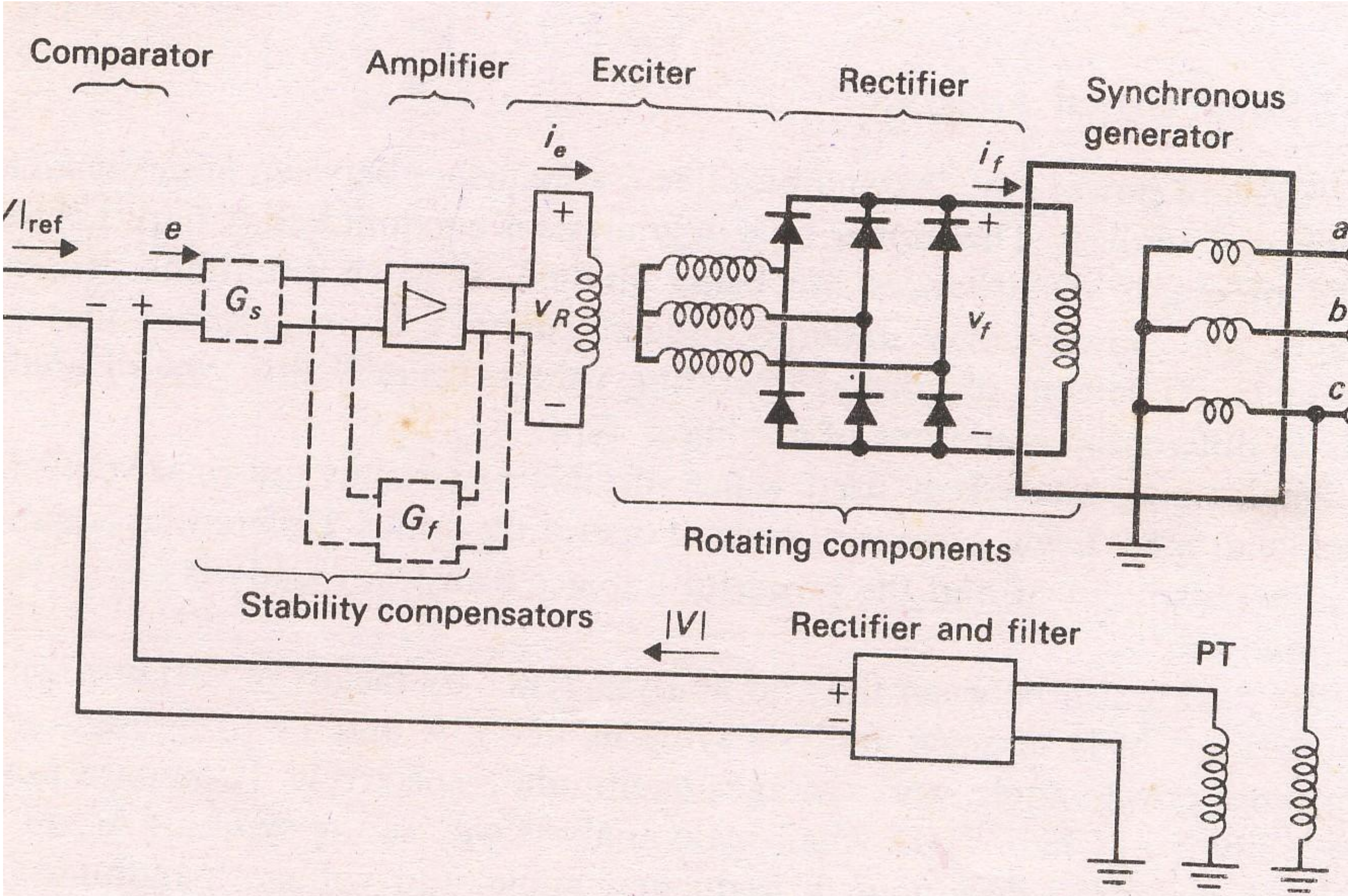


Fig. 3 Brushless AC Excitation system

In this arrangement, the exciter consists of an inverted three phase alternator which has its three phase armature on the rotor and its field on the stator. Its AC armature voltage is rectified in diodes mounted on the rotating shaft and then fed directly into the field of the main synchronous generator.

2.2 EXCITER MODELING

It is to be noted that error voltage e = $|V|_{ref}$ - |V|. Assume that for some reason the terminal voltage of the main generator decreases. This will result in decrease in |V|. This immediately results in an increased “error voltage” e which in turn, causes increased values of v_R, i_e, v_f and i_f. As a result of the boost in i_f the d axis generator flex increases, thus raising the magnitude of the internal generator emf and hence the terminal voltage.

Higher setting of $|V|_{ref}$ also will have the same effect of increasing the terminal voltage.

Mathematical modeling of the exciter and its control follows. For the moment we discard the stability compensator (shown by the dotted lines in the Fig. 3).

For the comparator $\Delta|V|_{ref} - \Delta|V| = \Delta e$ **(1)**

Laplace transformation of this equation is

$\Delta|V|_{ref}(s) - \Delta|V|(s) = \Delta e(s)$ **(2)**

For the amplifier

$\Delta v_R = K_A \ \Delta e$ **where K_A is the amplifier gain.** **(3)**

Laplace transformation of the above equation yields

$\Delta v_R(s) = K_A \ \Delta e(s)$ **(4)**

This equation implies instantaneous amplifier response. But in reality, the amplifier will have a time delay that can be represented by a time constant T_A. Then $\Delta v_R(s)$ and $\Delta e(s)$ are related as

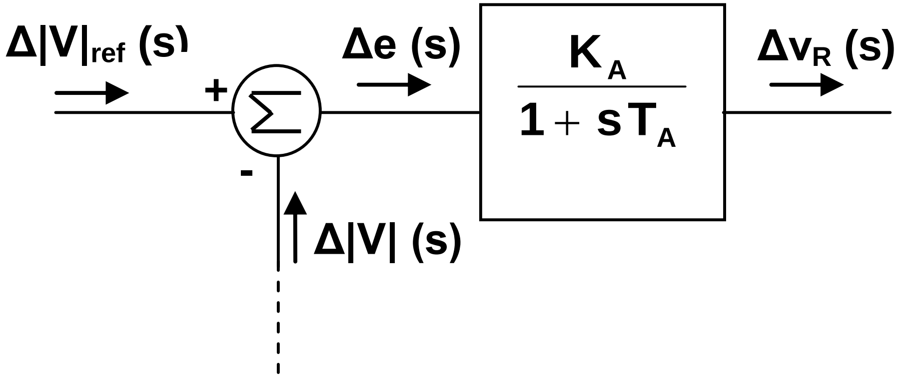
$$\Delta v_R(s) = \frac{K_A}{1 + s\,T_A} \Delta e(s) \qquad (5)$$

Here $\frac{K_A}{1 + s\,T_A}$ is the transfer function of the amplifier, $G_A(s)$.

The block diagram corresponding to equations (2) and (5) is shown below.

$$\Delta|V|_{ref}(s) - \Delta|V|(s) = \Delta e(s) \qquad (2)$$

$$\Delta v_R(s) = \frac{K_A}{1 + sT_A}\Delta e(s) \qquad (5)$$



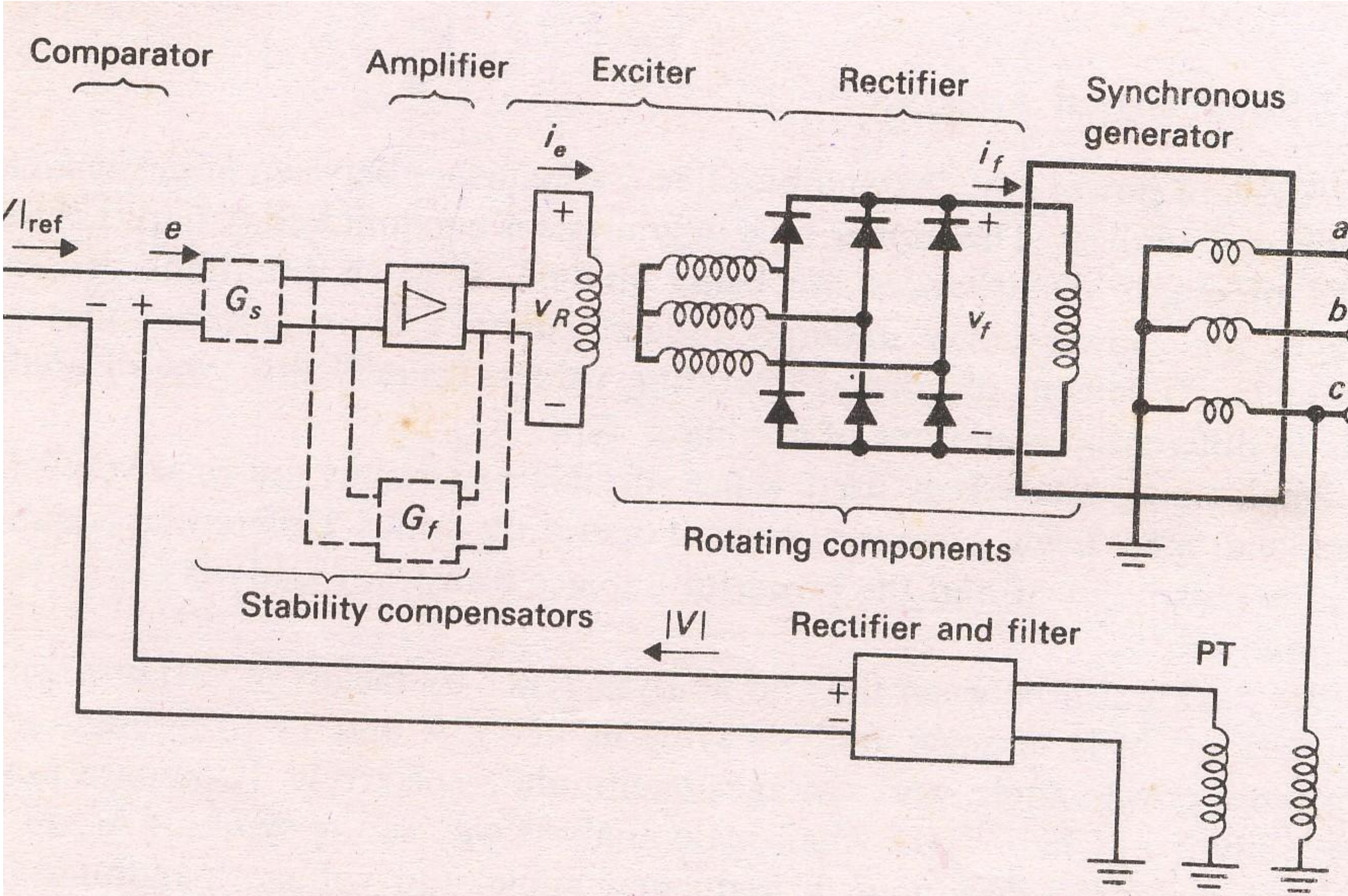


Fig. 3 Brushless AC Excitation system

Now we shall see the modeling of the exciter field. **If R_e and L_e represent respectively the resistance and inductance of the exciter field,** **then**

$$v_R = R_e\, i_e + L_e \frac{d}{dt} i_e \quad \text{and hence}$$

$$\Delta v_R = R_e\, \Delta i_e + L_e \frac{d}{dt}(\Delta i_e) \qquad (6)$$

The exciter field current i_e produces voltage v_f, which is the rectified armature voltage of the exciter. Then

$$\Delta v_f = K_1\, \Delta i_e \qquad (7)$$

where K_1 is the rectified armature volts per ampere of exciter field current.

Taking Laplace transformation of the above two equations and eliminating $\Delta i_e(s)$, we get

$$\Delta v_f(s) = \frac{K_e}{1 + s\,T_e}\, \Delta v_R(s) \qquad (8)$$

$$\text{where} \quad K_e = \frac{K_1}{R_e} \quad \text{and} \quad T_e = \frac{L_e}{R_e} \qquad (9)$$

Thus the transfer function of the exciter, $G_e(s) = \dfrac{K_e}{1 + s\,T_e}$.

Adding the representation of exciter as given by equation (8)

$$\Delta v_f(s) = \frac{K_e}{1 + s\,T_e}\,\Delta v_R(s) \qquad (8)$$

now we can draw the transfer function model of Comparator, Amplifier and Exciter portion of the AVR loop. This is shown in Fig. 4.

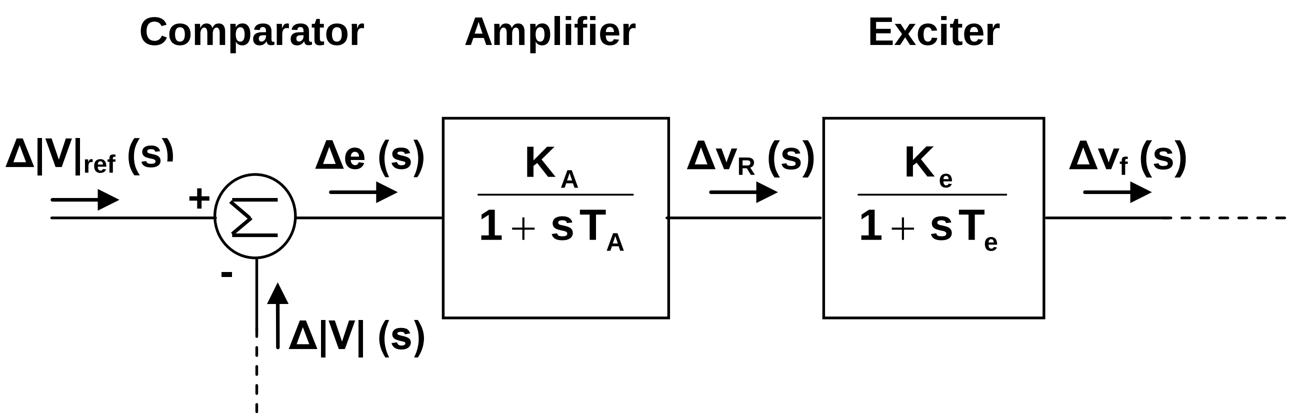


Fig. 4 Block diagram representation of comparator, amplifier and exciter

The time constants T_A will be in the range of 0.02 – 0.1 sec. while T_e will be in the range of 0.5 – 1.0 sec.

2.3 SYNCHRONOUS GENERATOR MODELING

We need to close the loop in Fig. 3 by establishing the missing dynamic link between the field voltage v_f and the synchronous generator terminal voltage |V|.

Considering the field of the synchronous generator, using KVL

$$\Delta v_f = R_f \Delta i_f + L_{ff} \frac{d}{dt}(\Delta i_f) \quad (10)$$

Taking Laplace transform $\Delta v_f (s) = [R_f + s L_{ff}] \Delta i_f (s)$ **(11)**

As the terminal voltage equals to internal emf minus the voltage drop across the internal impedance, it is clear that the relationship between v_f and |V| depends on the generator loading. The simplest possible relationship exists at low or zero loading in which case V approximately equals to internal emf E. In the generator, internal emf and the field currents are related as

$$E = \frac{\omega L_{fa} i_f}{\sqrt{2}} \quad (12)$$

Here L_{fa} is the mutual inductance coefficient between rotor field and stator armature.

Thus $$\Delta i_f = \frac{\sqrt{2}}{\omega L_{fa}} \Delta E \qquad (13)$$

Laplace transform of above eq. gives $$\Delta i_f (s) = \frac{\sqrt{2}}{\omega L_{fa}} \Delta E (s) \qquad (14)$$

Substituting the above in eq. (11), $\Delta v_f (s) = [R_f + s L_{ff}] \Delta i_f (s)$ results in

$$\Delta v_f (s) = \frac{\sqrt{2}}{\omega L_{fa}} [R_f + s L_{ff}] \Delta E (s)$$

Thus $$\Delta E (s) = \frac{\omega L_{fa}}{\sqrt{2}} \frac{1}{R_f + sL_{ff}} \Delta v_f (s)$$

From the above eq., the field voltage transfer ratio can be written as

$$\frac{\Delta E(s)}{\Delta v_f (s)} \approx \frac{\Delta |V|(s)}{\Delta v_f (s)} = \frac{\omega L_{fa}}{\sqrt{2}} \frac{1}{R_f + sL_{ff}} = \frac{K_F}{1 + s T'_{d0}} \qquad (15)$$

where $$K_F = \frac{\omega L_{fa}}{\sqrt{2} R_f} \quad \text{and} \quad T'_{d0} = \frac{L_{ff}}{R_f} \qquad (16)$$

We can now complete the AVR loop as shown in Fig. 5.

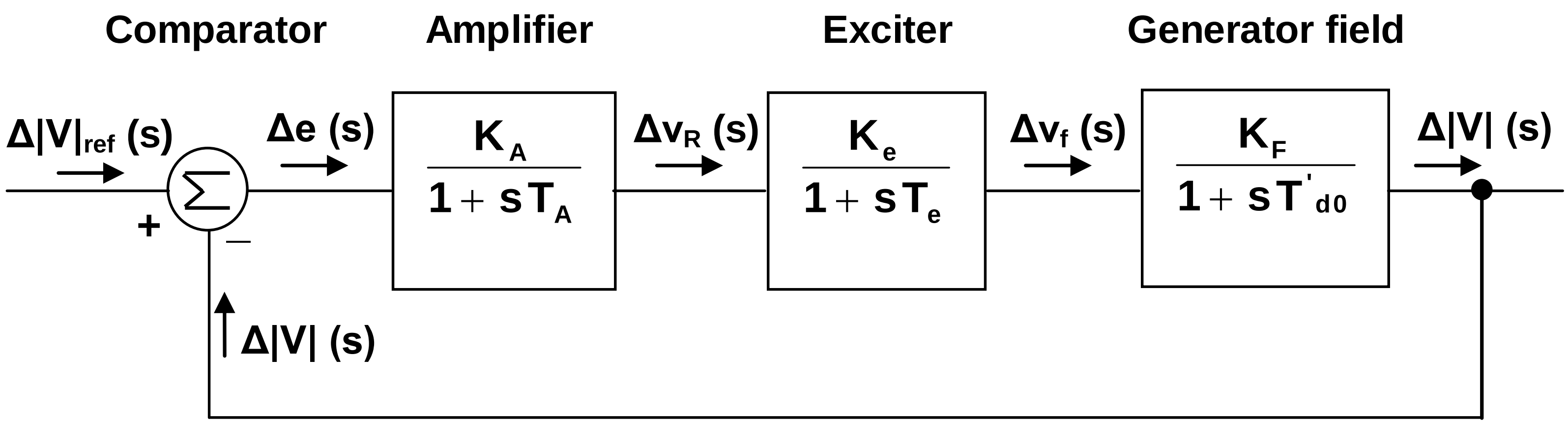


Fig. 5 Block diagram representation of AVR loop

The block diagram representation of AVR loop shown above can be simplified as shown in Fig. 6.

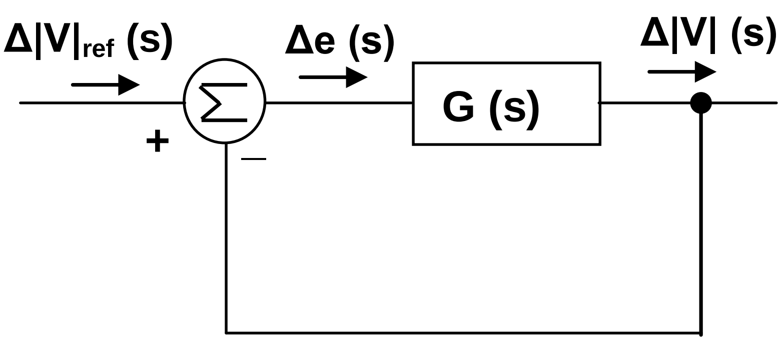


Fig. 6 Simplified block diagram representation of AVR loop

Here, the open loop transfer function G(s) equals

$$G(s) = \frac{K}{(1 + s\,T_A)\,(1 + s\,T_e)\,(1 + s\,T'_{do})} \qquad (17)$$

where the open loop gain K is defined by

$$K = K_A\, K_e\, K_F \qquad (18)$$

Block diagram of Fig. 6 can be further reduced as shown in Fig. 7.

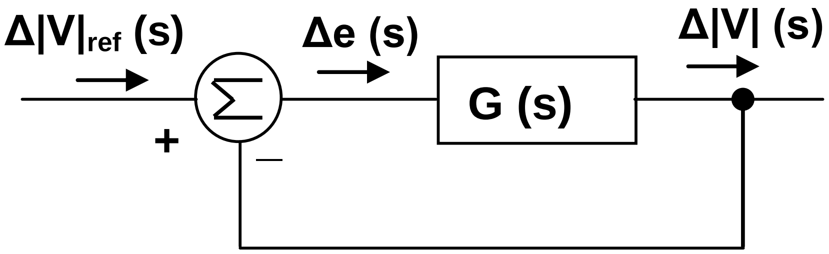


Fig. 6 Simplified block diagram representation of AVR loop

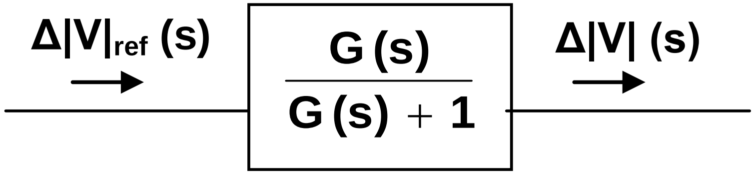


Fig. 7 Reduced Block diagram representation of AVR loop

2.4 STATIC PERFORMANCE OF AVR LOOP

The AVR loop must

1. **regulate the terminal voltage |V| to within the required static accuracy limit**
2. **have sufficient speed of response**
3. **be stable**

The static accuracy requirement can be stated as below:

For a constant reference input $\Delta|V|_{ref\ 0}$, the likewise constant error Δe_0 must be less than some specified percentage *p* of the reference input.

For example if $\Delta|V|_{ref\ 0} = 10$ V and the specified accuracy is 2%, then

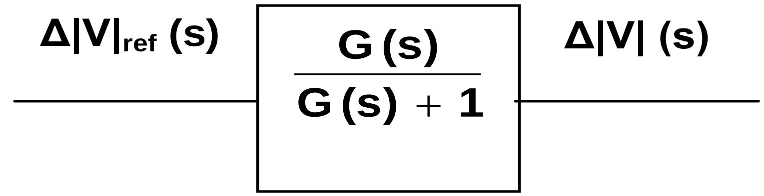
$$\Delta e_0 < \frac{2}{100} \times 10 \quad \text{i.e} \quad \Delta e_0 < 0.2 \text{ V}$$

We can thus write the static accuracy specification as follows:

$$\Delta e_0 = \Delta|V|_{ref\ 0} - \Delta|V|_0 < \frac{p}{100} \Delta|V|_{ref\ 0} \qquad (19)$$

$$\Delta e_0 = \Delta |V|_{ref\,0} - \Delta |V|_0 < \frac{p}{100} \Delta |V|_{ref\,0} \quad (19)$$

For a constant input, the transfer function can be obtained by setting s = 0. Thus



$$\Delta e_0 = \Delta |V|_{ref\,0} - \Delta |V|_0$$

$$= \Delta |V|_{ref\,0} - \frac{G(0)}{G(0)+1} \Delta |V|_{ref\,0}$$

$$= \left[1 - \frac{G(0)}{G(0)+1} \right] \Delta |V|_{ref\,0} = \frac{1}{G(0)+1} \Delta |V|_{ref\,0}$$

Thus $$\Delta e_0 = \frac{1}{K+1} \Delta |V|_{ref\,0} \quad (20)$$

where K is the open loop gain.

$$\Delta e_0 = \Delta|V|_{ref\,0} - \Delta|V|_0 < \frac{p}{100}\,\Delta|V|_{ref\,0} \qquad (19)$$

$$\text{Thus}\quad \Delta e_0 = \frac{1}{K+1}\,\Delta|V|_{ref\,0} \qquad (20)$$

It can be concluded that <u>the static error decreases with increased open loop gain.</u>

For a specified accuracy, the minimum gain needed is obtained substituting eq.(19) into eq.(20). i.e.

$$\frac{1}{K+1}\,\Delta|V|_{ref\,0} < \frac{p}{100}\,\Delta|V|_{ref\,0} \quad \text{i.e.}\quad K+1 > \frac{100}{p} \quad \text{i.e.}\quad K > \frac{100}{p} - 1 \qquad (21)$$

For example, if we specify that the static error should be less than 2% of reference input, the open loop gain must be > 49.

2.5 DYNAMIC RESPONSE OF AVR LOOP

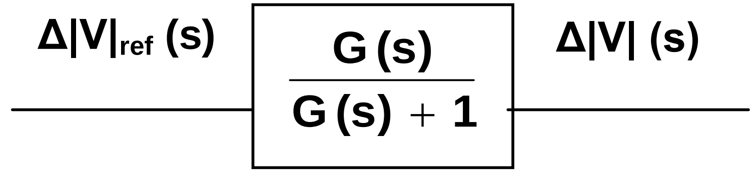


Fig. 7 Reduced Block diagram representation of AVR loop

Referring to block diagram in Fig. 7,

the time response is given by

$$\Delta|V|(t) = L^{-1}\left\{ \Delta|V|_{ref}(s)\ \frac{G(s)}{G(s)+1} \right\} \qquad (22)$$

Mathematically, the time response depends upon the eigenvalues or closed-loop poles, which are obtained from the characteristic equation G (s) + 1 = 0. The location of eigenvalues in the s-plane depends upon open-loop gain K and the three time constants T_A, T_e and $T'_{d\,o}$. Of these parameters only the loop gain K can be considered adjustable. It is interesting to study how the magnitude of this gain affects the location of three eigenvalues in the s-plane and thus the transient stability.

A root locus plot yields valuable information in this regard. Fig. 8 depicts the root-locus diagram for the AVR loop.

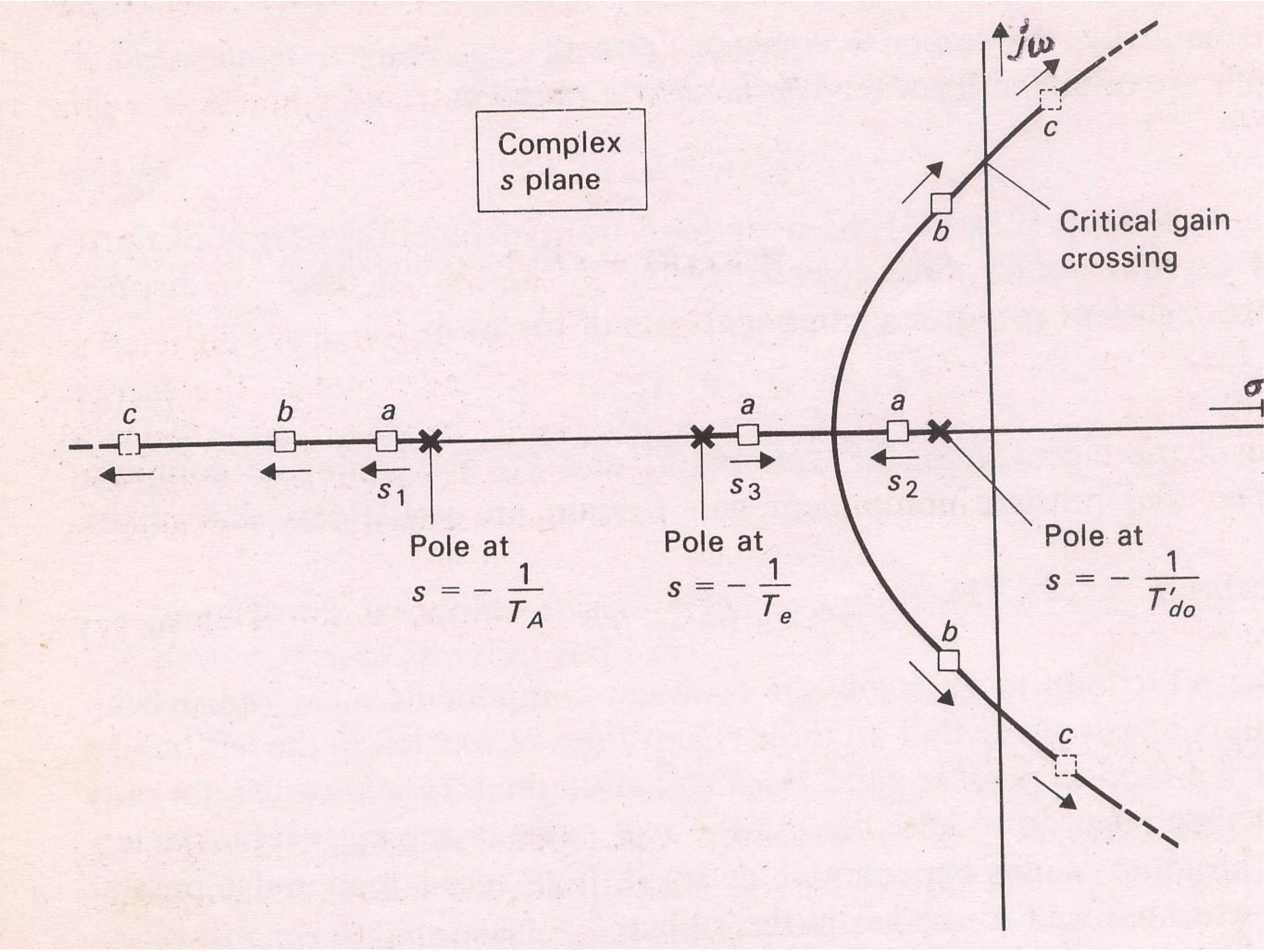


Fig. 8 Root-locus diagram of AVR loop

As we have seen earlier, open loop transfer function G(s) equals

$$G(s) = \frac{K}{(1 + s\,T_A)\,(1 + sT_e)\,(1 + sT'_{do})}$$

There are three loci, each starting from an open-loop pole (marked x). They are located at $s = -1 / T_A$, $-1 / T_e$ and $-1 / T'_{do}$ respectively. For low values of loop gains,K, the eigenvalues (marked □) are located close to the open-loop poles. Their positions are marked *a*. Because the time constant T'_{do} is comparatively large, the pole $-1 / T'_{do}$ is very close to the origin. The dominating eigenvalues s_2 is thus small, resulting in a very slowly decaying exponential term, giving the loop an unacceptable sluggish response. The gain K would not satisfy the inequality (21), $K > \frac{100}{p} - 1$ thus rendering an inaccurate static response as well.

By increasing the loop gain, the eigenvalues s_2 travels to the left and the loop response quickens. At certain gain setting, the eigenvalues s_3 and s_2 "collide".

Further increase in the loop gain results in s_3 and s_2 becoming complex conjugate. This dominant eigenvalues pair (b) makes the loop oscillatory, with poor damping. If the gain is increased further, the eigenvalues wander into the right-hand s-plane (c). The AVR loop now becomes unstable.

It is to be noted that there are three asymptotes. The three root locus branches terminate on infinity along the asymptotes whose angles with the real axis are given by

$$\Phi_A = \frac{(2\ell + 1)\,180}{n - m} \quad \text{for } \ell = 0, 1, 2, \; n-m-1 \quad (\text{ n = no. of poles and m = no. of zeros})$$

$$= (2\ell + 1)\,60 \quad \text{for } \ell = 0, 1, 2$$

$$= 60^0, 180^0 \text{ and } 300^0$$

2.6 STABILITY COMPENSATION

High loop gain is needed for static accuracy; but this causes undesirable dynamic response, possibly instability. By adding series stability compensator in the AVR loop, as shown in Fig. 3, this conflicting situation can be resolved.

As the stability problems emanate from the three cascaded time constants, the compensation network typically will contain some form of phase advancement. Consider for example, the addition of a series phase lead compensator, having the transfer function $G_s = 1 + s\,T_c$. With the addition of a zero, the open-loop transfer function becomes

$$G(s) = \frac{K(1 + sT_c)}{(1 + s\,T_A)(1 + sT_e)(1 + sT'_{do})} \qquad (23)$$

The added network will not affect the static loop gain K, and thus the static accuracy.

The dynamic response characteristic will change to the better. Consider for example the case when we would tune the compensator time constant T_c to equal to the exciter time constant T_e. The open-loop transfer function would then is

$$G(s) = \frac{K}{(1 + s\,T_A)(1 + sT'_{do})} \qquad (24)$$

In this case $\Phi_A = (2\ell + 1)\,90 \quad \ell = 0$ **and** 1; $\Phi_A = 90^0$ **and** 270^0

The root loci of the compensated system are depicted in Fig. 9.

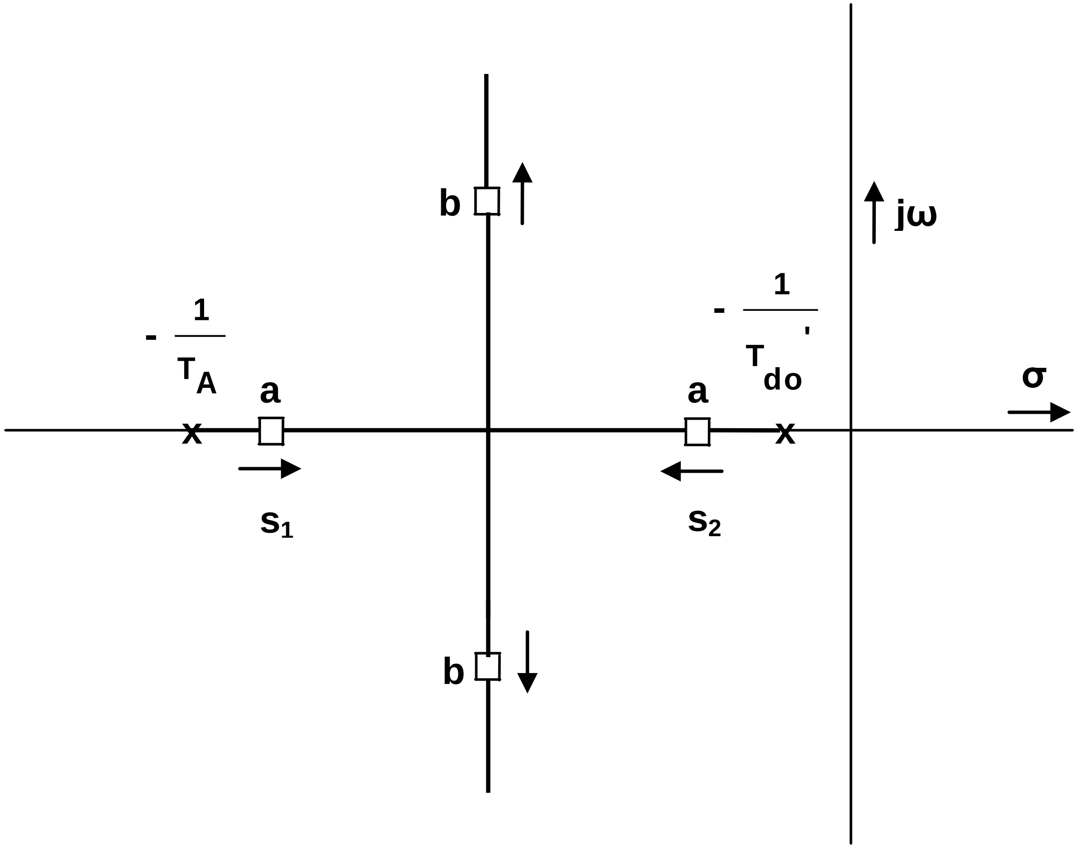


Fig. 9 Root loci for zero-compensated loop

Low loop gain (a) still results in negative real eigenvalues, the dominant one of which, s_2, yields a sluggish response term. Increasing loop gain (b) results in oscillatory response. The damping of the oscillatory term will, however, not decrease with increasing gain, as was in the case of uncompensated system.

3. VOLTAGE DROP / RISE IN TRANSMISSION LINE

Consider a transmission line between buses 1 and 2, which is supplying power to a load connected at bus 2. Bus 1 is the sending-end bus and bus 2 is the receiving-end bus. The line has an impedance of $(R + j X)\ \Omega$ as shown in Fig. 10.

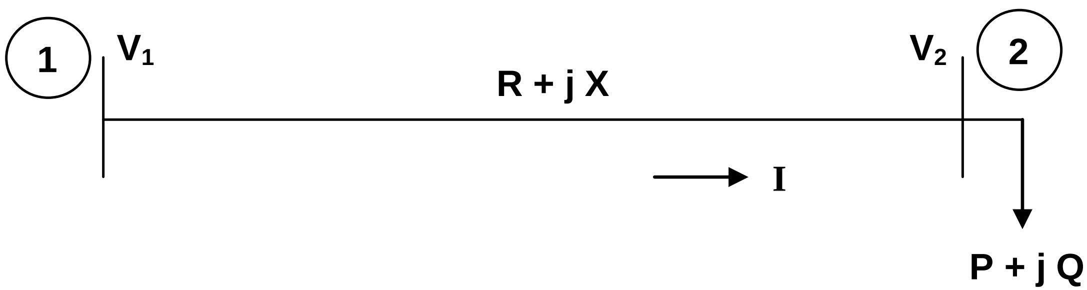


Fig. 10 Transmission line supplying a load

Taking voltage V_2 as reference, its phasor diagram is shown in Fig. 11.

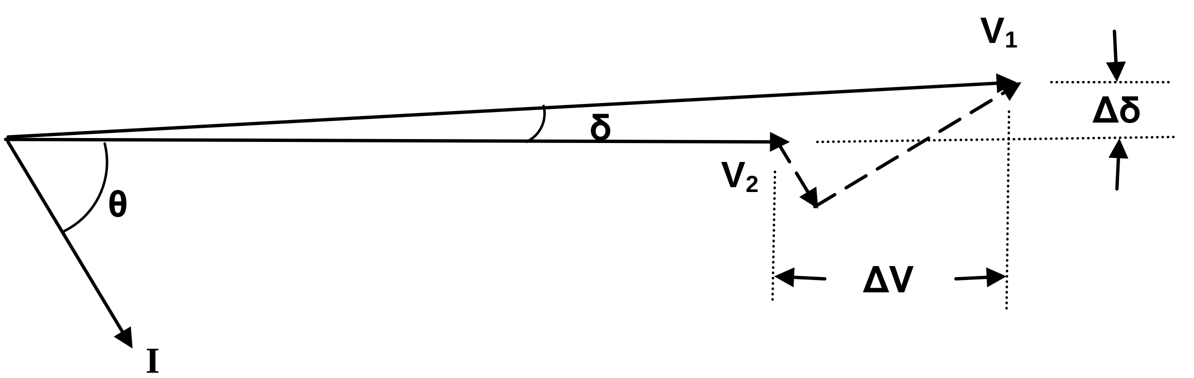


Fig. 11 Phasor diagram

Taking voltage V_2 as reference, its phasor diagram is shown in Fig. 11.

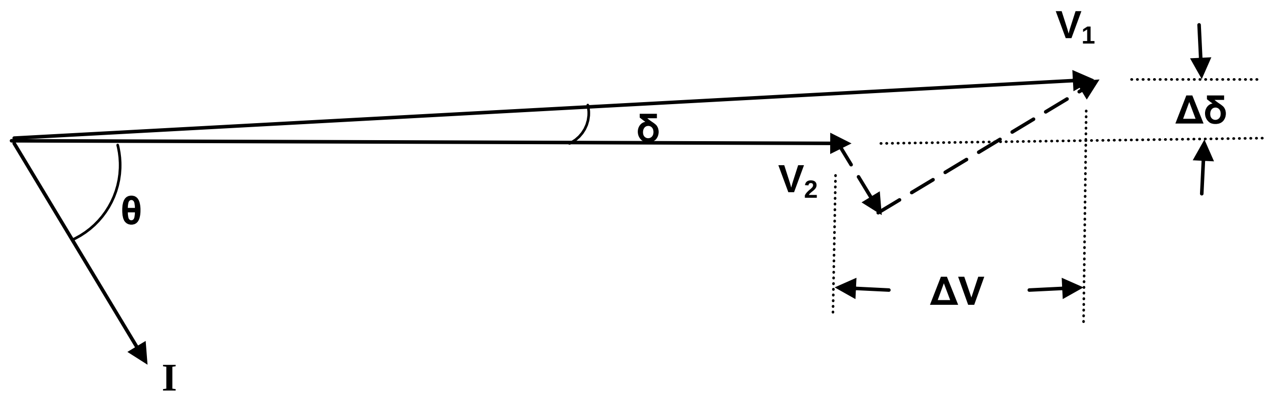


Fig. 11 Phasor diagram

From the phasor diagram, we can write

$$|V_1|^2 = (|V_2| + \Delta V)^2 + \Delta\delta^2 \qquad (25)$$

where

$$\Delta V = |I|R \cos\theta + |I|X \sin\theta \qquad (26)$$

$$\Delta\delta = |I|X \cos\theta - |I|R \sin\theta \qquad (27)$$

Knowing that $|V_2|\,|I|\cos\theta = P$ and $|V_2|\,|I|\sin\theta = Q$

$$|I|\cos\theta = \frac{P}{|V_2|} \quad \text{and} \quad |I|\sin\theta = \frac{Q}{|V_2|} \qquad (28)$$

Substituting eq. (28) in eqns. (26) and (27), we get

$$\Delta V = \frac{R\,P}{|V_2|} + \frac{X\,Q}{|V_2|} \tag{29}$$

$$\Delta\delta = \frac{X\,P}{|V_2|} - \frac{R\,Q}{|V_2|} \tag{30}$$

Generally, $\Delta\delta$ will be much smaller as compared to $|V_2| + \Delta V$. Thus from eq. (25) we can write

$$|V_1|^2 = (|V_2| + \Delta V)^2 \quad \text{i.e.} \quad |V_1| = |V_2| + \Delta V \tag{31}$$

Therefore, voltage drop in the transmission line is

$$|V_1| - |V_2| = \Delta V$$

$$= \frac{R\,P}{|V_2|} + \frac{X\,Q}{|V_2|} \tag{32}$$

For most of power circuit, resistance R will be much less as compared to reactance X. Neglecting the resistance of the transmission line, we get

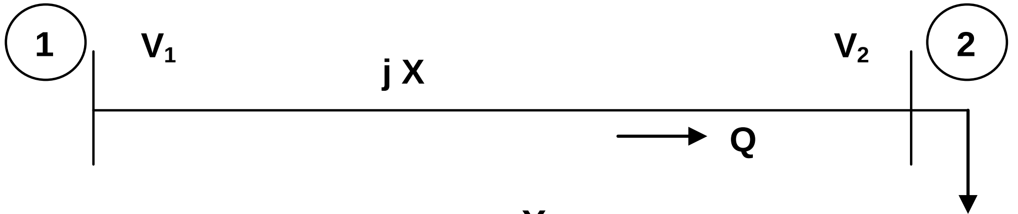
$$\textbf{Voltage drop } \Delta V = \frac{X\,Q}{|V_2|} \qquad (33)$$

From eq. (33), we can state that the voltage drop in the transmission line is directly proportional to the reactive power flow (Q-flow) in the transmission line.

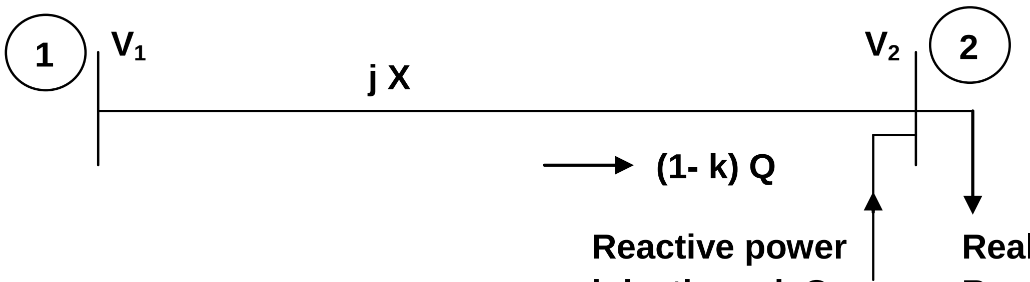
Most of the electric load is inductive in nature. In a day, <u>during the peak hours, Q-flow will be heavy,</u> resulting more <u>voltage drop</u>. However, <u>during off-peak hours</u>, the load will be very small and the distributed shunt capacitances throughout the transmission line become predominant making the <u>receiving-end voltage greater than the sending-end voltage</u> (Ferranti effect). Thus during off-peak hours there may be voltage rise in the transmission line from sending-end to receiving-end.

Thus the sending end will experience large voltage drop during peak load condition and even voltage rise during off-peak load condition.

<u>Reactive power control is necessary in order to maintain the voltage drop in the transmission line within the specified limits.</u> During peak hours, voltage drop can be reduced by decreasing the Q-flow in the transmission line. This is possible by externally injecting *"a portion of load reactive power"* at the receiving-end. Fig.(12) illustrates the effect of injecting the reactive power.



$$\text{Voltage drop } \Delta V = \frac{X}{|V_2|} Q$$



$$\text{Voltage drop } \Delta V' = \frac{X}{|V_2|}(1-k)\,Q = (1-k)\,\Delta V$$

Fig. 12 Effect of line reactive power injection

If 70% of load Q is injected at the receiving-end, then the value of k is 0.7 and the voltage drop will be only 30% of the original value.

Reactive power can be injected into the power network by connecting

1. **Shunt capacitors**
2. **Synchronous compensator (Synchronous phase modifier)**
3. **Static VAR compensator (SVC)**

During off-peak period, "voltage rise" can be reduced by absorbing the reactive power. This is possible by connecting

1. **Shunt reactor**
2. **Synchronous compensator (Synchronous phase modifier)**
3. **Static VAR compensator (SVC)**

Shunt capacitors

Shunt capacitor are used in circuit with lagging power factors such as the one created by peak load condition. Capacitors are connected either directly to a bus bar or to the tertiary winding of a main transformer. Reactive power supplied by the capacitor is given by

$$Q_C = |V|\,|I_C| \sin 90^0$$

$$Q_C = |V|\,|I_C| = \frac{|V|^2}{X_C} = |V|^2 \omega C \quad \text{VAR / phase} \qquad (35)$$

where |V| is the phase voltage and C is the capacitance / phase. Unfortunately, as the voltage falls, the VARs produced by a shunt capacitor reduce. Thus when needed most, their effectiveness falls.

Shunt reactors

Shunt reactors are used in circuit with leading power factors such as the one created by lightly loaded cables. The inductors are usually coreless type and possess linear type characteristics. If X_L is the inductive reactance per phase and |V| is the phase voltage, reactive power absorbed by the inductor is given by

$$Q_L = |V|\,|I_L| = \frac{|V|^2}{X_L} = \frac{|V|^2}{\omega L} \text{ VAR / phase} \qquad (36)$$

Synchronous compensators

A synchronous compensator is a synchronous motor running without a mechanical load. Depending on the value of excitation, it can either inject or absorb reactive power. When used with a voltage regulator, the compensator can automatically run over-excited at times of high load and supply the required reactive power. It will be under-excited at light load to absorb the reactive power.

Static VAR Compensator

Shunt capacitor compensation is required to enhance the system voltage during heavy load condition while shunt reactors are needed to reduce the over-voltage occurring during light load conditions. Static VAR Compensator (SVC) can perform these two tasks together utilizing the Thyristor Controlled Reactor (TCR).

SVC is basically a parallel combination of controlled reactor and a fixed capacitor as shown in Fig. 13.

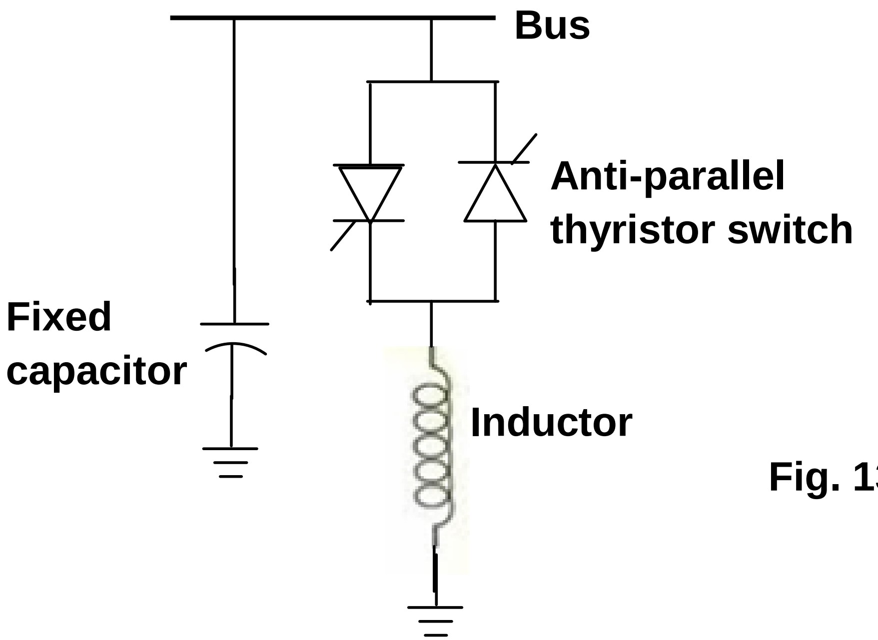


Fig. 13 Schematic diagram of SVC

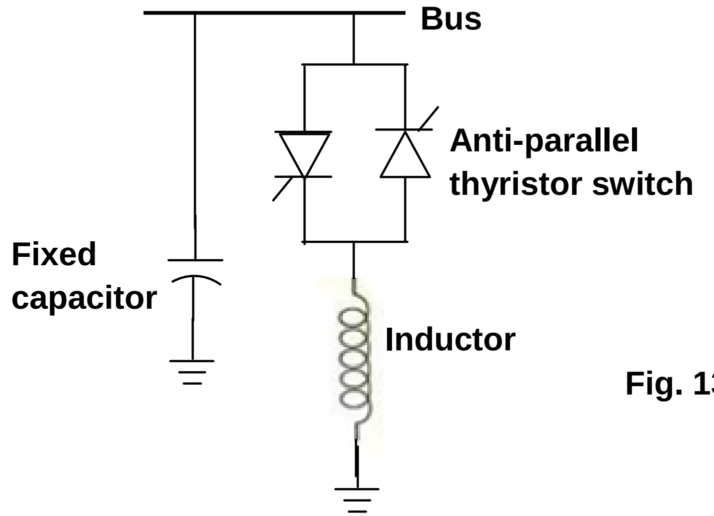


Fig. 13 Schematic diagram of SVC

The reactor control is done by an anti-parallel thyristor switch assembly. The firing angle of the thyristors governs the voltage across the inductor, thus controlling the reactor current. Thereby the reactive power absorption by the inductor can be controlled. The capacitor, in parallel with the reactor, supplies the reactive power of Q_C VAR to the system. If Q_L is the reactive power absorbed by the reactor, the net reactive power injection to the bus becomes

$$Q_{net} = Q_C - Q_L \quad (37)$$

In SVC, reactive power Q_L can be varied and thus reactive power Q_{net} is controllable. During heavy load period, Q_L is lesser than Q_C while during light load condition, Q_L is greater than Q_C. SVC has got high application in transmission bus voltage control. Being static this equipment, it is more advantageous than synchronous compensator.

VOLTAGE CONTROL USING TAP CHANGING TRANSFORMERS

Voltage control using tap changing transformers is the basic and easiest way of controlling voltages in transmission, sub-transmission and distribution systems. In high voltage and extra-high voltage lines On Load Tap Changing (OLTC) transformers are used while ordinary off-load tap changers prevail in distribution circuits. It is to be noted that tap changing transformers do not generate reactive power.

Consider the operation of transmission line with tap changing transformers at both the ends as shown in Fig. 14. Let t_s and t_r be the off-nominal tap settings of the transformers at the sending end and receiving end respectively. For example, a transformer of nominal ratio 6.6 kV to 33 kV when tapped to give 6.6 kV to 36 kV, it is set to have off-nominal tap setting of 36 / 33 = 1.09. The above transformer is equivalent to transformer with nominal ratio of 6.6 kV to 33 kV, in series with an auto transformer of ratio 33:36 i.e 1: 1.09.

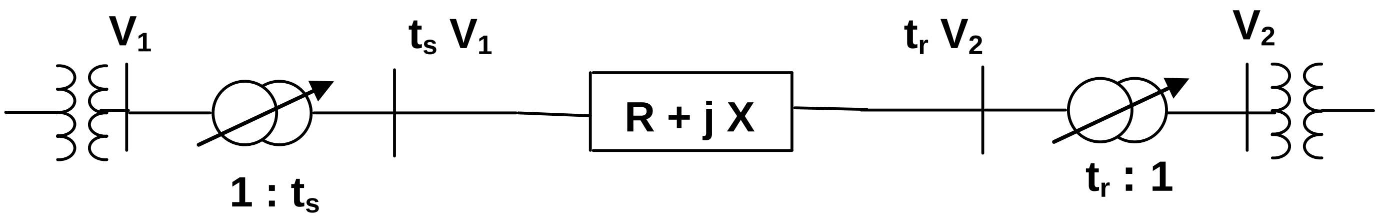


Fig. 14 Transmission line with tap setting transformers

In the following discussion, magnitudes of voltages are referred as V_1 and V_2. It is to be noted that V_1 and V_2 are the nominal voltages (Transmission line voltages such as 33 kV, 66 kV, 132 kV and 400 kV) at the ends of the line and the actual voltages being t_s V_1 and t_r V_2. It is required to determine the tap changing ratios required to completely compensate for voltage drop in the line. The product t_s t_r will be made unity; this ensures that the overall voltage level remains in the same order and that the minimum range of taps on both sides is used. The total impedance of line and transformers referred to high voltage side is (R + j X) Ω.

As discussed earlier, the voltage drop in the line is:

$$\Delta V = t_s V_1 - t_r V_2 = \frac{R P}{t_r V_2} + \frac{X Q}{t_r V_2} \quad \text{i.e.} \tag{38}$$

$$t_s V_1 = t_r V_2 + \frac{R P + X Q}{t_r V_2} \tag{39}$$

As $t_s t_r = 1$, $t_r = 1 / t_s$. Thus

$$t_s = \frac{1}{V_1}\left(\frac{V_2}{t_s} + \frac{R P + X Q}{V_2 / t_s}\right) \quad \text{i.e.} \quad t_s^2 = \frac{V_2}{V_1} + \frac{R P + X Q}{V_1 V_2} t_s^2 \quad \text{i.e.}$$

$$t_s^2 \left(1 - \frac{R P + X Q}{V_1 V_2}\right) = \frac{V_2}{V_1} \tag{40}$$

For complete voltage drop compensation $V_2 = V_1$.

Example

A 400 kV line is fed through 132 / 400 kV transformer from a constant 132 kV supply. At the load end of the line, the voltage is reduced by another transformer of nominal ratio 400 / 132 kV. The total impedance of the line and transformers at 400 kV is (50 + j 100) Ω. Both the transformers are equipped with tap changing facilities which are so arranged that the product of the two off-nominal settings is unity. If the load on the system is 200 MW at 0.8 p.f. lagging, calculate the settings of the tap changers required to maintain the voltages at the both ends at 132 kV.

Solution **We know** $$t_s^2\left(1 - \frac{RP + XQ}{V_1 V_2}\right) = \frac{V_2}{V_1}$$

The load is 200 MW at 0.8 p.f. i.e. 200 MW, 150 MVAR.

$$\frac{RP + XQ}{V_1 V_2} = \frac{50 \times (200 \times 10^6 / 3) + 100 \times (150 \times 10^6 / 3)}{(400/\sqrt{3})^2 \times 10^6}$$

$$= \frac{50 \times 66.6667 + 100 \times 50}{230.94^2} = 0.15625$$

t_s^2 (1 – 0.15625) = 1; i.e. t_s^2 = 1.1852;

Thus the tap settings are; t_s = 1.09 and hence t_r = 1/1.09 = 0.92

Questions on “ Automatic Voltage Control”

1. With necessary diagrams, briefly describe DC excitation systems, AC excitation systems and Brushless AC excitation systems.

2. Develop the block diagram of comparator and the amplifier in the excitation system.

3. From the necessary equations, obtain the block diagram of exciter in an AVR.

4. Develop the block diagram of generator field in the voltage regulator.

5. Draw the block diagram of the AVR loop, without stability compensator. Reduce it as a single block between the input and output.

6. What are the requirements of AVR loop?

7. What is static accuracy requirement in AVR?

8. **Static error in AVR deceases with increased loop gain. Justify this. Find the minimum value of open loop gain K, for the static error to be less than i) 1% ii) 2% and iii) 3% of reference input.**

9. **Consider the block diagram of the AVR loop without stability compensator. The values of the time constants are: T_A = 0.05 s; T_e = 0.5 s and T_F = 3.0 s. We would like the static error not to exceed 1% of reference input.**

   a) Construct the required root locus diagram and prove that the static accuracy requirement conflicts with the requirement of stability.

   b) Specifically, compute the closed loop poles if K is set at 99.

   c) Reduce K by 50% and repeat part b.

10. **In AVR, high open loop gain is needed for better static accuracy; but this causes undesirable dynamic response, possibly instability. Justify this.**

11. **Explain the role of stability compensator in the AVR.**

12. **Derive an approximate expression for the voltage drop in a transmission line.**

13. **Justify the need for reactive power injection.**

14. What do you understand by compensation by shunt capacitor and reactors?

15. Explain the working of static VAR compensator.

16. Explain the method voltage control using tap changing transformers.

17. A 132 kV line is fed through 11 / 132 kV transformer from a constant 11 kV supply. At the load end of the line, the voltage is reduced by another transformer of nominal ratio 132 / 11 kV. The total impedance of the line and transformers at 132 kV is (20 + j 53) Ω. Both the transformers are equipped with tap changing facilities which are so arranged that the product of the two off-nominal settings is unity. If the load on the system is 40 MW at 0.9 p.f. lagging, calculate the settings of the tap changers required to maintain the voltages at the both ends at 11 kV.

Answers

8. 99; 49; 32.333

9. a) For static accuracy requirement $K > 99$

For stability requirement $K < 78.284$

b) $s = -22.82$; $s = 0.2433 + j\,7.6407$; $s = 0.2433 - j\,7.6407$

c) $s = -21.585$; $s = -0.374 + j\,5.572$; $s = -0.374 - j\,5.572$

17. $t_s = 1.057$ and $t_r = 0.946$