

Excitation Control Systems

The parts of VMAF which are considered in these notes include:

- Chapters 9, Excitation systems: We specifically address Sections 9.1-9.3 and 9.12 of this chapter, which include:
 - 9.1: Simplified view of excitation control
 - 9.2: Control configurations
 - 9.3: Typical excitation configurations
 - 9.10: Computer representation of excitation systems (differential equations, we will not have time for this but I list it here to suggest you might skim this section).
 - 9.12: Effect of excitation on generator performance
- Chapter 10, Effect of excitation on stability: We specifically address Sections 10.1-10.3 of this chapter, which include:
 - 10.1: Introduction
 - 10.2: Effect of excitation on generator power limits
 - 10.3: Effect of the excitation system on transient stability
- App. E: Excitation control system definitions.

First, we will mainly study Ch. 10 material, to motivate the need for excitation systems in terms of transient instability, although we will occasionally move into Ch. 9 & App. E material. Then, at the end of these notes, we will return to Ch. 9 to obtain some understanding of the technology used to implement excitation control.

1.0 Purposes of excitation control

The fundamental purpose of excitation control for synchronous machines is to enable control of the terminal voltage of the machine and thus of the network voltage. It is possible to obtain network voltage control in four other ways:

- *Switched shunt capacitors and inductors*: These devices offer only discrete control, whereas excitation control is continuous;
- *Synchronous condensers (SCs)*: An SC is a synchronous generator that has no turbine; it may also be considered to be a synchronous motor that has no mechanical load. See Fig. 0a. In both cases, $P_m=0$ and therefore $P_e=0$. So it is a synchronous

machine that neither supplies nor consumes MW. But it *can* supply and consume reactive power (vars).

- *Static var compensators (SVCs)*: SVCs are functionally equivalent to SCs, but whereas SCs are rotating devices, SVCs are static, using thyristors – see Fig. 0a.
- *Static synchronous compensators (STATCOM)*: These are also functionally equivalent to SCs and SVCs. STATCOMs differ from SVCs in that, whereas SVCs are implemented with thyristors, STATCOMS are implemented with IGBTs. See Fig. 0a.



Fig. 0a: SC (left); SVC (middle); STATCOM (right)

Fig. 0b¹ provides a comparison between these four ways of providing network voltage control.

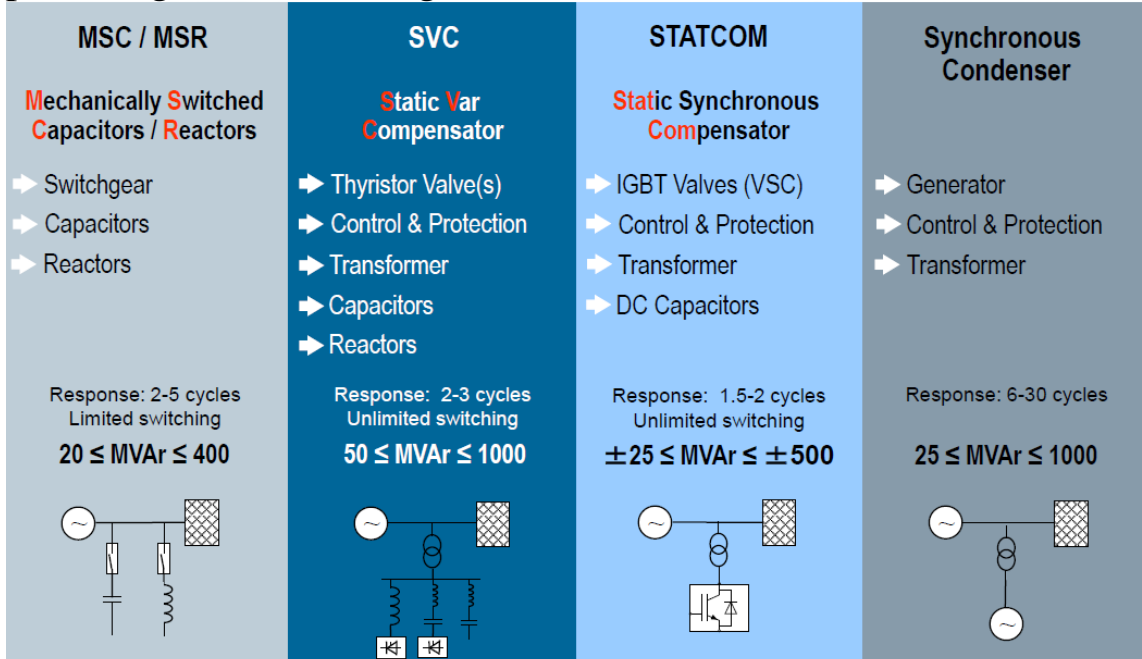


Fig. 0b

¹ C. Winter, D. Brown, and W. Zhu, "Evaluating dynamic reactive support options for Minnesota's North Shore," presentation slides, MIPSYCON, 2018, www.ccaps.umn.edu/documents/CPE-Conferences/MIPSYCON-PowerPoints/2018/EvaluatingDynamicReactiveSupport.pdf.

Although SCs, SVCs, and STATCOMS offer continuous control,

- relative to switched shunts, they are expensive, and
- relative to excitation control from synchronous generators, their voltage-control value is their only value.

On the other hand, for synchronous generators, excitation control is obtained as a secondary or ancillary feature. It is the ability to produce MWs that motivates the investment in a synchronous machine. So with synchronous generators, we pay the investment cost in order to get the MWs and then we get the MVARs along with it. (Aside: Wind and solar plants have tended to not provide as much voltage control in the past, but they can, and as penetrations increase, they will be increasingly required to do so.)

In controlling the terminal voltage of the synchronous machine, the excitation system provides three main benefits.

1. *Voltage profile*: The voltage profile of the entire network can be regulated. This includes buses at which no synchronous generator is located.
2. *Transient stability*: Excitation control can significantly improve transient stability, and the improvement tends to be greatest with fast, high-gain excitation systems. We will discuss this more in the next section.
3. *Oscillatory stability (damping)*: Power systems can exhibit negatively damped oscillations, where the amplitude of the oscillation grows with time. This problem is worsened by fast, high-gain excitation systems (which, per the last bullet, tend to improve transient stability performance). Fortunately, this undesirable effect of fast high-gain excitation systems on oscillatory stability effect is mitigated through use of power system stabilizers (PSS). We will study this phenomenon, together with PSS, when we address linearized analysis later in the course.

The apparent design conflict raised by points 2 and 3 above are well-captured in VMAF in Section 10.1. Please read this section closely. But I will relate an important part of that text here (see p. 409).

“The subject of excitation control is further complicated by a conflict in control requirements in the period following the initiation of a transient. In the first few cycles, these requirements may be significantly different from those needed over a few seconds. Furthermore, it has been shown that the best control effort in the shorter period may tend to cause instability later. This suggests the separation of the excitation control studies into two distinct problems, the transient (short-term) problem and the dynamic (long-term) problem. It should be noted that this terminology is not universally used. Some authors call the dynamic stability problem by the ambiguous name of “steady-state stability.” Other variations are found in the literature, but usually the two problems are treated separately as noted.”

2.0 Effect on transient instability

2.1 Introductory concepts

Transient stability, considered here as the ability of a synchronous machine to remain in synchronism during the first swing following a disturbance, greatly benefits from excitation control.

Without excitation control: Upon occurrence of a fault, without excitation control, the field flux linking the armature windings decays due to the demagnetization effect (sometimes called “armature reaction”) of the very high armature fault current. Since the voltage behind the transient reactance E'_q , is proportional to this field flux, it also decays. For the same terminal voltage V , a decline in E'_q , means that the power angle δ must increase further to transmit the same real power, since the power output of the machine during the transient can be approximated by

$$P = \frac{E'_q V}{X'_q} \sin \delta = VI \cos \theta \quad (1)$$

With excitation control: We can look at this in two different ways. The first way (also outlined in Example 10.1 in VMAF) we can look at this is to consider this equation for constant P and V , realizing of course that X'_q is

constant. The effect of excitation control is to boost E'_q . From the first part of (1), we obtain

$$\frac{PX'_q}{V} = E'_q \sin \delta \quad (2)$$

From the second part of (1), we obtain

$$\frac{P}{V} = I \cos \theta \quad (3)$$

Thus we see that the left-hand sides of (2) and (3) are constants and therefore the right-hand sides must be constant as well. Figure 1 below illustrates the locus of points associated with E'_q for which $E'_q \sin \delta$ must be constant, and the locus of points associated with I for which $I \cos \theta$ must be constant.

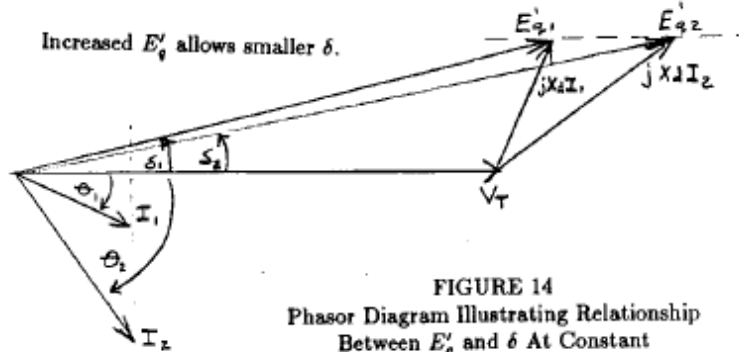


FIGURE 14
Phasor Diagram Illustrating Relationship
Between E'_q and δ At Constant
Real Power

Fig. 1

What we observe is that as E'_q increases from E'_{q1} to E'_{q2} (due to excitation control) I will increase from I_1 to I_2 , but δ will decrease from δ_1 to δ_2 . The fact that the torque angle decreases as excitation increases suggests that this is a stabilizing action for purposes of transient stability.

The second way we can look at this is to observe the power angle curves, per Fig. 2, for the condition where the post-fault internal voltage is high (left hand plot of Fig. 2) due to excitation control vs. the condition where the post-fault internal voltage is low (right-hand plot of Fig. 2) which is the case without excitation control. It is clear that excitation control allows less post-fault accelerating energy and more available deaccelerating energy, and the generator experiences less severe swings.

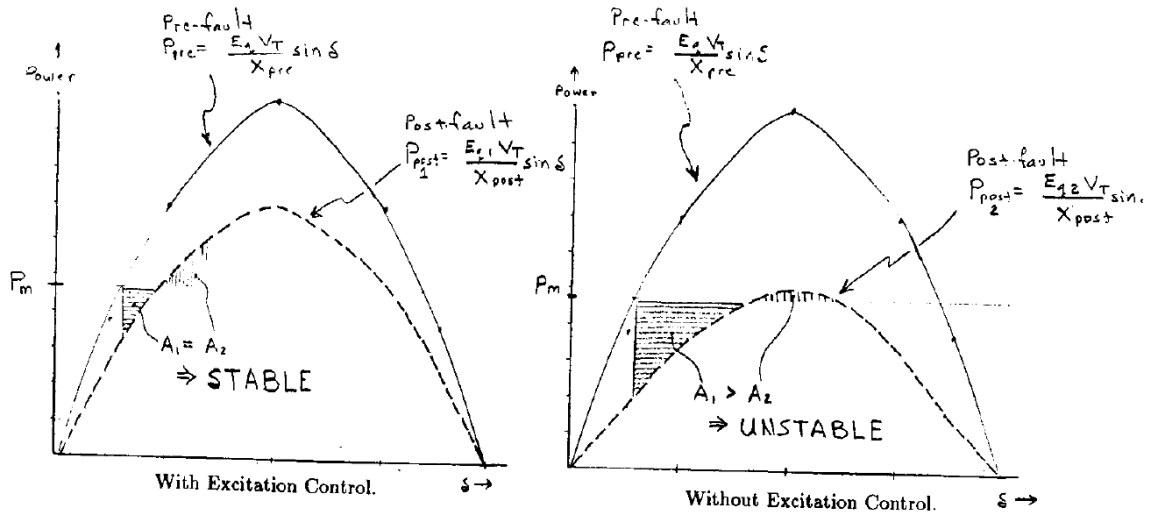


Fig. 2

In addition to Example 10.1, your text also addresses this concept in Section 10.1.1, p. 410. Before we read that, let's define a few terms (note that excitation definitions are so important that there is an IEEE standard dedicated to them [1], and VMAF provides section 9.4 and App. E on defining terms related to excitation control systems).

- Exciter: The equipment that provides the field current for the excitation of the synchronous machine [1].
- Amplifier: The device that increases the regulating signal power to that required by the exciter field, i.e., it amplifies the control signal. If electromechanical, it is often referred to as the pilot exciter, or the rotating amplifier. If solid-state, it is usually considered as part of the regulator.
- Automatic voltage regulator (AVR): A synchronous machine regulator that functions to maintain the terminal voltage of a synchronous machine at a predetermined value, or to vary it according to a predetermined plan [1]. In your text, VMAF describe the voltage regulator in Section 9.5, introducing it by saying it is the “heart” of the excitation system (p. 344) and that it “is the device that senses changes in the output voltage (and current) and causes corrective action to take place.” The AVR, or more simply, the regulator, is the device that couples the output parameters of the synchronous generator (e.g., voltage, current, frequency) to the input of the main exciter.

- Excitation system: The equipment providing field current for a synchronous machine, including all power, regulating, control, and protective elements [1], i.e., it includes the regulator, amplifier, and exciter.
- Excitation control system: The feedback control system that includes the synchronous machine and its excitation system. The term is used to distinguish
 - the performance of the synchronous machine and excitation system in conjunction with the power system
 - from that of the excitation system alone [1].

Figure 3 [1] illustrates the relation between the AVR, exciter, excitation system, and excitation control system.

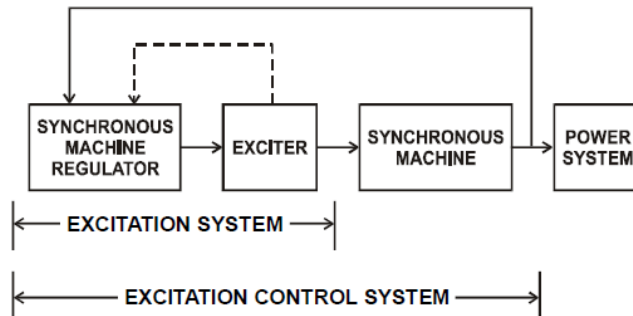


Fig. 3 [1]

- Ceiling voltage: The maximum direct voltage [field voltage] that the excitation system is designed to supply from its terminals [across the field winding] under defined conditions [1]. Ceiling voltages range from 1.2 pu for older DC systems to 2.0 pu for modern AC alternator or static systems.
- Synchronizing power: The amount of change in input power to a synchronous motor [or in output power from a synchronous generator] for a given change in power angle [2]. It is reflected by the slope of the tangent to the power angle curve. It characterizes the amount of power required by the machine to counteract a change in rotor angle. From Section 10.1.1 of VMAF (p. 410):

“In transient stability the machine is subjected to a large impact, usually a fault, which is maintained for a short time and causes a significant reduction in the machine terminal voltage and the ability to transfer synchronizing power. If we consider the one machine-infinite bus problem, the usual approximation for the power transfer is given by

$$P = \frac{V_t V_\infty}{x} \sin \delta \quad (10.1)$$

where V_t is the machine terminal voltage and V_∞ is the infinite bus voltage. Note that if V_t is reduced, P is reduced by a corresponding amount. Prevention of this reduction in P requires very fast action by the excitation system in forcing the field to ceiling and thereby holding V_t at a reasonable value. Indeed, the most beneficial attributes the voltage regulator can have for this situation is speed and a high ceiling voltage, thus improving the chances of holding V_t at the needed level. Also, when the fault is removed and the reactance x of (10.1) is increased [relative to pre-fault condition] due to switching, another fast change in excitation is required. These violent changes affect the machine's ability to release the power it is receiving from the turbine. These changes are effectively controlled by very fast excitation changes."

The remainder of section 10.1.1 describes the effect of excitation on the damping problem, which we will only briefly consider here (in the example of 10.3.2) and then consider in more depth in our work on linearized analysis.

Section 10.3.1, p415 also has some insightful text, particularly the following:

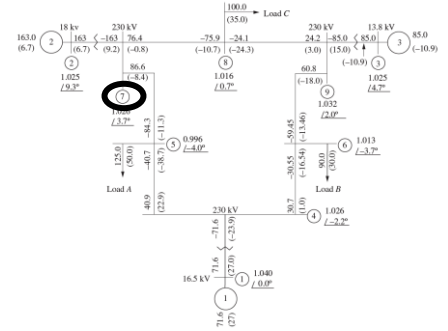
"In the classical model it is assumed that the flux linking the main field winding remains constant during the transient. If the transient is initiated by a fault, the armature reaction tends to decrease this flux linkage [15]. This is particularly true for the generators electrically close to the location of the fault. The voltage regulator tends to force the excitation system to boost the flux level. Thus while the fault is on, the effect of the armature reaction and the action of the voltage regulator tend to counteract each other. These effects, along with the relatively long effective time constant of the main field winding, result in an almost constant flux linkage during the first swing of 1 s or less. (For the examples in Chapter 8 this time constant $K_3\tau'_{do}$ is about 2.0s.)

It is important to recognize what the above reasoning implies. First, it implies the presence of a voltage regulator that tends to hold the flux

linkage level constant. Second, it is significant to note that the armature reaction effects are particularly pronounced during a fault since the reactive power output of the generator is large. Therefore the duration of the fault is important in determining whether a particular type of voltage regulator would be adequate to maintain constant flux linkage.”

2.2 Some interesting examples

Section 10.3 offers two useful examples, one in 10.3.1 and one in 10.3.2. But first, let’s look at Example in Section 9.12 (pp. 400-402):



The nine-bus three-machine system shown in Figure 2.18 has been used to perform simulations of 5.0 s in duration using the Powertech Transient Stability Assessment Tool (TSA) [61]. A three-phase fault was applied at bus 7 at $t = 1.0$ s and cleared 16 cycles (0.27 s) later. Since clearing times for most high voltage protective systems are between 4 and 10 cycles, this represents a delayed-clearing condition. No component is outaged following fault clearing. Three simulations were conducted, each one with different excitation system conditions modeled at the three generators. In simulation (a), no excitation system was modeled, i.e., the field voltage remained constant throughout the simulation for all three machines. In simulation (b), a Type DC1 excitation system was modeled at each of the three machines; in simulation (c), a Type ST2 excitation system was modeled at each of the three machines. Data used to characterize the DC1 and ST2 excitation systems are provided in Table 9.11. The Type DC1 data also represented saturation with points $(e_1, S_{e1}) = (2.8, 0.30)$ and $(e_2, S_{e2}) = (3.73, 1.29)$.

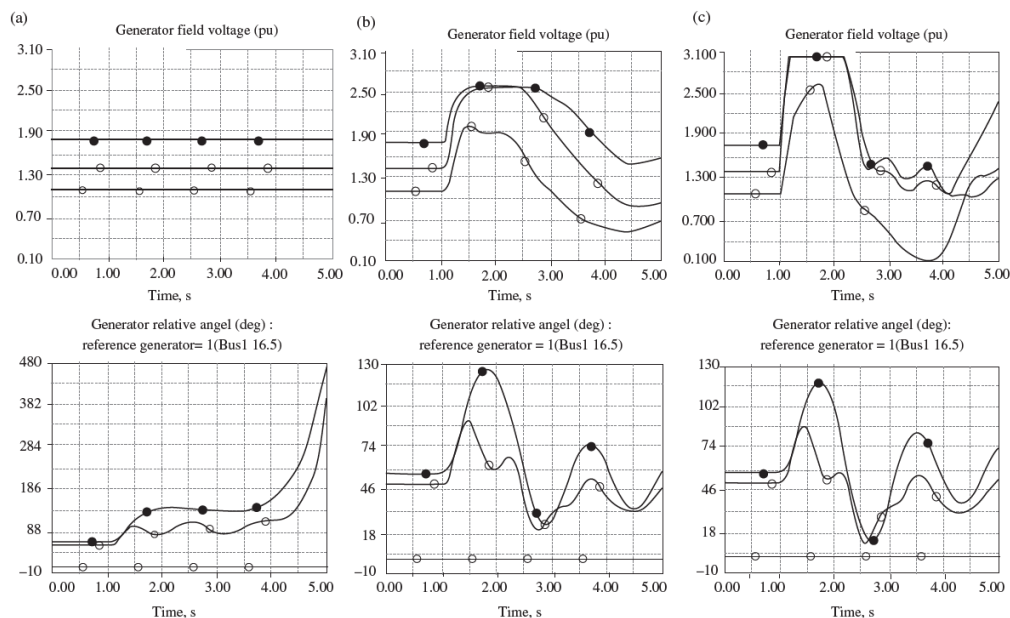


Figure 9.70 Field voltage and relative rotor angle response to three-phase fault for three different excitation systems. (a) No excitation system. (b) Type DC1 excitation system. (c) Type ST2 excitation system.

Example of Section 10.3.1 (stability limit for various response ratios, p. 416)
 To understand this example, it is important to understand two terms.

- Power limit: this is the maximum pre-fault power output of the machine for which post-disturbance performance is stable and acceptable.
- Response ratio (RR): In [1], it is called the excitation system nominal response and defined as the rate of increase of the excitation system output voltage determined from the excitation system voltage response curve, divided by the rated field voltage. This rate, if maintained constant (curve ac), would develop the same voltage-time area as obtained from the response (curve ab) over the first half-second interval (unless a different time interval is specified). The RR is a measure of the speed of response for the excitation system; the higher the RR, the faster the response. The response ratio is illustrated in Fig. 4 below where we see from the given formula that it may be interpreted as the normalized (to the rated exciter voltage) voltage increase (cd) per second. VMAF treats RR in sec 9.4.1.

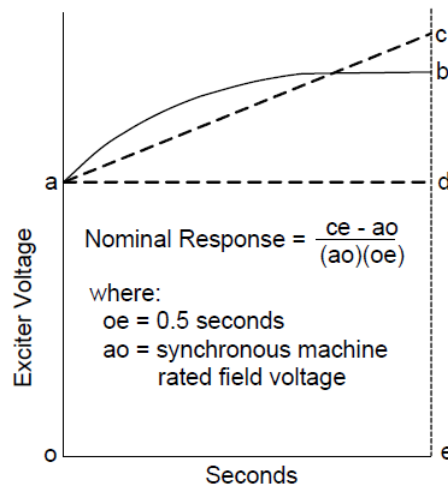


Fig. 4: Response ratio

So in this example, which VMAF reports from a paper by Crary [3], the power limit was identified as a function of clearing time for a fault near the generator terminals; the machine modeled excitation having varying response ratios. The system used for this study is shown in Fig. 5 (copied from Crary's paper, not Fig. 10.7 in the book); results are given on p. 417, repeated in Fig. 6. The results of Fig. 6 are shown for a 200 mile-long system (left) and a 600 mile-long system (right). (VMAF only gives the 200 mile-long results). An immediate observation is that the power limits for the 600

mile-long system are significantly lower than those of the 200 mile-long system, a consequence of the larger reactance between the internal voltage and the load. 2nd and 3rd observations, made in either figure, are that (a) the power limit increases as fault clearing time decreases; (b) the power limit increases as the speed of exciter response increases (i.e., as the RR increases).

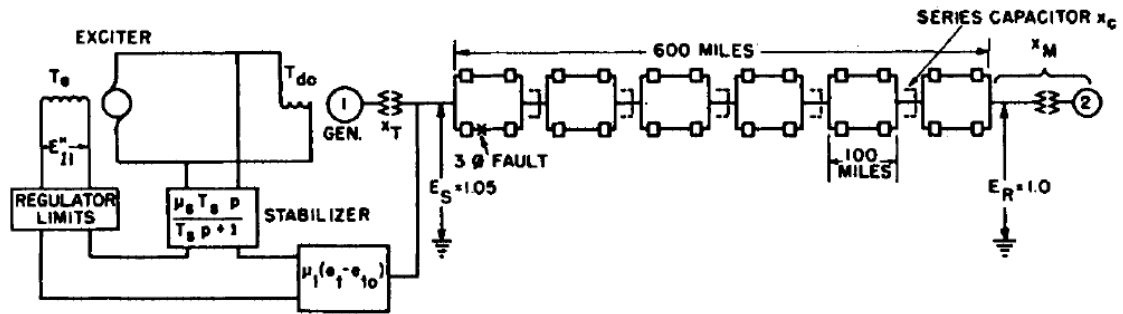


Fig. 5: System used

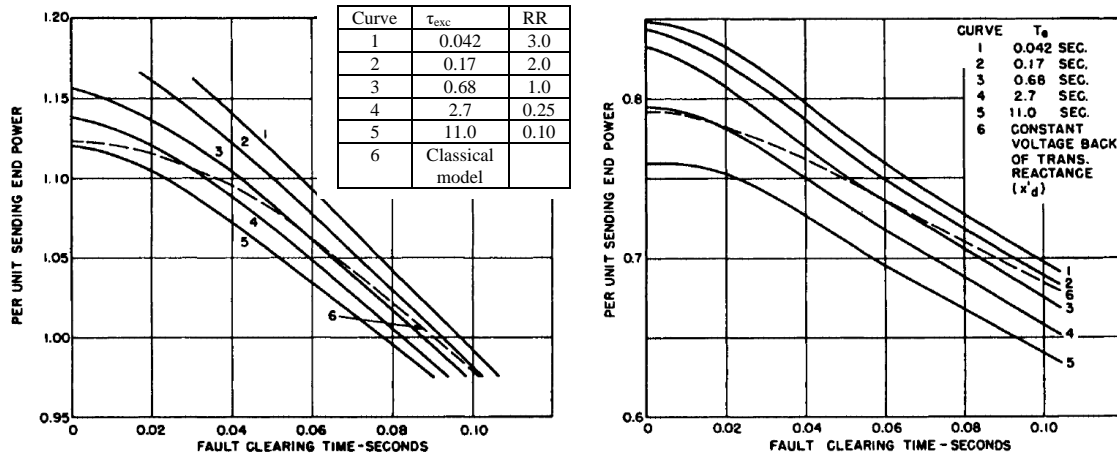


Fig 6: Results. Left – 200 mile system; Right – 600 mile system

On p. 416, VMAF make additional comments related to Fig. 6.

- Relation of RR to excitation system speed: An excitation system having RR=0.10 (curve 5) would correspond to a “nearly constant field voltage condition,” whereas an excitation system having RR=3.0 “would approximate the response of a modern fast excitation system.”
- Classical model: A&F state, “it appears that the classical model corresponds to a very slow and weak excitation system for very short fault clearing times, while for longer clearing times it approximates a rather fast excitation system. If the nature of the stability study is such that the

fault clearing time is large, as in “stuck breaker” studies [15], the actual power limits may be lower than those indicated when using the classical model.”

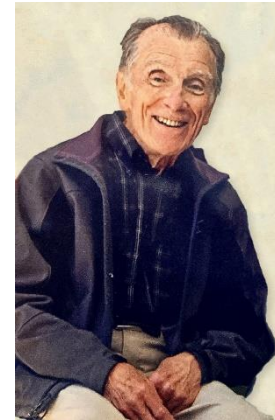
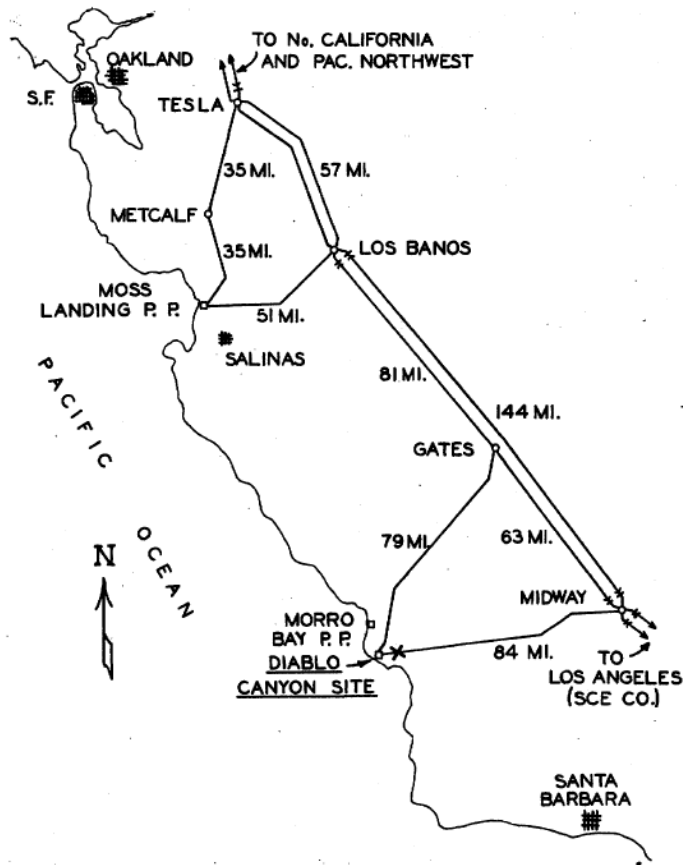
→ In other words, the classical model, with constant internal voltage, will outperform slower excitation systems for long-duration faults. The reason for this is that, for long-duration faults...

- whereas a classical model will not boost the voltage during the fault, it will hold the internal voltage constant without any influence of armature reaction from the fault current;
- for a slow excitation system, the internal voltage gets little boost during the fault, and the effects of armature reaction from the fault current dominate, and so the overall effect will appear to be a decrease in internal voltage of the machine.

This tendency is not so observable for short-duration faults because constant flux linkage theorem (CLFT) inhibits armature reaction effect when fault time is almost zero.

Example of Section 10.3.2 (stability performance with different exciters)

This example, obtained from [4], shows how stability performance is affected by different excitation systems. The system studied was the Western Interconnection for three-phase faults near to the terminals of the Diablo Canyon Nuclear Power Plant. This system is illustrated in Fig. 7 below. Unlike the system used in your project (and unlike the actual system in place today), the system shown in Fig. 7 has only one line between the Diablo Canyon 500 kV bus and the Midway 500 kV bus. The reason for this is that as the authors, in 1971, were studying conditions between commissioning of unit 1 and commissioning of unit 2, expected to be in 1973, and so they assumed only one 1400 MW generation unit at Diablo Canyon. The additional line to Midway was planned for service when the second unit was added, and so the authors assumed in this study that the second Diablo-Midway 500 kV line was unavailable. Actually, seismic concerns and a design error prevented unit 1 commissioning until 1985 and unit 2 commissioning until 1986 – see the “History” section of the Diablo Canyon wikipedia page https://en.wikipedia.org/wiki/Diablo_Canyon_Power_Plant.



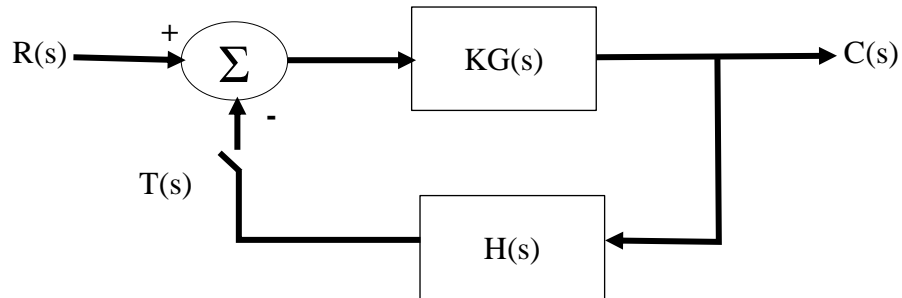
James F. Luini

Fig. 7 [4, by H. Perry, J. Luini, and J. Coulter]

To understand these results, we first define the term “rate feedback.” Rate (or derivative) feedback provides a stabilizing action for excitation systems that use rotating exciters (see p. 375 of VMAF). Without rate feedback, such excitation systems with moderate to high amplifier gain have right-half-plane poles (and thus are unstable); with rate feedback, the excitation system is stabilized. This is illustrated by VMAF, using root locus, in Chapter 9 on pp. 372-380.

Aside: What is root locus?

To answer this, one first needs to realize that a linear control system can be characterized by a block diagram, or, equivalently, a transfer function of the closed loop system. Consider identifying the transfer function characterizing the forward path as $G(s)$ and the transfer function characterizing the feedback path as $H(s)$ (where “ s ” is the Laplace operator). This system is shown below.



Some definitions and guiding thoughts:

- the open loop transfer function is $T(s)/R(s)=KG(s)H(s)$, when the switch is open;
- the closed loop transfer function is $C(s)/R(s)=KG(s)/[1+KG(s)H(s)]$ when the switch is closed;
- the characteristic equation is obtained by setting the denominator of the closed-loop transfer function to zero, i.e., $1+KG(s)H(s)=0$;
- the poles of the closed-loop transfer function are the roots of the characteristic equation;
- the location of the poles in the real-imaginary plane determine the stability of the closed-loop transfer function:
 - if all poles are in the left-half plane, the closed-loop system is stable;
 - if any pole is in the right-half plane, the closed-loop system is unstable.
 - if there are no poles in the right-half plane, but one or more poles are on the $j\omega$ axis, the system is marginally stable.
- The location of the poles of the closed loop system varies as K is increased from 0 to ∞ . Because K represents gain and is therefore an operational parameter which can be and often is modified on-site once the controller is deployed, it is useful to understand how the stability performance of the closed-loop system changes as K is increased from its minimum level of 0 to its maximum level of ∞ .
- Root locus is a method of identifying how the poles of the closed-loop system change as K is increased from 0 to ∞ . Application of the “root-locus” method provides a “locus of the roots” of the characteristic equation as K is increased from 0 to ∞ . There are a number of “root locus rules” to facilitate drawing a root locus; these rules can be found

in any classical controls textbook; some I have on my shelf include [5, 6, 7]. Here, we will identify only three of these rules. Key to application of these rules is the following concept:

➔ Although the root locus identifies the location of poles of the closed-loop transfer function, it is drawn by operating on the open-loop transfer function.

The three rules that we will focus on are as follows:

- $K=0$: The poles of the closed loop transfer function are the roots of the open-loop transfer function.
- $K=\infty$: The poles of the closed loop transfer function are the zeros of the open-loop transfer function.
- $0 < K < \infty$: The poles of the closed loop transfer function vary from the poles at $K=0$ to the poles at $K=\infty$.

The remaining root locus rules help to construct exactly how the variation of the last rule takes place.

Back to the excitation system rate feedback issue:

Specifically, compare Fig. 9.55 (without rate feedback) to Fig. 9.59, Case II-B (with rate feedback). I have done a similar study and include the associated block diagrams and root locus plots in Fig. 8 (without rate feedback) and Fig. 9 (with rate feedback).

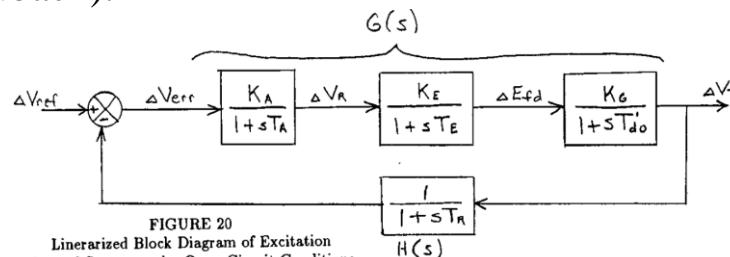


FIGURE 20
Linearized Block Diagram of Excitation Control System under Open Circuit Conditions without Rate Feedback

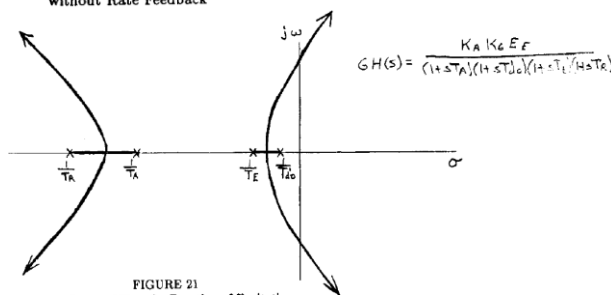


FIGURE 21
Root Locus of Transfer Function of Excitation Control System under Open Circuit Conditions without Rate Feedback; To Find Uncompensated Pole Locations

Fig. 8: Without rate feedback

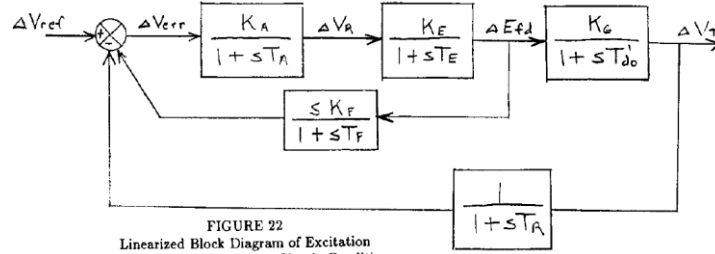


FIGURE 22
Linearized Block Diagram of Excitation Control System under Open Circuit Conditions with Rate Feedback

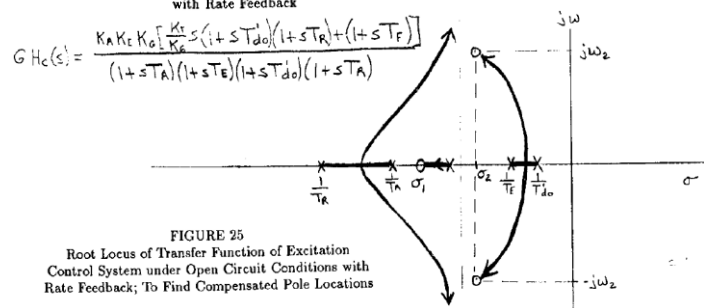


FIGURE 25
Root Locus of Transfer Function of Excitation Control System under Open Circuit Conditions with Rate Feedback; To Find Compensated Pole Locations

Fig. 9: With rate feedback

- The study compared stability performance for 3 different excitation systems:
- A. An excitation system with response ratio of 2.0, with rate feedback;
 - B. An excitation system with a low time constant and with rate feedback (this excitation system is faster than that of (A)).
 - C. The same excitation system as (B) but without rate feedback.

Results are shown in Fig. 10 (these results are in VMAF, p. 418, but Fig. 10 plots were taken from the original source [4]). Observations are as follows:

- The left-hand plot of Fig. 10 indicates importance of rate feedback on oscillatory stability, as oscillations indicated for the case w/ excitation system (C) are quite large and not well-damped, meaning there is a complex pole, though stable, close to the $j\omega$ axis (see Fig. 8 root locus).
- The right-hand plot of Fig. 10 indicates the importance of speed of response on transient (early-swing) stability, as the performance under the excitation system (A) is unstable.

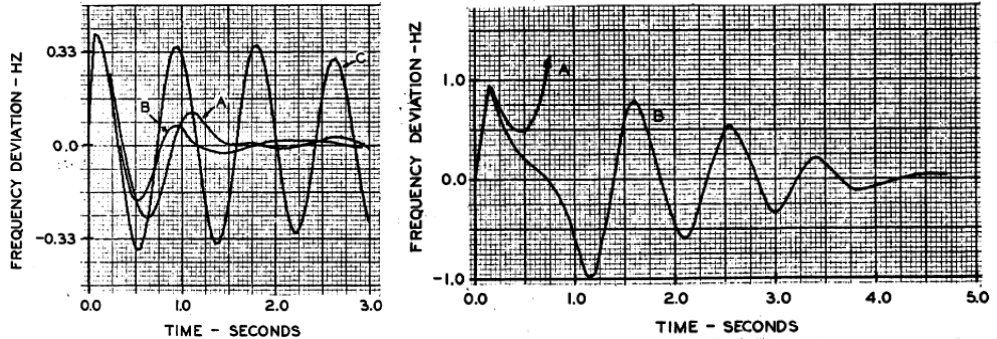


Fig. 10: Frequency deviation for 4 cycle fault (left) & 9.6 cycle fault (right)

3.0 Types of excitation systems

We provide a high-level view of the excitation control system architecture in Fig. 11 [8]. This may be thought of as an expanded view of Fig. 3 (repeated below for convenience), where the block labeled “excitation control elements” is essentially the AVR. It is Fig. E.1 in VMAF, p. 728.

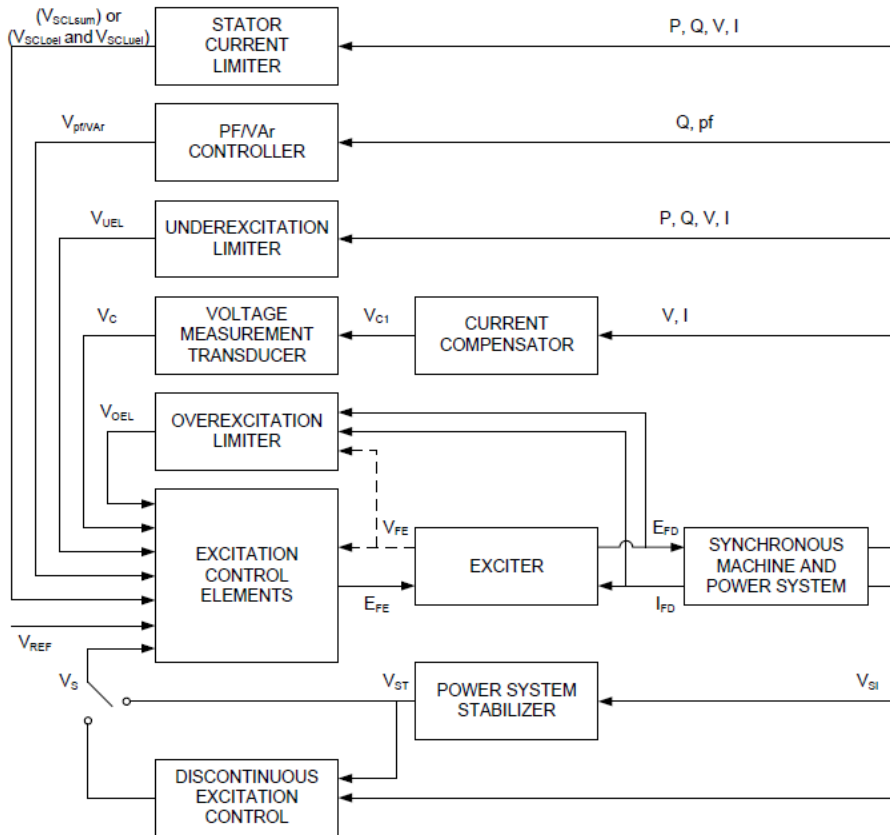


Fig. 11

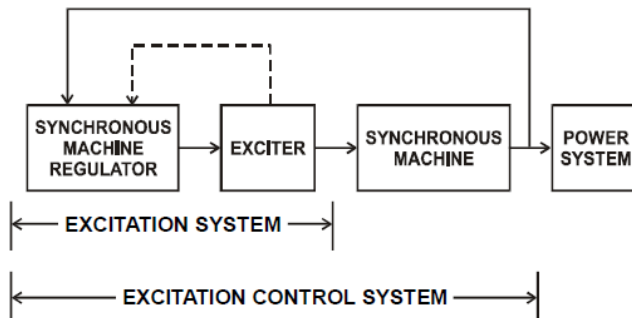
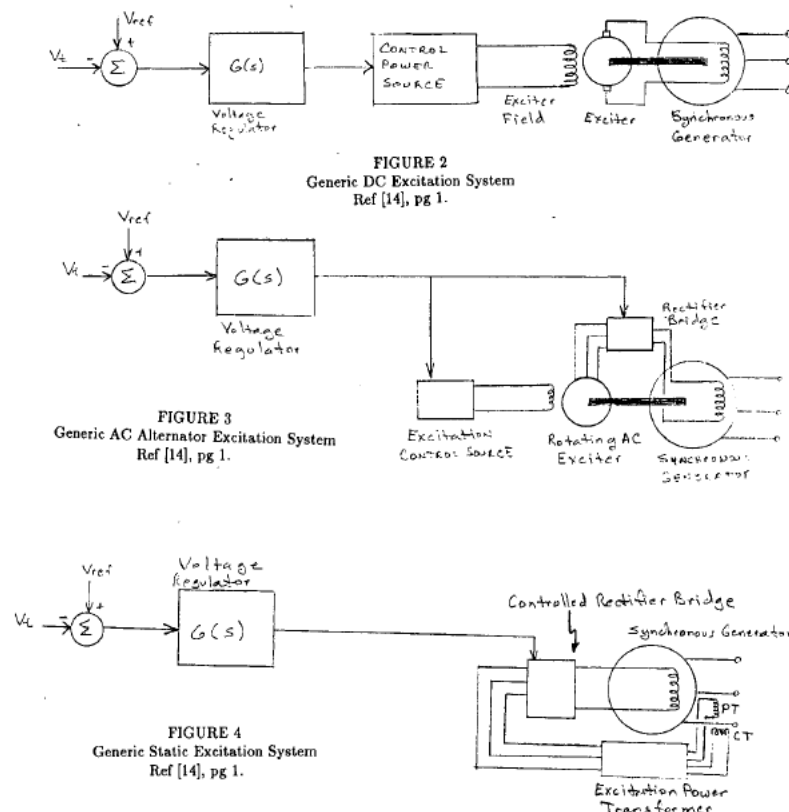


Fig. 3 [1]

In this section, we want to provide some insight into the configurations associated with the AVR/exciter. There are three basic configurations:

1. Direct current commutator rotating exciter
2. Alternator supplied rectifier excitation systems
3. Static excitation systems

Figure 12 provides a schematic of each type.



DC excitation systems are shaft-mounted and armature winding (on rotor) developed AC converted to DC via commutator/brush arrangement and then applied to the synchronous gen field winding via slip rings and brushes.

Field controlled with slip rings: exciter AC output on stator converted to DC and then applied to synchronous gen field winding via slip rings & brushes.
Inverted brushless design: Exciter field on stator; AC on rotor converted to DC via power electronics.

Static exciter: No rotating device; power source is synch gen terminals, then rectified, then uses slip rings and brushes to apply to synch gen field.

Fig. 12

We address these in each of the following three subsections.

3.1 Direct current commutator rotating exciter

VMAF describe this type of excitation control system in Section 9.3.2.

In the top picture of Fig. 12, we show a generic DC commutator excitation system where the main exciter is mounted on the shaft of the synchronous machine. The exciter may be self-excited, separately excited, or connected in the ‘buck-boost’ configuration, which is the most common arrangement. Here, as indicated in Fig. 13, a rotating amplifier is connected in series with the field winding of a self-excited main exciter and is controlled so that it can either buck (reduce) or boost (increase) the exciter field current. Three commonly used rotating amplifier regulators are the Westinghouse Rototrol,

the GE Type NA1 Amplidyne, and Allis-Chalmers Regulex. Signal amplification may also be done magnetically, as is the case for the Westinghouse WMA Mag-A-Stat and the GE Amplistat regulators. Another type of DC excitation system still used on older installations are rheostatic, i.e., the field current of the main exciter is controlled by varying the main exciter field series resistance.

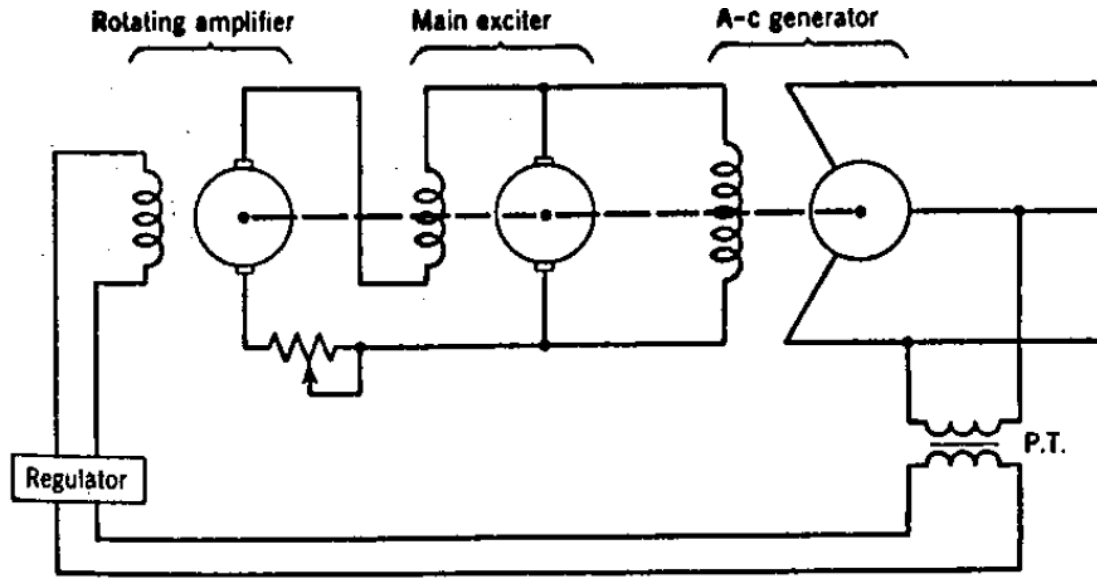


Fig. 13: Buck-boost DC Rotating Excitation System

Relative to the AC and static types of excitation control, the DC type has two distinct disadvantages. These are the (1) the commutator, brushes, and slip rings coupling the main exciter to the synchronous generator field require high maintenance, and (2) the rate of response to voltage deviations is considerably slower due to the high time constants of the rotating devices and the mechanical or electromechanical regulators. In addition, some DC exciters may experience a 'deadband' of voltage deviation below which they will not respond at all. The only motivation for using DC excitation systems today is that they were the first type installed, and where they are still in place, it may be more cost-effective to continue using them rather than to replace them.

3.2 Alternator supplied rectifier excitation systems

VMAF describe this type of excitation control system in Section 9.3.3.

This type of excitation system is distinguished from DC excitation systems in that an AC alternator, with AC to DC rectification, is used to supply the field winding of the synchronous generator. The most salient differences among AC alternator exciters are (1) whether the regulator controls the field voltage or the output voltage of the alternator, and (2) whether the system is brushless or uses slip rings to couple the exciter to the rotor mounted synchronous field winding. There are basically three types of rotating AC excitation systems, as follows:

1. Field controlled with slip rings
2. Brushless, field controlled
3. Brushless, output controlled

An interesting feature of these arrangements is as follows:

- In the field-controlled with slip rings configuration (#1), the alternator is shaft-mounted with the field winding on the rotor and the armature winding on the stator. Although this is a typical design for a synchronous machine (and thus easy to build), it has the disadvantage that the output of the alternator must be connected to the (rotating) field winding via slip rings and brushes.
- But in both brushless configurations, the shaft-mounted alternator is “inverted,” meaning that the field winding is on the stator and the armature winding is on the rotor. Thus, the AC-to-DC rectification is performed on the shaft and then applied to the field winding. Since the AC output of the alternator, the rectifier, and the field winding of the synchronous machine are all on the shaft, no slip rings or brushes need be used.

3.3 Static excitation systems

VMAF describe this type of excitation control system in Section 9.3.4-9.3.7.

The distinguishing features of static excitation systems are the (1) they are composed entirely of solid-state circuitry, i.e., they contain no rotating devices, and (2) they are self-excited, i.e., the power source for the

synchronous generator field is the output voltage and/or current of the synchronous generator. The most salient differences among static excitation systems are (1) whether simply terminal voltage or terminal voltage and current are used as the power source, and (2) whether a field control loop is utilized. There are basically three types of static excitation systems, as follows:

1. Potential source
2. Compound source
3. Potential or compound source with field control loop

The advantages of the static types of excitation systems over the AC and DC are that they are inherently more reliable and maintenance free due to the fact that the components are entirely solid-state instead of electromechanical. For this same reason, static systems are usually less expensive. The only disadvantage is that the regulator power supply may be lower during faults – exactly when the regulation action is needed most. This disadvantage can be partially compensated for by using the compound source.

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