CHAPTER- 10

HYDRO GENERATOR EXCITATION SYSTEMS

10.1 General

Excitation systems supply and regulate the amount of D. C. current required by generator field windings and include all power regulating control and protective elements. The excitation system should be specified to meet the power requirements and required response characteristics to meet the power system to which generator will be connected. Overall performance and capacity of the excitation system represented earlier by excitation response and response ratio is now expressed as nominal system response (ANSI/IEEE std. 421-1-1996). Standard excitation system voltages defined in ANSI C50-12 are 62.5, 125, 250, 375 and 500 V DC.

10.2 Excitation System Type

Modern static excitation systems have completely replaced older shaft mounted rotating exciters with DC field current controlled by motor operated field rheostat. Brushless excitation system and static excitation systems are being used in modern systems.

**Brushless Exciter:** An alternator-rectifier exciter employing rotating rectifiers with a direct connection to the synchronous machine field thus eliminating the need for field brushes, is typically shown in Figure 10.1. Brushless system may be used for small hydro generators up to about 10 MVA where large DC current Capacity is not required. Unless the field of the exciter is supplied from the PMG, a provision for field flashing the field of the rotating exciter for startup purposes is required.

**Static Excitation System:** The static excitation system is the most commonly used excitation system for hydro generators. It is typically shown in figure 10.1. Static excitation systems consist of two basic types depending upon the speed of generator field suppression required. The full inverting bridge type uses six thyristor connected in a three-phase full wave bridge arrangement. It allows reversed DC voltage to be applied to the generator filed to force faster field suppression, thereby quickly reducing the generator terminal overvoltage during a full load rejection. The semi-inverting type uses three thyristor and three diodes connected in a three-phase full wave bridge. The semi-inverting type drives the positive DC voltage to zero during a full load rejection, but does not allow negative filed forcing. Potential excitation source systems (from generator leads) are common for new generators and require slip ring for supplying power to the field winding. Field flashing equipments is necessary for potential source excitation systems which obtain power from machine terminals. In such cases, adequate self-cooling may be specified for startup without the need for auxiliary cooling power.

Digital controllers have proved to be more reliable and should be preferred.
Excitation system specifications should be carefully prepared with attention to requirement of power system to which the generator will be connected.

A comparison of the characteristics of two-excitation system is given in table 10.1.

### TABLE 10.1

<table>
<thead>
<tr>
<th>Features</th>
<th>Potential controlled rectifier</th>
<th>Brush less exciter (rotating rectifier exciter)</th>
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</thead>
<tbody>
<tr>
<td>High initial response</td>
<td>Yes</td>
<td>No (see note 1)</td>
</tr>
<tr>
<td>Sustained fault current support</td>
<td>No</td>
<td>No (see note 1)</td>
</tr>
<tr>
<td>Online rectifier maintenance possible</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Spare exciter user</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Field monitoring ground relaying</td>
<td>Yes</td>
<td>Yes, if Aux. Slip rings, or opto/EM/RF coupling is used</td>
</tr>
<tr>
<td>Rapid de-excitation</td>
<td>Yes, for half wave control, field breaker discharge resistor is required</td>
<td>No</td>
</tr>
<tr>
<td>General maintenance</td>
<td>Brushes and collectors</td>
<td>Exciter diode check</td>
</tr>
</tbody>
</table>

**Note 1:** may be possible with special provisions (refer IEEE std. 421.4-2004).

### 10.3 Steady State Excitation System Requirement

10.3.1 **Rated Field Current:** The direct current in the field winding of the generator when operating at rated voltage, current, power factor and speed.

10.3.2 **Exciter Rated Current:** Continuous current rating should be specified to equal or exceed the maximum required by the synchronous generator field under any allowed continuous operating condition including continuous overload rating.

10.3.3 **Exciter rated Voltage:** Exciter voltage rating should be sufficient to supply necessary continuous current to generator field at its maximum under rated load conditions.
10.3.4 **Rated Field Voltage**: The voltage required across the terminals of the field winding of the synchronous machine under rated continuous load conditions of the synchronous machine with its field winding at (1) 75°C for field windings designed to operate at rating with a temperature rise of 60°C or less; or (2) 100°C for field windings designed to operate at rating with a temperature rise greater than 60°C.

10.4 **Transient Requirements**

10.4.1 **Large Generator**

Transient requirement of excitation system of generator is determined from following considerations.

The stability of a hydro turbine generator set while connected to its power system is critically important. However, the designer must also consider the unit’s characteristics when operating alone, or in an isolated “island” much smaller than the normal power system.

One example of a unit operating is a main unit serving as the station service source in a plant that becomes separated from its power distribution system. The unit will have to accept motor starting loads, and other station service demands such as gate and valve operation, while maintaining a safe and stable output voltage and frequency. All this will be accomplished while operating at a fraction of its rated output.

When operating in an “island” the unit may be required to operate in parallel with other units while running at speed-no-load in order to provide enough capacity to pick up blocks of load without tripping off line. In this case, stable operation without the stabilizing effect of a very large system is critically important to restoring service, and putting the system back together.

10.4.2 **Small Generator**

For small units producing energy for a very large system, stability is not so critical since system voltage support will be beyond the small unit’s capability. Nonetheless, for its own safe operation, good voltage control is important. An extremely high response system is not necessary, but the system should respond rapidly enough to prevent dangerous voltage excursions.

10.4.3 **Ceiling Voltage**

The maximum direct voltage, which the excitation system is able to supply from its terminals under following conditions.

1. **No-load conditions**
2. The ceiling voltage under load with the excitation system-supplying ceiling current.
3. Under power system disturbance conditions: System studies are normally required for fixing excitation system parameters for large generators from stability considerations. For small generators under consideration producing energy for a very large system, stability is not so critical since system voltage support will be beyond the small unit’s capability. Nonetheless, for its own safe operation, good voltage control is important. An extremely high response system is not necessary, but the system should respond rapidly enough to prevent dangerous voltage changes.
4. For excitation systems employing a rotating exciter, the ceiling voltage is determined at rated speed.

The ceiling voltage of high initial response static excitation system is normally specified directly after system studies as the ceiling voltage is reached in less than 0.1 second. Ceiling voltage for potentials source (from generator bus) static excitation system with high initial response for the generator under considerations may be specified 1.5 – minimum recommended by IEEE Std.

For brushless system, it may be considered a function of the nominal response, which could be specified.
10.4.4 Excitation System Nominal Response

The excitation system nominal response is 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 (formerly called exciter response). The rate, if maintained constant, would develop the same voltage time area as obtained from the actual curve over the first half-second interval. This may be specified for brushless excitation system only.

Excitation systems response based on a ceiling voltage for high initial response static excitation system and for the brushless system is compared in Figure 10.3.

10.5 Power System Stabilizer

The excitation system stabilizer is used for fast acting high initial excitation system to stabilize oscillations that may occur between the machine and the systems by providing damping at power system frequency to control oscillation in the post fault period. IEEE std. 421.4-2004 requires power system stabilizer for grid connection at 66 kV and above so as to avoid oscillations in post fault period.

10.6 Under Excitation Limiter

Under excitation limiter should be provided on all small hydro generators which are normally equipped with VAR (power factor control) and disconnected from the system on system disturbances to feed local loads/station service systems.

10.7 Over Excitation Limiter

Over excitation limiter should be provided on all generators to avoid overheating of the generator field winding in case of faults.

10.8 Volts-per Hertz (V/Hz) Limiter

The Volts-per Hertz (V/Hz) Limiter may be provided to prevent overheating that may arise from excessive magnetic flux due to under frequency operation or overvoltage operation, or both.

Figure 10.3
10.9 VAR or PF Control System (Small Grid Connected Hydro Generator)

The generators in small hydro cannot follow the changes in the system voltage and therefore must be equipped with power factor control regulators. These Grid connected power units require a power factor regulator as well as field current regulator with automatic change over from voltage control mode to power factor control mode after synchronizing with the grid. Further minimum and maximum field exciter limit are also required.

10.10 Redundancy of Equipment

Manual control as a back up to excitation controller failure is generally adequate.

Power rectifier bridge redundancy is generally provided by providing parallel rectifiers of which at least one is redundant. Redundant cooler should also be provided to ensure adequate cooling. This may be provided for generators above 5 MVA.

10.11 Environmental Considerations

Environmental considerations to be specified include electrical transients, radio interference, temperature extremes, humidity, altitude, vibration, corrosive atmosphere etc.

Special requirement include tropicalization, seismic considerations etc.

10.12 Excitation Characteristics of Mega Hydro Generators for Stability

10.12.1 Performance Modeling

Generators with normal characteristics are specified and Excitation characteristics are specifically determined to meet special requirement as regard stability etc. as mentioned in Para 9.4.9.

System studies carried out to fix the excitation characteristics of the large power plant at Dehar are given below. It may be noted that these studies were carried out in 1970-71 by the consultants of Equipment suppliers M/s Bharat Heavy Electrical-English Electric Co. U. K. Highlight of the study as presented at Institution of engineers meeting are given here in under. Performance modeling for fixing the excitation characteristics should be carried out with the latest IEEE standard (IEEE std. 421.5-1992).

Detailed studies were carried out to fix up the static excitation response, the required ceiling voltage and overvoltage requirement etc. of 174 MVA Dehar Generators on Beas Satluj Link Project. Main parameters of Dehar generators intimated by the manufacturer are given in table 10.2.

<table>
<thead>
<tr>
<th>Table 10.2: Main Parameters of Dehar Generators</th>
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<tbody>
<tr>
<td>Short circuit ratio</td>
</tr>
<tr>
<td>Synchronous reactance, $X_d$ pu</td>
</tr>
<tr>
<td>Synchronous reactance, $X_q$ pu</td>
</tr>
<tr>
<td>Transient reactance, $X'_d$</td>
</tr>
<tr>
<td>Sub-transient reactance, $X''_d$</td>
</tr>
<tr>
<td>H pu</td>
</tr>
<tr>
<td>Transient time constant $T'_d$</td>
</tr>
<tr>
<td>Direct axis OC time constant, $T_{d0}$ Sec $T'_{d0}$</td>
</tr>
</tbody>
</table>

(i) All reactance values are in p u on MVA base.
(ii) H, the inertia constant of the machine, is in kW sec/kVA on 100 MVA
10.12.1 Introduction

In the first stage of the 1000 MW Dehar hydro electric power pant of the Beas-Sutlej Link, four generators of 165 MW each, 0.95 power factor were proposed to be installed. Two more units of equivalent capacity were to be added in the second stage. The power plant occupied a significant position in the Northern Regional Grid of India with which it is interconnected, in the first stage by 60 km long double circuit 220 kV line at Ganguwal and by a 280 km long single circuit 420 kV line at Panipat. A second 420 kV line was to be added along with the two second stage units.

420 kV was being introduced in the region for the first time. In the initial stages of development of EHV system, problems of stability are likely to be critical because of weak system, lower short circuit level, operation at leading power factor, and need for economy in providing transmission outlets and fixing the size and parameters of generating units.

In the early stage of design of Dehar power plant it was decided that generators with normal characteristics be specified and requirements of stability be achieved by optimizing parameters of other factors involved. Preliminary transient stability studies indicated that only marginal stability would be obtained. It was, therefore, decided that high speed static excitation equipment be used to improve stability margins.

Detailed studies were carried out to determine optimum characteristics of the static excitation equipment at Dehar power plant with the primary object of optimizing the static excitation system and included the determination of:

(i) Excitation system response ratio, to fix up required ceiling voltage (optimization for transient stability conditions).
(ii) Necessity or otherwise of auxiliary feedback signals for damping (optimization for dynamic stability).
(iii) Over voltage withstand requirements of the excitation system.

10.12.2 System Description

Figure 10.4 shows the main interconnected transmission system of 220 kV and above to which Dehar power plant will be connected. The power generation sources in the region comprise distinct groups. One group consist essentially of hydro electric power plants in the north comprising mainly of existing power plants of the Bhakra complex and those under various stages of construction at Dehar, Pong, Siul and Salal. A complex of thermal power plants around Delhi, that is, Badarpur, Indraprastha and faridabad, from the second group. Other important stations in the region are Bhatinda thermal and Rajasthan atomic power stations.

Fig 10.5 shows the proposed interconnection of Dehar power plant with the grid. Dehar 400 kV sending end step up substation has double bus arrangement.

At Panipat receiving end substation, present and future installations are shown in Figure 10.5.

10.12.3 General Considerations

• Stability Criteria

It was considered that the aim should be to design a system which is transiently stable for a permanent fault on the 400 kV line involving unsuccessful reclosure on to the fault and dynamically stable for all conditions when the 400 kV line is removed. It was further considered desirable that these aims should be met under 3-phase fault conditions. The probability of such faults occurring in practice, though small, was not considered small enough to be regarded as an acceptable risk.

• Generation Schedule

For the purpose of these studies it was considered that the most stringent requirements for the excitation system of Dehar generators will be obtained when 400 kV Dehar-Panipat line carries the
maximum power. As such the generation schedule for conditions of maximum hydro generation in the month of September was adopted.

- **Fault Clearance Time**

Taking into consideration the critical stability conditions, it was decided to adopt low values of fault clearance time. It has been shown that with modern industrial practice a fault clearance time in EHV system of 80 m sec (40 m sec for circuit breaker operation and 40 m sec for protection operation) is feasible. The same is being provided for Dehar EHV system. However, the studies were carried out with a total fault clearance time of 100 m sec.

For Dehar 400 kV system, the question of providing reclosing has yet not been decided. It was decided that the studies be carried out with reclosure time following fault clearance ranging from 0.3 sec to 0.5 sec.

- **Generator Disconnection**

It was further considered that in the first stage after the 400 kV line is removed, one of the two 165 MW generating units supplying the Dehar 400 kV bus may be switched out simultaneously with the line. This is a condition which could further aid stability.

![Figure 10.4: Dehar EHV System and interconnected northern regional grid single line diagram (Source: Paper by Author in Journal of Institution of Engineers 1977)](image-url)
Figure 10.5: Interconnection of Dehar Power Plant with Grid
(Source: Paper by Author in Journal of Institution of Engineers 1977)

Figure 10.6: Reduced System Used for Detailed Studies
(Source: Paper by Author in Journal of Institution of Engineers 1977)
10.12.4 System Representation for Stability Studies

No bus in the system could be considered infinite for any accurate study. For the purpose of detailed study it was decided to aim at a reduced system in which the Dehar machines were represented in full, and rest of the system was concentrated at essentially two bus bars—Ganguwal and Panipat giving a system with four machines groups—two at Dehar, one (equivalent) at Ganguwal and one (equivalent) at Panipat (Figure 10.6). In this way the identity of the most important elements of the system was fully preserved. These elements are the Dehar machine, transformers and the bus bars, 220 kV lines from Dehar to Ganguwal and 400 kV line from Dehar to Panipat, the bus bars at Ganguwal and Panipat. Reduction was carried out with a network reduction digital computer programme which yields values for all equivalent interconnections between preserved bus bars. Swing curves obtained for full system were used for comparison with similar swing curves obtained for the reduced system so as to establish the validity of reduced system.

10.12.5 Representation of Dehar Generators

The four identical first stage Dehar generators—two feeding 220 kV bus bars and two 400 kV bus bars—were considered in the groups, that is, one equivalent machine on 220 kV and two separate machines on 400 kV so as to study the effect of generator disconnection on stability. All the machines of Dehar were represented in the system studies by generalized two axes model which includes the more important damper winding effects. Main parameters of Dehar generators are given in table 10.1.

10.12.6 Representation of Excitation System

The static excitation system block diagram used in stability studies is shown in figure 10.7. Negative excitation is being adopted to cater for line charging requirements. Examination of available literature and experience of other power utilities indicated that two types of stabilizing feedback signals on the AVR could prove useful in maintaining stability and providing additional damping in the post fault period. These are derived respectively from rotor speed change and acceleration. Both these types were accordingly included in the representation for detailed studies as shown in block diagram of Figure 10.7.

10.12.7 Representation of Governor

The governor was represented in accordance with Figure 10.8. The pipe line effect of the turbine was represented by an additional transfer function block, between the guide vane action and mechanical torque signals.
10.12.8 Exciter Response Ratio

In a static AVR the response is defined essentially by the field voltage limits. The familiar half second definition of the excitation system response ratio for a static excitation system can be derived from ceiling voltage ratio in accordance with the IEE Committee Report as given in Appendix (current practice is as per Para 10.4.3 & 10.4.4).

10.12.9 Initial Choice of Field Voltage Limits

Transient stability studies with a constant voltage behind transient reactance representation carried out indicated that the aim set forth in stability criteria might not be realized in the severe case of unsuccessful reclosure. The case of a 3-phase fault at the Panipat end of the 400 kV line followed, however, by successful reclosure indicated significant deviation from normal frequency, though no loss of synchronism between machines occurred. Though these results had been obtained without representation of the excitation system and governor characteristics and without representation of damping, they suggested, however, that a high value of excitation system response would be required. Accordingly a high value of 1.48 of exciter ceiling ratio $r$ as defined in Appendix, was chosen. This corresponds to exciter response ratio of 1.83. This is based on the maximum capability of one thyristor leg. It was considered that increased ceiling over and above this is achievable by increasing the thyristors and thereby involving considerable increase in cost. Values on both sides of the ceiling were tried to obtain final values of AVR parameters so as to achieve the above aims to the maximum extent possible.
10.12.10 Transient Stability Studies With Detailed Machine Representation

A large number of transient stability studies were carried out by digital computer (i) to determine accurately the system behaviour under a number of different fault conditions, (ii) to fix values of excitation response ratio and field voltage limits, and (iii) to obtain an assessment of the effects of stabilizing signals of the kind described earlier applied to the Dehar excitation system.

The studies were of real time duration ranging between 4 and 14 sec to fully gauge the effects in the post-fault period. In all cases 3-phase faults cleared in 0.1 sec from both ends were considered. The studies may be grouped under three different headings in terms of their swing behaviour and damping characteristics, as follows:

No Auto Reclosure, Both 400 kV Machines in Circuit-Case (i).

Figure 10.9 shows the rotor angles and speed change with time up to 6.7 sec from fault inception for a typical case. This shows marked rise in speed of all machines over this period so that the apparently violent behaviour of rotor angles depicted is understandable. Examination of the figure reveals that there is no loss of synchronism of the machines relative to each other, the swing curves following each other consistently with a maximum angular separation of machines (actually Dehar 400 kV and Badarpur) of 74° occurring at about 0.5 sec.

Figure 10.9: Swing speed curves for Dehar 400 kV, Dehar 220 kV, Bhakra and Badarpur, 3 phase fault at Panipat end of 400 kV line cleared in 0.1 sec. no reclosure
(Source: Paper by Author in Journal of Institution of Engineers 1977)
Figure 10.10: Three phase fault at Dehar end of 400 kV line; Line cleared in 0.1 sec; Dead time reclosure 0.5 sec.
(Source: Paper by Author in Journal of Institution of Engineers 1977)

Figure 10.11: Three phase fault at Panipat end of 400 kV line; Line cleared and one Dehar 400 kV machine disconnected at 0.1 sec. Dead time reclosure 0.3 sec.
(Source: Paper by Author in Journal of Institution of Engineers 1977)
10.12.11 Auto Reclosure, Both Dehar 400 kV Machines in Circuit Throughout-case (ii)

Rotor angles and speed changes with time for a typical case are shown in Figure 10.10. Again large rotor angle fluctuations are indicated with all machines swinging essentially together, but by the end of the 8.8 sec covered by the run, all angles have almost settled to new values with the same separations as in the steady state. During the swing the maximum angular machine separation (which is again between dehar 400 kV and Badarpur) is 71°, occurring at 0.5 sec after fault inception. There is, therefore, no loss of synchronism between machines.

This case utilized a dead time to successful reclosure of 0.5 sec and involved a fault close-up to Dehar so that the results are a clear demonstration that with auto reclosure at the maximum dead time specified and both Dehar 400 kV machines in service throughout, there is no transient stability problem for successful reclosure.

10.12.12 Auto Reclosure, One Dehar 400 kV Machine Disconnected When Line is Cleared-Case (iii)

Under this condition one of the two units feeding the Dehar 400 kV bus bars was disconnected from the system at fault clearance time. Rotor angle for a typical case for a fault at Panipat end of 400 kV line is shown in Figure 10.11. This case is with a lower limit of static excitation ceiling voltage ratio, that is, 1.40 instead of 1.48 pu for case (ii) and 1.80 pu for case (i). This indicates that disconnection of generation may aid stability to a small degree.

10.12.13 Excitation Response Recommended

The results of large number of stability runs carried out by digital computer on the reduced equivalent network with different parameters of excitation system and network condition as described clearly indicate that the system is able to recover following a 3-phase fault near Dehar or Panipat on the 400 kV line and is quite adequate when the main gain is set to 400 and the maximum values for upper and lower field voltage limits in the normal (Positive field current) condition are used. These limits are indicated in Figure 10.12. There is no loss of synchronism in any condition investigated and the result suggested that a significant margin exists on response ratio. Nevertheless, there seems little point in choosing field voltage limits smaller in magnitude than the maximum design figures. The conclusion is, therefore, drawn that for positive field current, these are satisfactory and should be employed. The studies yield no information on the negative field current values.

10.12.14 Auxiliary Feedback Signals

An examination of the swing curves and speed against time curves of cases (i), (ii) and (iii) revealed that the machine continues to oscillate for a long time following three-phase fault on the Dehar-Panipat 400 kV line. The natural frequency of these oscillations is of the order of 1 cycle/sec. it, therefore, appeared desirable to employ additional damping of the excitation feedback signals of the type discussed earlier to ensure that the system returns to steady operation as quickly as possible.

10.12.15 Stabilization Feedback Signal and Transient Stability

The effect of families of such signals based on velocity feedback with varying values of gain and time constants was tried but such signals were found to be ineffective in providing damping. Another family of signals was found, however, to have significant effect in damping out the oscillations in the system. These gives relief to acceleration feedback only. It was found that a signal in the form of a positive feedback of per unit rotor acceleration through a lag function was effective. Per unit rotor acceleration is

\[ \frac{d}{dt} \left( \frac{\omega}{\omega_0} \right) \]

Where \( \omega \) and \( \omega_0 \) are respectively actual and 50 Hz rotor angular velocities. The gain (\( \mu_1 \)) of this function may lie between 3 and 7 and the time constant (\( \tau_1 \)) should be of the order of 20 m sec (as the delay in the appropriate firing circuits will be of this order). Damping is most effective with the higher values of gain while with \( \mu_1 = 1 \) there is little effect. The results with a gain of 5 (Figure 10.13) may be compared with
Figure 10.10 where no stabilizing signals were employed. The new steady state conditions in the network would be different from those existing before the inception of the fault. Therefore, the final steady state values would be different for the pre-fault conditions.

10.12.16 Stabilizing Feedback Signal and Dynamic Stability

It was necessary to check whether these feedback signals would also be suitable from the point of view of dynamic stability (small disturbance). Under small perturbation conditions, the improvement in damping is less significant with the values indicated above and would be better with a gain less than unity. On the other hand, the system is dynamically stable with the suggested values (and indeed without stabilizing feedback). Thus, since recovery from major disturbances is likely to be of great importance, it is seen that an optimum solution is affected using $\mu_1 = 5$ and $\tau_1 = 0.02$ sec.

As a final check of the stability calculations, one dynamic stability run was carried out using the transient stability programme but specifying a small disturbance in the network. This was specified as a step change of $-5\%$ in the voltage at Dehar 400 kV machines terminals. The curve of the above voltage against time (Figure 10.14) shows that damping in the system is quite satisfactory.

10.12.17 Stability Signal Recommended

It is concluded that $\mu_1$ should be continuously variable over a range to allow for adjustments to be made at site. The range should cover the value $1 \leq \mu_1 \leq 10$ but if wider limits can be readily achieved this could be an advantage. Similarly, $\tau_1$ should be adjustable. A value of 20 m sec was therefore recommended. It is portable that 0 is a better value but there will presumably be a lower limit in practice due to inherent delay in the firing circuit and this might be of the order of 25 m sec. If that is so then the recommended stabilizing control block amounts to no more than the gain ($\mu_1$) operating on $\frac{d}{dt} \left( \frac{\omega}{\omega_h} \right)$. Nevertheless, the results of dynamic stability suggest that if small perturbations are of greater importance, a time constant ($\tau_1$) of 1.5 sec is more appropriate. Thus it was decided that $\tau_1$ should be adjustable from zero to two sec.

Figure 10.12 shows the parameters of the AVR adopted for both transient and dynamic stability.

Adjustments depend to some degree on the means used to derive the actuating signal $\frac{d}{dt} \left( \frac{\omega}{\omega_h} \right)$. Two methods were considered. A direct method employing a toothed wheel device on the rotor shaft was expected to prove difficult. An indirect method considered was to derive a suitable signal from generator terminal power which is most readily measurable on the actual machine. It can be shown that within seconds before the governor has had time to alter input torque the machine electrical output torque varies linearly with acceleration $\frac{d}{dt} \left( \frac{\omega}{\omega_h} \right)$. 

![Figure 10.12: Arrangement for Dehar hydro generators Excitation system](image-url)
Figure 10.13: Speed of Dehar 400 kV Machine – as in figure 10.12.7 with acceleration feedback $\mu=5$, $\tau=0.02$ sec.

Figure 10.14: Dynamic stability machine terminals voltage versus time. A step charge of -5% terminal voltage of Dehar 400 kV machines

Figure 10.15: Load throw off at Panipat end of 400 kV line acceleration feedback ($\mu=5$, $\tau=0.02$ sec.). Present Dehar machine terminal and field voltages, and Panipat end voltage versus time  
(Source: Paper by Author in Journal of Institution of Engineers 1977)

Actual adjustment further depends upon studies under various operating conditions and network connections.
10.12.18 Overvoltage Withstand Requirement

Sudden load throw-off at the receiving end of a long transmission EHV line causes the generator or the group of generators at the receiving end to enter almost instantaneously under excited conditions in which case very high over voltages may occur at machine terminals as well as at the remote end of the line. Over voltages are due to the sudden replacement at the machine terminals of normal load by a highly capacitive load demanding leading MVARs. The problem is most sever when a single line connects an isolated source of generation to a load centre some distance away. It was considered that under certain circumstances the 400/220 kV interlinking transformer at Dehar may be out of service and the complete output of Dehar machines will be fed to Delhi area through the 400 kV line and the conditions described earlier will prevail. Therefore, to compute the maximum dynamic over voltages the system studies consisted simply of Dehar generators supplying the normal maximum loads. The excitation system will have to withstand the over voltages that are likely to occur.

RMS voltage at the terminals of the machines feeding the Dehar 400 kV bus bars may rise by 75% almost instantaneously when the equivalent of one machine (150 MW) is feeding on to these bars. This rise is accompanied by rise of 158% and 184% at the sending and the receiving ends of the line. If two machines are feeding the 400 kV bus bars, these figures are approximately halved. Effect of feedback signals on over voltages as studied is shown in figure 10.15. The curves indicate that the effect of the stabilizing signal (µ₁ = 5) is to cause voltage to continue to rise for about 1.2 sec following load rejection and only then the voltage starts decreasing. Without the stabilizing signals voltage decrease after initial almost instantaneous voltage rise. Accordingly it was decided to trip the stabilizing feedback signal upon loss of load.

These high values of over voltages can be obviated by the use of reactors and it has been considered that in the worst case of overvoltage this value should not exceed 1.5. Maximum overvoltage withstand requirement of about 1.7 was therefore specified for a period of 3 sec for Dehar excitation system.

10.12.19 Conclusion

Static excitation system (Figure 10.12) with the values of response as given in Table 10.3 was found to be economical and adequate.

Stabilizing feedback signals are necessary to achieve damping of system transient oscillation if a fast acting static excitation system is adopted. Signals derived from rotor acceleration were particularly useful at Dehar. This signal could be derived from machine terminal power.

| Upper limit of field voltage (V₁ Max.) | 480 | 326 |
| Lower limit of field voltage (V₁ Max.) | 326 | 408 |
| Full load normal field voltage (E₁FD) | 275 | 275 |
| Forward gain (K₁) | 400 | - |
| Response ratio (Appendix 2) | 1.38 | - |

The feedback signal should have adjustable parameters with the gain continuously variable over the range $1 \leq \mu_1 \leq 10$ and the time delay to be adjustable from zero to two sec. Studies on a continuous basis are recommended for selecting optimum setting for the gain and time constant depending upon changing network conditions and generation.

Arrangements are required to be made to trip stabilizing circuit upon load rejection so as to prevent higher overvoltage.

Maximum power frequency overvoltage withstand requirement of 1.7 for a period of 3 sec. having been prescribed, the overvoltage are required to be suitably controlled to values bellows this limit.
10.13 Examples

1. Static excitation system – Block diagram for 9 MW, 11kV, 0.9 PF is given in figure 10.16.
2. Brush less excitation system for 1.5 MW Pacha project in Arunachal Pradesh (grid connected) is at figure 10.17.
Appendix

Excitation System Definition and Characteristics

Definitions

Ceiling voltage ratio \( r = \frac{V_{R_{\text{Max.}}}}{V_L} \)  

Where \( V_{R_{\text{Max.}}} \) (Figure 10.7) is the upper limit of field voltage of the machine and \( V_{FL} \) the value of field (EFD) which gives rated terminal voltage under normal full load conditions. \( V_{R_{\text{Min.}}} \) (Figure 10.7) where used in this paper in pu terms are defined as follows:

\[
\frac{V_{R_{\text{Max.}}}}{V_{R_{\text{Min.}}}} \; \text{(in pu)} = \frac{V_{\text{so}} / V_{R_{\text{Max.}}}}{V_{io}} \; \text{(in V)}
\]

Where \( V_{\text{so}} \) is the value of field voltage (EFD), which gives rated terminal voltage with the machine on open circuit.

Excitation Response Ratio

Figure A-1 shows the response of the static exciter, then where the response ratio \( r' \) is given by the slope of the line ab and the areas abca and defc are made equal. \( \tau \) is a small delay in the thyristor firing circuits.

\[
r' = (4 - 8 \tau) \left( \frac{V_{R_{\text{Max.}}}}{V_{FL}} - 1 \right)
\]

or, substituting from equation (1)

\[
r' = (4 - 8 \tau) (r - 1)
\]

The two quantities \( r \) and \( r' \) are thus quite different in concept. In the present case a numerical comparison for maximum field voltage limits (Figure 10.7) is as follows:

\( V_{R_{\text{Max.}}} = 408 \text{ V} \) and \( V_{FL} = 275 \text{ V} \)

Therefore, \( r = 1.48 \)

From equation (2), taking \( \tau = 0.025 \text{ sec.} \)

Exciter response ratio \( r' = 1.83 \)
References

A. Standards and Codes (Latest)

- IEEE std. 421.1-1986, IEEE standard definitions for excitation systems for synchronous machines
- IEEE std. 421.2™-1990, IEEE Guide for identification, testing, and evaluation of the dynamic performance of excitation control system
- IEEE std. 421.5™-1992, IEEE recommended practice for excitation system models for power system stability studies

B. Other references

- U.S. Army Corps of Engineer – EM 11102-3000 – June 30,194 – Hydro electric power plants electrical design