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Evolution and Development of Excitation Control

1.1 Overview

In the modern power system, improving and maintaining the stability of synchronous generator operation is fundamental to the safe and economic operation of the power system. Of the numerous measures to improve the stable operation of synchronous generators, the use of modern control theory for improved excitation control is recognized as an economic and effective way.

Since the 1950s, with the passage of time, significant progress has been made both in control theory and in the development and application of electronic devices, further accelerating the development of the excitation control technology.

This chapter briefly describes the evolution of excitation control in different historical periods over the past half century, and develops useful conclusions from the main principles recognized from industry practice rather than from derivations based on mathematical logic.

1.2 Evolution of Excitation Control

In the early 1950s, the main function of an automatic voltage regulator (AVR) was to maintain the generator voltage at a given value, and most voltage regulators were mechanical. Following that, electronic and electromagnet types were introduced.

In the late 1950s, with the increase in the size of the power system and the growth in the unit capacity of generators, the function of AVRs was no longer limited to maintaining the generator voltage constant; they were designed to improve the static and dynamic stability of generators for improved stability of the power system. This marked a fundamental shift in the functional requirements of exciter regulators.

In the 1950s, there were different opinions about the role of forced excitation. There was a view that in the event of a system fault the role of excitation should be limited to preventing generator stator current overload. However, Soviet scholars concluded through experiments and practice that the use of forced excitation could accelerate voltage recovery after the removal of the system fault, and could shorten the time of stator current overload, which would be extremely favorable for shortening the recovery time of system voltage and for maintaining system stability after the fault.

Since the 1950s, great progress has been made in excitation control. In a nutshell, the evolution of excitation control has undergone several stages, including proportional control for single variable input and output, multivariable feedback control for linear multivariable input and output, and nonlinear multivariable control supported by control theory; these are separately described below.

1.2.1 Single Variable Control Based on Classical Control Theory

In the early 1950s, with the development of power and electronic technology, the power system continued to impose new requirements on the control function of the generator excitation system, mainly reflected in
the shift of the functional requirement on automatic excitation regulators from maintaining constant voltage at the generator side to increasing the steady-state stability limit of generator operation [1]. In this historical period, generators usually used DC exciter excitation, the regulation of excitation was usually effected on the field winding side of the DC exciter, and the regulation of generator excitation could only be enabled through the exciter power element with considerable inertia, namely, a slow excitation control system. During this period, in terms of excitation control, the following types of excitation regulation were usually used:

1. Proportional excitation regulation based on generator terminal voltage deviation.
2. Duplex excitation compensation regulation based on the generator stator current as a disturbance variable.
3. Phase compensation excitation regulation based on signals such as the generator terminal voltage and stator current and power factor angle. As the DC exciter was the main mode at the time, the excitation regulator was composed of magnetic elements and was virtually able to meet the requirements of the operation mode.

In this period, Soviet researchers made many important discoveries in research on power system stability. For example, in the 1950s, C. A. Lebedjew and M. M. Botvinick first proposed the concept of a synchronous generator operating in the artificial stable zone in their research on power system stability. They pointed out that, as long as the automatic excitation regulator exhibits inert-zone-free functional performance, the generator stable operation zone can be extended to the rotor power angle $\delta > 90^\circ$ zone even under the law of simple control based on generator voltage deviation negative feedback. Given the generator operation power angle limit $\delta = 90^\circ$ in the absence of excitation regulation, the power angle $\delta > 90^\circ$ extended operation zone was called the “artificial stable zone.”

In terms of the excitation control law, most excitation regulators of the period adopted proportional regulation based on generator voltage deviation negative feedback or proportional–integral–differential (PID) regulation based on generator voltage deviation.

### 1.2.1.1 Proportional Control

The expression for the transfer function of proportional control is

$$\frac{U}{\Delta U_i} = K_P$$

$$\Delta U_i = U_{\text{ref}} - U_i(t)$$

where

- $U$ – output;
- $\Delta U_i$ – input;
- $K_P$ – proportional regulation factor;
- $U_{\text{ref}}$ – reference voltage;
- $U_i(t)$ – average of real-time three-phase effective values of generator terminal voltage.

The expression for the transfer function of PID regulation based on generator voltage deviation is

$$\frac{U}{\Delta U_i} = (K_P + K_I\tau_s) \frac{1}{1 + K_D\tau_s}$$

where

- $K_P, K_I, K_D$ – proportional, integral, and differential regulation factors, respectively.

The block diagrams of the transfer functions of the closed-loop system corresponding to Eqs. (1.1) and (1.2) are shown in Figures 1.1 and 1.2, respectively.
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\[ U_{\text{ref}} \rightarrow \Delta U_{i} \rightarrow K_{P} \rightarrow U \rightarrow \text{Controlled object} \rightarrow U_{i}(t) \]

Figure 1.1 Block diagram of transfer function of univariate proportional control.

\[ U_{\text{ref}} \rightarrow \Delta U_{i} \rightarrow \frac{K_{P} + K_{D}s}{1 + K_{I}s} \rightarrow U \rightarrow \text{Controlled object} \rightarrow U_{i}(t) \]

Figure 1.2 Block diagram of transfer function of PID control.

\[ X_{R}(s) \rightarrow E(s) \rightarrow K_{P} \rightarrow G(s) \rightarrow Y(s) \]

\[ H(s) \rightarrow Y(s) \rightarrow H(s) \rightarrow H(s) \]

Figure 1.3 SISO closed-loop regulation system.

The physical concept of PID control shown in Figure 1.2 is hereby further elaborated. As can be seen from Eq. (1.2), the transfer function of PID control is composed of the sum of the proportional element \( K_{P} \) and the differential element \( K_{D}s \) in series with the inertia element \( \frac{1}{1 + K_{I}s} \). If the time constant of the inertia element is large enough, or \( K_{I}s \gg 1 \), the value 1 can be ignored. Here, the inertia element is similar to an integral element \( \frac{1}{K_{I}s} \). Thus, the control mode can be called the PID control system based on generator voltage deviation.

The performance characteristics of the single-variable input and output (SISO) PID control system shown in Figure 1.3 are discussed below.

In Figure 1.3, \( X_{R}(s) \), \( Y(s) \), and \( E(s) \) respectively represent the Laplace transform function of the input \( X_{R}(t) \), the output \( y(t) \), and the regulation error \( e(t) \). \( K_{P} \) and \( G(s) \) respectively represent the transfer function of the forward paths. \( H(s) \) represents the transfer function of the feedback channel.

As can be seen from the classical regulation principle, for the closed-loop control system shown in Figure 1.3, as the gain \( K_{P} \) increases, the dominant root of the closed-loop system characteristic equation will move to the right of the complex plane. When the gain \( K_{P} \) exceeds its critical value \( K_{C} \), a pair of closed-loop system characteristic roots will appear on the right half of the complex plane. At this point, the closed-loop system will be unstable, and the dynamic response of the system will show an increased oscillation. Therefore, the gain \( K_{P} \) of the proportional regulation system will be limited to the range of \( K_{P} < K_{C} \) to ensure system stability. At this point, if only generator voltage deviation control is adopted, for a long-distance transmission system, the weaker the electrical connection between the generator and the system, the smaller the allowable critical gain \( K_{C} \) will be, usually 5–20.

However, requirements for excitation regulation performance involve not only stability but also accuracy. For the closed-loop system shown in Figure 1.3, its static error is

\[ \varepsilon(\infty) = \lim_{t \to \infty} e(t) \]

According to the standard applicable in China, the static error \( \varepsilon(\infty) \) of generator terminal voltage regulation shall not be greater than 0.5%.
For the system shown in Figure 1.3, its closed-loop transfer function is
\[
Y(s) = \frac{K_p G(s)}{1 + K_p H(s)G(s)}
\]  (1.3)

The transfer function between the static error \( \varepsilon(t) \) and the input \( X_R(t) \) is
\[
E(s) = \frac{X_R(s) - H(s)Y(s)}{X_R(s)} = \frac{1}{1 + K_p H(s)G(s)}
\]  (1.4)

With Eq. (1.4), the following can be obtained:
\[
E(s) = \frac{1}{1 + K_p H(s)G(s)} X_R(s)
\]  (1.5)

It is assumed that the input \( X_R(t) \) is a unit step function and its Lagrangian transform function is \( X_R(s) = \frac{1}{s} \).

At this point, for the closed-loop regulation system shown in Figure 1.3, the static error Laplace transform expression under the action of the unit step function is
\[
E(s) = \frac{1}{1 + K_p H(s)G(s)} \times \frac{1}{s}
\]  (1.6)

As can be seen from the final value theorem in the regulation principle, the steady-state value of the static error is
\[
e(\infty) = \lim_{t \to \infty} e(t) = \lim_{s \to 0} sE(s)
\]

If Eq. (1.6) is substituted into the above equation, \( H(s)G(s) \) can be written in the polynomial form of \( s \):
\[
e(\infty) \lim_{s \to 0} \frac{1}{1 + K_p \frac{b_m}{a_m} + \cdots + b_1 a_1 + 1} = \frac{1}{1 + K_p}
\]  (1.7)

As can be seen from Eq. (1.7), for a SISO closed-loop regulation system, its static error \( e(\infty) \) approximates the reciprocal of the closed-loop gain \( K_p \) under the action of the unit step function, because \( K_p \gg 1 \) in the general case. The following can be obtained in turn:
\[
e(\infty) \approx \frac{1}{K_p}
\]

It can be concluded from the above equation that the open-loop gain \( K_p \) of the excitation system should be no smaller than 200, so that the static error of the generator voltage can be kept less than 0.5% under the action of the unit step function. However, in proportional excitation control, an excessive open-loop gain may cause unstable operation of the excitation system. Therefore, both requirements should be taken into account in selection of the gain \( K_p \).

1.2.1.2 PID Control

When consideration is given to both the static error and the transient stability of the system, the structure of the transfer function of the excitation regulator can be changed to divide the gain of the excitation regulator into two parts. One part is the delay-free transient gain \( K_D \), and the other part is the delay steady-state gain \( K_s \). The block diagram of the corresponding excitation regulator transfer function is shown in Figure 1.4a. Figure 1.4b is an equivalent simplified block diagram.

If the unit step function \( E(s) = \frac{1}{s} \) is added to the system input side at \( t = 0^+ \), as can be seen from the initial value theorem, the transient output of the control side is
\[
u(0^+) = \lim_{t \to 0^+} u(t) = \lim_{s \to \infty} sU(s) = \lim_{s \to \infty} \left[ \frac{(K_D + K_p) + K_D T_s}{1 + T_s} \times \frac{1}{s} \right]
\]
\[
= \lim_{s \to \infty} \frac{(K_D + K_p) + K_D T_s}{1 + T_s} = K_D
\]  (1.8)
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\[ E(s) = \frac{U_{\text{ref}}}{s} \]

\[ U(s) = \frac{E(s)}{s} \]

\[ U_{\text{ref}} = \frac{1}{s} \]

\[ U(s) = \frac{(K_D + K_S + K_D T_s)}{1 + T_s} \]

\[ (a) \]

Figure 1.4 Block diagrams of static and transient gain transfer functions of excitation regulator: (a) transfer function, (b) equivalent transfer function.

Meanwhile, as can be seen from the final value theorem, the control output of the unit step output \( E(s) = \frac{1}{s} \) in the steady state is

\[ u(\infty) = \lim_{t \to \infty} u(t) = \lim_{s \to 0} sU(s) = \lim_{s \to 0} \left[ \frac{s (K_D + K_P) + K_D T_s}{1 + T_s} \times \frac{1}{s} \right] = K_D + K_P \]  

(1.9)

From Eq. (1.9), if the gain of the excitation regulator is divided into two parts (steady-state and transient), its transient gain is equivalent to the proportional regulation whose gain is \( K_D \) at the beginning of the transition process, and its steady-state gain is equivalent to the proportional regulation whose gain is \( K_D + K_S \).

The transient gain reduction can be used for the coordination between precision and stability regulation. That is the basic role of PID excitation regulators.

It is emphasized that since the 1950s the control law of most univariate excitation regulators has been based on analysis of the performance of the excitation system in the \( s \) frequency domain under the classical adjustment principle. Under the condition of linearized small deviation, the excitation control law can be regulated on the basis of generator voltage deviation or the PID rule. On the basis of the frequency characteristics of the excitation system transfer function, the Bode plot is given. In turn, the excitation system’s amplitude-frequency and phase frequency margin are obtained, and the appropriate corrective actions are selected.

Determining the no-load stability of the generator excitation system with the excitation system’s open-loop characteristics and determining the parameters of the power system stabilizer (PSS) with the excitation system’s closed-loop characteristics is the basic analysis method of the classical regulation principle applied so far.

It should be noted that, in the 1950s, with the application of high initial rapid ion excitation systems, the so-called dynamic stability problem appeared. When the system restores the original mode of operation after the disturbance of a major fault, a fast excitation system is helpful for the rotor swing braking in the rotor’s swing period. However, in the subsequent dynamic stabilization process, the fast excitation system may extend the rotor swing time, increase power angle oscillation, and even cause oscillation and loss of synchronization in special cases.

In this regard, Soviet researchers realized that to suppress such power oscillation and loss of synchronization, a generator-power-related additional quantity should be added to the control law of the excitation regulator to improve the transient stability of the generator in operation.

In the 1950s, the so-called “strong excitation regulator” developed by the Soviet Union was multi-parameter regulator based on the above basic idea. However, since the measurement of the generator rotor power angle was difficult, the power angle \( \delta \) signal was replaced by a value approximately equal to the action angle \( \delta \).

The signals in the strong excitation regulator included such parameters as generator voltage deviation, voltage derivative, frequency deviation, frequency derivative, and generator rotor current. Under the condition of small deviation disturbance, a strong excitation regulator could make the system stability power limit 10%–12% higher than that in the case of a proportional excitation regulator. As can be seen, although the strong excitation regulator applied classical regulation theory to parameter setting, it adopted the so-called
D domain division method. The relation between two parameters could be studied on an $s$ frequency plane, so that the common stability domain of each parameter such as $\Delta U$, $\Delta f$, and $f'$ could be determined. Thus, a multi-parameter setting could be realized. But that method was too complicated. When any system structure parameters changed, its modification was complex. Therefore, the method was not applied internationally. The strong excitation regulator primarily took the voltage deviation $\Delta U$ and the differential $U'$ as regulation signals and introduced the rotor voltage soft negative feedback $\Delta U'$ to reduce the transient gain and maintain a high steady-state gain. In addition, it took the frequency deviation $\Delta f$ and the differential $f'$ as power damping signals. So, in essence, the Soviet strong excitation regulator was the equivalent of a PID excitation regulator with the stable power signal $\Delta f$.

Subsequently, in the mid-1960s, with the wide application of fast excitation systems, low-frequency power oscillation and oscillation and loss of synchronization in the process of dynamic stability restoration after major disturbance faults were frequently seen on some large power transmission systems. In this regard, American researcher F. D. Demello and C. Concordia probed the causes for deterioration of dynamic stability under the condition of a fast excitation system and specific power system parameters, starting with an analysis of the mechanism of low-frequency oscillation. Using the mathematical model based on the linearized small deviation theory proposed by R. A. Phillips and W. G. Ephron, they concluded that deterioration of the positive damping torque of a single generator on an infinite system was primarily caused by the hysteresis characteristics of the excitation system and the generator excitation winding.

Under normal operating conditions, the generator closed-loop excitation regulation system with the generator terminal voltage $\Delta U_1$ as negative feedback is stable. As can be seen from Figure 1.5, there is a certain phase lag between the two phases $\Delta U_i$ and $\Delta E'_q$ (transverse axis transient electromotive force deviation), and the lagged phase is related to the frequency. Therefore, when the rotor power angle oscillates, $\Delta E'_q$ lags behind $\Delta U_i$. That is, the phase of the excitation current that the excitation system provides lags behind the rotor power angle. At a certain frequency, when the lag angle reaches $180^\circ$, the original negative feedback will become positive feedback. The change in the excitation current will in turn lead to oscillation of the rotor power angle. That is, the so-called “negative damping” will be generated.

If an excitation system adopts PID control, excitation regulation with the generator voltage deviation signal is helpful in improving the dynamic and static stability of the generator voltage. Meanwhile, the leading phase output provided for the excitation system compensates to some extent for the lag phase of the excitation current and the negative damping torque. But PID regulation is primarily designed for the voltage deviation signal; the leading phase frequency it generates is not necessarily the same as the low-frequency oscillation frequency. That is, it may not necessarily meet the need for the phase required for negative damping compensation. Besides, in order to control the voltage in the PID regulation system, the voltage deviation should be continuously regulated. Thus, it is impossible to distinguish between positive and negative damping torque.

![Figure 1.5](image-url)
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and difficult to simultaneously regulate the generator voltage and ensure a positive damping torque. So, the role of PID regulation in suppressing the low-frequency oscillation of the system is limited.

The PSS based on the theory by F. D. Demello and C. Concordia is designed to just suppress the low-frequency oscillation and improve the power system dynamic stability. At present, it has been widely used in excitation systems.

In the PSS excitation control mode described above, the excitation control law retains PID control based on generator voltage deviation and adds a power-related signal, for example, generator power, frequency, speed, or the rotor power angle.

Since PSS parameter selection is usually determined by specific operating conditions, when the system parameters change, the effective suppression frequency band set by the PSS will deviate from the actual system oscillation frequency band, and the control effect will significantly decrease. Therefore, in recent years, multi-parameter and adaptive PSSs have emerged to address a wider range of application when the power system parameters change.

A promoted new technology should be perfected and improved in practice. PSS applications once had some negative effects. For example, the PSSs developed by the US companies Westinghouse and GE take the generator speed $\omega$ as the input signal. In the case of torsional vibration of the unit, the inherent torsional vibration frequency of a certain order in the generator shaft system will be amplified by the PSS gain component that takes the speed $\omega$ as the signal. This further stimulates resonance of the torsional vibration, eventually damaging the generator shaft system. In December 1970 and October 1971, respectively, Mohave Power Station located in Nevada encountered two torsional vibration resonance faults, which caused breakage of the exciter coupled to the generator shaft. On another large steam turbine manufactured by Westinghouse, torsional vibration resonance as a result of the PSS's amplification of the shaft system torsional vibration signal caused breakage of the low-pressure cylinder blades. In 1987, a GE-made 800 MW steam turbine installed at Taiwan Ma’anshan Power Station also encountered breakage of the low-pressure cylinder blades caused by torsional vibration resonance. In view of that, Westinghouse and GE added the trap component to their PSSs that take the speed $\omega$ as the signal. Based on the difference in the order of the inherent torsional vibration frequency of the generator shaft system, when the set torsional vibration frequency order appears, the trap will prevent the speed signal from passing it through, thus avoiding intensification of the torsional vibration.

Any other PSS line that takes a physical variable other than the speed $\Delta \omega$, for example, the generator terminal power $P$ or the rotor power angle $\delta$, as input signal does not need to add a trap.

1.2.2 Linear Multivariate Control Based on Modern Control Theory

1.2.2.1 Linear Optimal Control Principle

Since P. E. Kalman laid the foundation for the modern control theory in 1960, some well-known researchers have put forward the application of modern control theory in power system research.

Since a power system is a complex nonlinear multivariate system, there are many restrictions on analysis of the system with classical linear univariate control theory. Linear multivariate modern control theory based on the state space description method can address these restrictions more easily.

In 1970, Canadian Dr. Yu Yaonan conducted the first research on the linear multivariate optimal control law for power systems with modern control theory.

In China, a group of researchers on power system stability represented by Professor Lu Qiang from Tsinghua University achieved much success in applying linear multivariate optimal control theory to synchronous generator excitation system control.

Optimal control theory is a developed and more widely applied key branch of modern control theory. Its goal is to select the optimal control law that will make performance of the control system under certain conditions optimal.

The state equation of a time-invariant system can generally be expressed as

$$\dot{X} = AX + BU$$  \hspace{1cm} (1.10)
Where,

\( X \) – \( n \)-dimensional phasor;
\( U \) – \( r \)-dimensional state control phasor;
\( A \) – state coefficient matrix;
\( B \) – control coefficient matrix.

The eigenvalues of the system state equation are determined by the matrix \( A \). To change its characteristics, the feedback of the state phasor can be introduced to form a closed-loop system, as shown in Figure 1.6.

The state phasor of the feedback system is

\[
U = V - KX
\]  
(1.11)

where

\( K \) – state feedback gain matrix.

If Eq. (1.11) is substituted into Eq. (1.10), the following is obtained:

\[
\dot{X} = AX + B(V - KX)
\]
\[
= (A - BK)X + BV
\]  
(1.12)

At this point, the eigenvalues of the closed-loop system will be determined by the matrix \( A - BK \). Therefore, the optimal control law is in essence to select a \( K \) value and make the performance of the controlled system optimal under the given control rule under certain conditions.

1.2.2.2 Quadratic Performance Index

System performance indicators are usually determined on the basis of the project’s actual requirements. Different performance indicators lead to different control laws.

The SISO control system shown in Figure 1.7 is taken as an example.

When the unit step function is entered in the system shown in Figure 1.7, the output is that shown in Figure 1.8b.
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Figure 1.8 Error response under the action of unit step function: (a) unit step input, (b) ideal dynamic response and actual dynamic response, (c) error response, (d) absolute value of error response, (e) square of error response.

It is assumed that $y(t)$ is the actual response of the system, and $\xi(t)$ is the expected dynamic response. The optimal control performance indicators minimize the deviation $y(t) - \xi(t)$. There are three common forms of performance indicators represented by mathematical expressions:

$$J = \xi(t) - y(t) = J_{\text{min}}$$  \hspace{1cm} (1.13)

$$J = \int_0^\infty [\xi(t) - y(t)] \, dt = J_{\text{min}}$$  \hspace{1cm} (1.14)

$$J = \int_0^\infty [\xi(t) - y(t)]^2 \, dt = J_{\text{min}}$$  \hspace{1cm} (1.15)

Figures 1.8c–e show the graphs of the deviation value $\xi(t) - y(t)$, the deviation integral value, and the deviation quadratic integral value.

Equation (1.14) shows that the definite integral of the absolute value of the deviation of the actual response $|y(t)|$ from the expected response $|\xi(t)|$ is minimal. $J$ is a generic function that changes with the function $|y(t)|$. Equation (1.15) shows that the expected value for the definite integral value of $[\xi(t) - y(t)]^2$ is minimal. In addition, Eq. (1.15) also shows equal treatment of positive and negative deviations and greater emphasis on large deviations.

Since Eq. (1.15) obtains the definite integral of the square of the deviation in the $0 \sim \infty$ time interval, it is called the quadratic performance index.

For a multivariate system, the above concept can also be used to determine its performance indicators.

If the actual state phasor is expressed as $X(t)$ and the expected state phasor is expressed as $\hat{X}(t)$, the quadratic performance index that requires the state phasor deviation to be minimal is

$$J = \int_0^\infty [\hat{X}(t) - X(t)]^T [\hat{X}(t) - X(t)] \, dt = J_{\text{min}}$$  \hspace{1cm} (1.16)
However, when the above-mentioned optimal control performance criterion is met, it may be hard to achieve because of the need for excessively controlled variable. Therefore, the control phasor $U(t)$ is also limited. It is expressed as follows:

$$J = \int_0^\infty \left\{ [\hat{X}(t) - X(t)]^T Q[\hat{X}(t) - X(t)] + U^T(t)RU(t) \right\} \, dt = J_{\text{min}}$$  \hspace{1cm} (1.17)$$

where

$Q, R$ – weight matrix corresponding to the state phasor and the control phasor, respectively.

Equation (1.17) expresses the degree of emphasis on the phase phasor deviation and the control phasor amplitude, indicating that the sum of the phasors accumulated over the whole control process and the generalized control energy weights consumed will be minimal.

In engineering, in order to facilitate analysis, the balance of the control system is often placed at the origin of the state space. When the system is disturbed, the state phasor will deviate from the origin. If the system is asymptotically stable, the state phasor will eventually tend to the origin. Under such conditions, the expected state phasor is just the origin, that is, $\hat{X}(t) = 0$. At this point, Eq. (1.17) can be rewritten as

$$J = \frac{1}{2} \int_0^\infty \left[ X^T(t)QX(t) + U^T(t)RU(t) \right] \, dt = J_{\text{min}}$$  \hspace{1cm} (1.18)$$

Equation (1.18) is just the quadratic performance index of the optimal control of the linear time-invariant system.

1.2.2.3 Linear Optimal Controller

In order to improve the static and dynamic stability of generators under small interference conditions, China's scientists once applied linear multivariate optimal control theory to the control of excitation systems. The linear optimal excitation control (LOEC) regulator developed by Tsinghua University was once applied at some large hydropower stations.

The purpose of designing a linear optimal control system is to identify the optimal control phasor in all possible control phasors.

It is assumed that a controllable linear time-invariant system is expressed as

$$\dot{X} = AX + BU$$  \hspace{1cm} (1.19)$$

where

$X$ – $n$-dimensional state phasor;

$U$ – $r$-dimensional state control phasor;

$A, B$ – $n \times n$ and $n \times r$ constant matrix, respectively.

If the optimal control system is designed on the basis of the quadratic performance index shown in Eq. (1.18), it can be proved that the optimal control law exists and is unique. It is expressed as follows:

$$U = -R^{-1}B^T PX = -KX$$  \hspace{1cm} (1.20)$$

where

$P$ – $n \times n$-dimensional symmetric constant matrix, which is the positive definite solution of the Riccati algebraic matrix.

In order to minimize the generalized function $J$ of Eq. (1.18), the necessary condition should satisfy the Riccati algebraic matrix equation, as follows:

$$-PA - A^T P + PBR^{-1}B^T P - Q = 0$$  \hspace{1cm} (1.21)$
1.3 Linear Multivariable Total Controller

In recent years, some countries have made rapid progress in the development of linear multivariable optimal controllers based on modern control theory. For example, in the late 1980s, Japan’s Fuji Electric developed a multivariable generator total controller, called Total Automatic Generation Controller (TAGEC).

1.3.1 Overview of TAGEC [2]

The total controller developed by Fuji Electric was designed to integrate a generator’s excitation and speed control systems in one unit. In the traditional control mode, the reactive power of the generator is controlled by the excitation regulator and the active power by the governor. Because of the large inertia time constant of the mechanical governor, when the active power oscillates, generator excitation control is usually adopted. For example, the oscillation is suppressed with the PSS’s additional power signal, while the speed governing system fails to govern the speed in a timely manner.

In recent years, due to the digitization of control systems, their inertia time constant has been greatly reduced. This provides the possibility of directly suppressing the oscillation of active power with the speed governing system.

TAGEC takes the minimum linear quadratic integral LQI deviation in modern control theory as the performance index. Conventional univariate excitation regulators usually take the generator voltage deviation $\Delta U$ as the feedback control variable, while governors take the speed deviation $\Delta \omega$ as the control variable. The two feedback deviations $\Delta U$ and $\Delta \omega$ act independently.

In TAGEC, the feedback variables include the generator’s state variable $U$, power $P_e$, current $I$, magnetic field flux $\Phi_h$, speed $\omega$, and power angle $\delta$ as well as the prime mover’s state variable servomotor opening $P_m$ and mechanical torque $T_m$. In addition, the power-system-related state variables are taken as feedback variables.

The schematic diagram of the TAGEC control system is shown in Figure 1.10.
The main characteristics of the system are as follows:

1. It is a multivariable control system based on modern control theory.
2. It is capable of total control of excitation and the governor.
3. It is able to calculate the internal state of the generator and the gain value adapted to the operation in advance in case of any great change in the operating state.
4. It has a regulating function for hydropower stations that is capable of considering the dynamic characteristics of hydraulic systems.
5. It is able to control judgment and processing of start, stop, and load shedding programs.
6. It has the fail-safe function.
7. It is able to record generator state changes in transient processes such as system faults.

With the above functions, it can automatically compensate for negative damping, improve the system dynamic stability, and inhibit long-time power swing.

In addition, if a major disturbance change occurs in the state of the system connected to the generator, for example, failure of one of the circuits of the two-circuit transmission line, the control system can obtain the optimal gain, thus delivering good robustness.

It is able to control multi-computer systems well. Besides, it has the self-test function, which is capable of an automatic switch if a hardware failure occurs.

1.3.2 TAGEC Control

1.3.2.1 TAGEC-I
As shown in Figure 1.11, all of the regulation functions before the phase shift trigger circuit for the excitation and before the servomotor for the governor are replaced by the adaptive TAGEC.

This mode is applicable to new hydro turbines that pose no special requirements for governor control.

1.3.2.2 TAGEC-II
As shown in Figure 1.12, generator excitation control is the same as that in the TAGEC-I mode. For governor control, while the conventional governor control system functions are retained, a compensation signal is added by TAGEC, with its amplitude limited. This is similar to the function of PSS's additional signal, which acts on the excitation control's feeding point and achieves synthesis.
1.3 Linear Multivariable Total Controller

As shown in Figure 1.13, in this control mode, TAGEC provides an additional signal and acts on the given points of the excitation regulator and the governor accordingly to obtain the total compensation function without changing the original excitation regulator and governor. This mode is applicable to modernization of units that have been in operation.
1.3.3 Mathematical Model of TAGEC Control System

Under the condition that the generator and the system are operating in parallel, the related Park equation is listed as the basis for establishing the mathematical model of the TAGEC control system.

Generally, the TAGEC’s sampling operation time is about 20 ms. Under the condition that the stator resistance and the damping circuit are neglected, the following basic equation of the generator can be obtained on the basis of the basic mathematical models corresponding to the TAGEC-I and TAGEC-II control systems:

\[
\Phi_{fd} = [(r_f / X_{ad})U_e - r_f(\Phi_{ld} - \Phi_{ad}) / X_{ld}]\omega_0
\]

(1.22)

The equation operating in parallel with the system is

\[
\dot{\omega} = [(T_m - T_e) - D(\omega - \omega_0)] / M
\]

\[
\dot{\delta} = \omega - \omega_0
\]

(1.23)

(1.24)

The generator output equation is

\[
U_t = K_6 \Delta \Phi_{fd} + K_5 \Delta \delta + U_{tb}
\]

(1.25)

\[
P_e = K_2 \Delta \Phi_{fd} + K_1 \Delta \delta + P_{eb}
\]

(1.26)

The water turbine and governor system equations are

\[
\dot{P}_m = (1 / T_g)(U_g - P_m)
\]

\[
\dot{q} = (2 / T_\omega)(P_m - q)
\]

\[
T_m = 3q - 2P_m
\]

(1.27)

(1.28)

(1.29)

Equations (1.27)–(1.29) express the relation between the governor opening \(P_m\) and the flow \(q\) and the mechanical torque \(T_m\) when the hydraulic system model is considered.

Under ideal conditions, the transfer function of the hydraulic system model can be written as

\[
\omega(s) = \frac{1}{1 + 0.5T_\omega s}
\]

For the steam turbine governor, there are the following relations:

\[
\dot{X}_g = \frac{-K_g[K_f(\omega - \omega_0) + P_e - P_s]}{T_g}
\]

\[
\dot{T}_{mh} = \frac{X_g - K_g[K_f(\omega - \omega_0) + P_e - P_s + U_g - T_{mh}]}{T_h}
\]

\[
\dot{T}_{ml} = (T_{mh} - T_{ml})/T_{th}
\]

\[
\dot{T}_m = T_h T_{mh} + K_1 T_{ml}
\]

(1.30)

(1.31)

(1.32)

(1.33)

where

- \(\Phi_{fd}\) – excitation flux;
- \(\omega\) – rotation angular velocity;
- \(r_f\) – excitation winding resistance;
- \(U_e\) – excitation voltage control;
- \(\Phi_{ad}\) – \(d\)-axis interlocking flux;
- \(X_{ld}\) – excitation winding leakage reactance;
- \(T_m\) – mechanical torque;
- \(T_e\) – electrical torque;
1.3 Linear Multivariable Total Controller

- \( D \) – damping coefficient;
- \( M \) – inertia coefficient;
- \( \delta \) – power angle;
- \( U_t \) – terminal voltage;
- \( U_{th} \) – voltage linearization base value;
- \( P_e \) – output power;
- \( P_{eb} \) – output power linearization base value;
- \( K_1, K_2, K_5, K_6 \) – W. G. Ephron mathematical model coefficients;
- \( U_g \) – governor opening instruction;
- \( P_m \) – governor opening;
- \( T_g \) – governor primary inertia time constant;
- \( T_{\omega} \) – hydraulic system time constant;
- \( q \) – water flow;
- \( X_g \) – governor PI regulator integrator output;
- \( K_g, T_g \) – integrator gain and time constants;
- \( K_f \) – frequency deviation measurement circuit gain;
- \( P_s \) – output setpoint;
- \( T_{mh} \) – high-pressure cylinder output torque;
- \( T_{m1} \) – medium- or low-pressure cylinder output torque;
- \( T_h \) – time constant of high-pressure cylinder with governor time lag;
- \( T_{rh} \) – time constant of re heater with medium- or low-pressure cylinder time lag.

On the basis of the above mathematical model equation, the state equation is linearized and discretized. Through operation with the following quadratic performance index function, the optimal gain value of each variable can be calculated:

\[
J = \sum_{j=0}^{\infty} [Q_v(\Delta U_{ij})^2 + Q_p(\Delta P_{ej})^2 + R_e(\Delta U_{ij})^2 + R_p(\Delta U_{gij})^2]
\]  

(1.34)

where

- \( Q_v, Q_p, R_e, R_p \) – weight coefficients;
- \( \Delta U_{ij} \) and \( \Delta P_{ej} \) – deviations of real-time value from setpoint at the point \( j \);
- \( \Delta U_{ij} \) and \( \Delta U_{gij} \) – deviations of real-time value from excitation and governor control variable at the point \( j \).

1.3.4 Composition of TAGEC System

The block diagram of the TAGEC system based on a high-speed microcomputer is shown in Figure 1.14.

1.3.4.1 Sampling Operation

As shown in Figure 1.15, the control input of the excitation and governor system is operated, and a judgment is made and the data logging function is performed on the basis of the program conditions.
Evolution and Development of Excitation Control

Figure 1.14 Block diagram of TAGEC system.

Figure 1.15 Block diagram of total control system.
1.3.4.2 Matrix Operation
On the basis of the equivalent system reactance, the optimal control model is calculated, and the optimal gain at the time of changes in the generator’s and the system’s operating state is determined.

1.3.4.3 Stability Margin Monitoring Control
The vertical and horizontal axis synchronous reactance of the generator and the vertical axis component of the generator terminal voltage are calculated, so that the stability margin’s control of excitation increase or output power reduction for the generator can be ensured.

Conventionally, monitoring of generator stability margin is achieved with a leading phase reactive power monitoring relay. The action principle is that when a single generator is operating in parallel with an infinite system, if the excitation of the generator remains constant and the output of the generator is gradually increased, as the vertical axis component $U_d$ of the generator terminal voltage $U_t$ is increased to the maximum value $U_{d_{\text{max}}}$, beyond the point the generator will be in the acceleration state till it loses synchronization. $U_{d_{\text{max}}}$ is the value when the excitation remains unchanged, as shown in Figure 1.16a.

The expression for $U_{d_{\text{max}}}$ can be written as

$$U_{d_{\text{max}}} = \frac{X_q}{X_q + X_{\text{ex}}} U_b$$

where

$X_q$ – horizontal axis reactance of generator in operating state;

$X_{\text{ex}}$ – external reactance;

$U_b$ – infinite system line voltage.

It can be seen from Figure 1.16b that when the excitation of the generator is increased, the terminal voltage changes from $U_i$ ($U_d$, $U_q$) to $U_i'$ ($U'_d$, $U'_q$) and the rotor power angle changes from $\delta_0$ to $\delta'_0$.

Figure 1.16 Principle of $U_{d_{\text{max}}}$: (a) basic phasor, (b) $U_d$ and $U_q$ phasor characteristics of generator. $U_{qi}$ – $X_q$ post voltage, $U_i$ – generator terminal voltage, $I$ – generator current, $U_d$ – $U_i$ vertical axis component, $U_q$ – $U_i$ horizontal axis component, and $\delta$ – power angle.
Table 1.1 TAGEC input and output physical quantities.

<table>
<thead>
<tr>
<th>Measured value</th>
<th>TAGEC internal operation processing capacity</th>
<th>State variable</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$-axis pulse</td>
<td>$\delta$</td>
<td>$U_t$</td>
<td>TAGEC-I and II</td>
</tr>
<tr>
<td>$U_t$ three-phase</td>
<td>$\Phi_{ad}$</td>
<td>$P_e$</td>
<td>General</td>
</tr>
<tr>
<td>$I_t$ three-phase</td>
<td>$U_{t(rms)}$</td>
<td>$\Phi_{td}$</td>
<td></td>
</tr>
<tr>
<td>$I_f$</td>
<td>$P_{f(rms)}$</td>
<td>$\omega$</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td>$U_e$ (excitation output)</td>
<td>$\delta$</td>
<td></td>
</tr>
<tr>
<td>$P_m$</td>
<td>$U_s$, $P_m$, and $U_g$ (governor output)</td>
<td>$P_m$ and $q$</td>
<td>TAGEC-I</td>
</tr>
<tr>
<td>$P_s$</td>
<td>$U_g$ (governor output) band-pass filter, amplitude limit $\pm a%$</td>
<td>$X_q$, $P_m$, $T_h$, and $T_i$</td>
<td>TAGEC-II for hydropower stations</td>
</tr>
</tbody>
</table>

For stability margin monitoring, it is assumed that the maximum change in the external reactance is $\Delta X_{ex}$. It can be seen from Eq. (1.35) that, at this point $U_{d}^{\text{max}} = \frac{X_q}{X_q + X_{ex} + \Delta X_{ex}} U_b$. The stability margin after the excitation of the generator is increased is determined by the real-time value $U_d < U_{d}^{\text{max}}$. As can be seen from the above discussion, in the TAGEC control system, operation of the stability margin depends on $X_q$ and $X_{ex}$ corresponding to the operating output state, especially the value $X_q$. As can be seen from actual measurement, the value $X_q$ will significantly decrease with an increase in the load. On a 700 MW steam turbine, for example, the design value $X_q$ is 1.65 p.u. and will decrease to 1.40 p.u in the rated load state.

1.3.4.4 TAGEC Input and Output

The input and output physical variables of TAGEC are shown in Table 1.1.

The following physical variables for the monitoring values are entered directly from the outside into the TAGEC control system:

1. $d$-axis pulse (the excitation magnetic pole position signal measured from the steam turbine shaft end or an equivalent signal).
2. Generator terminal voltage signal (TV secondary three-phase voltage) $U_t$.
3. Generator output current (TA secondary three-phase current) $I_t$.
4. Generator excitation current $I_f$.
5. Speed $\omega$.
6. Speed output measured by the turbine or the generator shaft end sensor.
7. Governor opening $P_m$.
8. Output setpoint (for TAGEC-II only) $P_s$.

1.3.5 Digital Simulation Test of Power Transmission System

Fuji Electric conducted a stability test for two generators to an infinite system with thermal power 200 kVA and hydropower 30 kVA simulated transmission line equipment.

1.3.5.1 Composition of Power System

The power system consisted of a 500 kV/300 km (or 600 km) two-circuit line of a simulated transmission system.

1.3.5.2 Generators

Two simulated four-pole non-salient pole 100 kVA/90 kW generators were used: voltage: 220 V; speed: 1500 r min$^{-1}$ (or 1800 r min$^{-1}$); $X_q = 167\%$, $X'_q = 43\%$, $X''_q = 37\%$, $T_s = 0.3$ s, and $T'_d = 3.0$s.
1.3.5.3 Excitation and Speed Governing System
In order to compare the performance of the TAGEC control system, only three modes (AVR, AVR-PSS, and TAGEC-II) are adopted in excitation control.

The turbine speed governing system is electric. However, for the TAGEC-II control mode, the opening of the speed governing system is controlled by the compensation correction signal of TAGEC.

1.3.5.4 Power System Stability Test
The two generators, G1 and G2, adopt different excitation control modes, such as AVR-AVR, AVR-PSS, PSS-PSS, and PSS-TAGEC (or TAGEC-AVR/TAGEC-PSS).

The stability limit test is carried out under the condition of constant G2 output power and gradually increasing G1 output power. For the base value of the stability limit, the corresponding value of AVR-PSS is taken as the basis for the comparison. The added stability limit power of G1 is expressed as the per-unit value.

1.3.5.5 Power System Stability Test Result
Under the condition of two generators in an infinite system, the static, dynamic, transient, and long-cycle dynamic stability tests are conducted. The static stability test result in the AVR-PSS mode is shown in Figure 1.17 as a basic value for the comparison. The load of G2 remains unchanged during the test.

Figure 1.18 shows the result of the dynamic stability test of the two-generator system. The test condition is that one of the circuits of the transmission line is cut off.

![Diagram](image)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Power Limit (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVR/AVR</td>
<td>1.25</td>
</tr>
<tr>
<td>G2:AVR</td>
<td>1.5</td>
</tr>
<tr>
<td>G2:AVR</td>
<td>1.5</td>
</tr>
<tr>
<td>G2:AVR</td>
<td>1.65</td>
</tr>
<tr>
<td>G2:AVR</td>
<td>1.76</td>
</tr>
<tr>
<td>G2:AVR</td>
<td>1.8</td>
</tr>
<tr>
<td>G2:AVR</td>
<td>110.8</td>
</tr>
</tbody>
</table>

Table 1.17 Static stability limit of two generators on an infinite system.

Figure 1.17 Static stability limit of two generators on an infinite system.
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Figure 1.18 Dynamic stability test of two-generator system when one of the circuits of transmission line is cut off.

Figure 1.19 shows the transient stability test when one of the circuits of the transmission line is three-phase shorted out for four cycles and then cut off.

Figure 1.20 shows the long-cycle stability evaluation when a 300 km transmission line of one of the branches of the two-circuit transmission line is cut off in two generators in an infinite system. At this point, the squared value of the generator voltage is used as the stability evaluation index.

It should be emphasized that, as can be seen from Figure 1.20, the ability to maintain the generator terminal voltage with TAGEC is lower than with the corresponding value of the conventional excitation mode AVR-AVR or AVR-PSS.

In addition to the above simulation test, a prototype industrial operation test was conducted by Fuji Electric on a 32 MW hydro turbine in 1990, which delivered a good result.

### 1.4 Nonlinear Multivariable Excitation Controller [3]

Over the past two decades, with the continuous path-breaking progress in research on modern differential geometry, numerous achievements have also been made in studies on the application of differential geometry to nonlinear control systems. Moreover, a new discipline – the differential geometry theoretic system of nonlinear control systems – has been formed on this basis. In this regard, Professor A. Isdori from Sapienza University of Rome pointed out: "Just as the introduction of the Laplace transform and the transfer function before the 1950s and the introduction of the linear algebraic method in the 1960s brought major achievements
in control theory in terms of SISO and multivariable linear systems, respectively, introduction of the differential geometry method into nonlinear control systems will also bring breakthroughs in control theory." A branch of the new modern differential geometry theoretic system – the nonlinear system state feedback accurate linearization theory – has been developed very rapidly and applied to projects.

Professor Lu Qiang from Tsinghua University applied nonlinear system control theory based on the differential geometric method to complex power systems, gave the first rigorous mathematical proof of the optimal properties of the nonlinear control solution internationally, and further developed a decentralized nonlinear optimal excitation controller (NOEC) for power systems. A large number of simulation study results and field tests show that the nonlinear excitation control law can significantly improve the transient stability of power systems and the power transmission limit of transmission corridors, thereby maximizing the capacity of generator units.

However, a real-world engineering control system is always more or less affected by various uncertainties or external disturbances. This must be considered in research on controllers for power systems which are typical nonlinear systems. Without exceptions, some controllers applied to power systems including PID, PSS, LOEC, and NOEC adopt models with fixed structure and parameters in modeling. That is, the impact of uncertainties (e.g., external interferences and unmodeled dynamics) is not taken into account.

The nonlinear differential geometry control method is also built upon an accurate mathematical model of the controlled object. Although it provides an analytical method for design of nonlinear control, the controller design suffers from inherent defects due to ignorance of the uncertainties of the model in modeling. In the case of disturbances due to the uncertainties, it is difficult to achieve the desired performance indicators. Given this,
a branch of modern control theory called robust control was formulated. In system modeling and controller design, the impact of uncertainties on system performance is considered, and the actual control system is regarded as a system family. On this basis, the analytical method is used to design controllers, enabling the controlled object to meet the desired performance indicators as far as possible, even in the case of changes in the model.

For a nonlinear system subject to external uncertain disturbances, its nonlinear $H_{\infty}$ control law can be obtained by solving an HJI inequation. However, the HJI inequality is a first-order partial differential inequality, and its general analytical solution cannot be obtained mathematically. However, in linear cases, the inequality can be reduced to a Riccati inequation. Solving the algebraic inequation is not mathematically difficult.

On the basis of the above idea, from a summary of NOEC, Professor Lu conducted the pioneering methodological integration of the differential geometry control theory, the dissipation system theory, the differential strategy, and the $H_{\infty}$ method based on nonlinear robust control theory and exported the exact analytic expression of the nonlinear robust power system stabilizer (NR-PSS) control strategy from that, thus completing the creation of the nonlinear robust control theoretical system of power systems.

Besides, since the control strategy expression contains only the local parameters and the local and unit state variables and does not contain the power network parameters, robust excitation controllers have higher adaptability to network structure and parameter changes and better ability to suppress various external interferences to make the control law highly robust.
The establishment of this scientific theoretical system is of great significance in academia. Since American researchers put forward the classical PSS excitation control theory in the 1960s, the NR-PSS excitation control strategy and the complete theoretical system created by Chinese researchers have undoubtedly set a new milestone in the field of excitation system control.

Under the basic design philosophy of NR-PSS, the nonlinear model of a multi-generator excitation system considering interferences is built, and the original nonlinear system is accurately linearized with the linearization technique. Then the linear H\(_\infty\) control law is designed for the linearized model, and the control law is brought back to the nonlinear feedback law set in the precise linearization process. Thus, the NR-PSS control law of the original system is obtained. This makes the designed controller strongly robust theoretically, thus ensuring the ability to suppress such uncertainties as external interferences and internal unmodeled dynamics and higher practicability in engineering applications.

Similar to conventional PSS applications, a NR-PSS applied to a project superimposes its output on the output point of the AVR in the form of additional signals. The outputs of the two systems are independent of each other. The connection is shown in Figure 1.21.

The NR-PSS nonlinear robust excitation control law obtained on the basis of the nonlinear robust control design principle is

\[
V_{f_{\text{PSS}}} = E_{q_i} - \frac{T_{d0i}}{i_{q_i}} [E'_{q_i} + (X_{q_i} - X'_{d_i})(i_{q_i} \dot{i}_{d_i} + i_{d_i} \dot{i}_{q_i})] \\
+ C_{i_{q_i}} \omega_0 \left( k_{1i} \Delta \delta + k_{2i} \Delta \omega - k_{3i} \frac{\omega_0}{T_i} \Delta P_e \right)
\]

(1.36)

where

- \(i\) – parameters and state variables of the generator \(i\) (subscript \(i\));
- \(E'_{q_i}, E_{q_i}\) – transient potential and no-load potential of synchronous generator respectively (p.u.);
- \(T_{d0i}\) – time constant of excitation winding at the time of stator open circuit \(s\);
- \(i_{d_i}, i_{q_i}\) – \(d\)-axis and \(q\)-axis components of armature current;
- \(\dot{i}_{d_i}, \dot{i}_{q_i}\) – differential variable of \(i_{d_i}\) and \(i_{q_i}\) respectively;
- \(X_{q_i}, X'_{d_i}\) – \(q\)-axis synchronous reactance and \(d\)-axis transient reactance (p.u.);
- \(T_{ji}\) – rotational inertia \(s\);
- \(\omega_0\) – synchronous angular velocity rad s\(^{-1}\);
- \(\Delta \delta\) – rotor operating angle deviation rad;
\[ \Delta \omega \] – angular velocity deviation rad s\(^{-1}\); 
\[ \Delta P_e \] – electromagnetic power deviation (p.u.); 
\[ k_{1i}, k_{2i}, k_{3i}, C_{1i} \] – accommodation coefficients.

As can be seen from Eq. (1.36), the NR-PSS control law has the following characteristics:

1. As suppression of interferences is fully considered in the system design, the designed control law has a significant inhibitory effect on external interferences. Since the control law contains only locally measurable parameters (parameters of the generator), which are thus independent of the network parameters. So, it is adaptable to network structure changes, thereby ensuring robustness.

2. The parameters in the control law are all locally measured, and they are not directly related to the state or output variables of other units, which ensures applicability to decentralized coordination control of multi-generator systems.

3. The control law takes into account the transient salient pole effect of the generator on the basis of the generator's biaxial model and eliminates the original assumption that the NOEC \( X'_d = X'_{q} \), thus making the designed control law more accurate. This extends the scope of application of the controller theoretically.

When a NR-PSS and an AVR are used in combination, the total control law is

\[ V_{fi} = C_{3i} V_{iAVR} + C_{2i} V_{iNR-PSS}(C_{1i}) \]  \hspace{1cm} (1.37)
where

\[
V_{fPSS} = E_{qi} - \frac{T_{d0}'}{i_{qi}} [E_{qi}' + (X_{qi} - X_{di})(i_{qi} \dot{i}_{di} + i_{di} \dot{i}_{qi})] \\
+ \frac{T_i' T_{d0}'}{\omega_0} \left( k_{i1} \Delta \delta + k_{2i} \Delta \omega - k_{3i} \frac{\omega_0}{T_j} \Delta P_e \right) \\
V_{AVR} = (k_p + k_{DS}) \frac{1}{1 + k_1 s} \Delta V_t
\]

The nonlinear robust excitation control engineering algorithm routine is shown in Figure 1.22.

### 1.5 Power System Voltage Regulator (PSVR) [4]

#### 1.5.1 Overview

A conventional AVR is designed to keep the generator voltage constant. A system voltage drop caused by a transmission line failure will result in an increase in the reactive power loss of the entire system, thus reducing the system voltage stability.

Moreover, in recent years, in some countries such as some metropolises in Japan, with the popularity of refrigerating units, loads have had a voltage characteristic that is close to constant power. Meanwhile, due to the application of cables to power supply systems, there is an obvious downward trend in the trunk line system voltage in power supply to downtown areas with long-distance 275 kV high-voltage transmission systems. Therefore, the maintenance of trunk line system voltage stability has become important. In the 1990s, Japan set up a new PSVR, which can improve high-voltage transmission system voltage and maintain it at a certain value on generator units connected with 500 kV and 275 kV systems.

#### 1.5.2 Effect of SVR on Improvement of System Voltage Characteristics

Figure 1.23a shows the conventional AVR mode. In the system, the voltage deviation of the generator is regulated as the feedback variable, and the voltage of the generator is maintained at a given value.

Under such conditions, any transmission line failure will cause a drop in the system voltage \( U_s \). When \( U_s \) drops to the voltage at the intersection with the leading edge of the \( P-U \) curve, the generator’s ability to provide reactive power will be determined by the intersection of the AVR’s control characteristics and the leading line of \( P-U \), as shown in Figure 1.24b.

If the PSVR mode shown in Figure 1.23b is adopted to maintain the high-voltage side voltage of the power station at a high level, it can improve not only the generator output reactive power limit but also the system voltage stability.

It should be noted that the PSVR just applies the generator’s potential limit reactive power capacity, but it is not an overload condition in which the generator exceeds the allowable reactive capacity. A simulated system of the PSVR is shown in Figure 1.24a. The reactive power range that can be regulated by the PSVR is shown in the shaded area in Figure 1.24b.

To explain the effect of PSVR on the improvement of the system voltage characteristics, the compensation effect is described when the power system is equipped with a power capacitor, a synchronous rotary condenser, and a PSVR, respectively.

It is assumed that the model of a single generator on a single load system is shown in Figure 1.25.
Figure 1.23 Generator excitation control modes: (a) AVR, (b) PSVR.

Figure 1.24 PSVR and AVR control characteristics when system voltage drops: (a) simulated system, (b) PSVR and AVR control characteristics.

Figure 1.25 Model of a single generator on a single load system.
The parameters of the power system include $X_t = 15\%$, $X_e = 35\%$, $P + jQ = 1000 + j329$ ($Q$ is a constant value), and $\cos \varphi = 0.95$.

(1) Compensation characteristic when a power capacitor is installed

It is assumed that the power capacitor’s admittance is $Y_{SC}$. At this point, the generator power expression is

$$P^2 + \left[ \left( \frac{1}{X_e + X_t} - Y_e - Y_{SC} \right) U_L^2 + Q \right]^2 = \frac{U_g^2 U_L^2}{(X_e + X_t)^2} \tag{1.38}$$

where

- $P$ and $Q$ – active and reactive power of load, respectively;
- $U_g$ – generator terminal voltage;
- $U_L$ – load terminal voltage;
- $X_e$ – transmission line reactance;
- $X_t$ – boosting transformer reactance;
- $Y_c$ – admittance of power capacitor on load side before fault.

(2) Compensation characteristic when a synchronous rotary condenser is installed (compensation capacity $Q_{RC}$)

The expression for the compensation characteristic when a synchronous rotary condenser is installed is

$$P^2 + \left[ \left( \frac{1}{X_e + X_t} - Y_c - (Q - Q_{RC}) \right) U_L^2 + (Q - Q_{RC}) \right]^2 = \frac{U_g^2 U_L^2}{(X_e + X_t)^2} \tag{1.39}$$

(3) Compensation characteristic when a PSVR is installed

At this point, the reactance of the boosting transformer is compensated by the PSVR to $X'_t = \alpha X_t$, where $\alpha$ is the compensation factor. Then

$$P^2 + \left[ \left( \frac{1}{X_e + \alpha X_t} - Y_c \right) U_L^2 + Q \right]^2 = \frac{U_g^2 U_L^2}{(X_e + \alpha X_t)^2} \tag{1.40}$$

If the power system parameter values shown in Figure 1.25 are substituted into Equations (1.38)–(1.40), the corresponding $P–U$ curves can be obtained, as shown in Figure 1.26.

As can be seen from Figure 1.26, when a power capacitor or synchronous rotary condenser is installed, with the increase in installed capacity, the leading edge voltage of the $P–U$ curve shows an obvious upward trend. That is particularly obvious when a power capacitor is installed. The voltage stabilization limit is defined by the leading voltage becoming lower than the load terminal voltage rating.

When the PSVR is set, the reactance of the boosting transformer can be partially compensated to decrease the leading edge voltage. This can improve the system voltage stability. Its effect is equivalent to that of an addition of transmission system and transformer capacity.

The same effect can be achieved for multi-generator systems. Figure 1.27 shows the simulation test result for a 500 kV system when the generator adopts a PSVR.

Table 1.2 shows the reactive load balance when the one of the circuits of the 500 kV transmission system is cut off.

As can be seen from Figure 1.27, when one of the circuits of the 500 kV transmission system is cut off, the PSVR mode can make the system voltage of the central part drop by 12–14 kV. This can improve the system’s voltage maintenance level to a certain extent.

In addition, this can reduce the system’s reactive power loss by about 1.7 Mvar.
Figure 1.26 $P$–$U$ curve for model of a single generator on a single load system: (a) $P$–$U$ curve when power capacitor is installed, (b) $P$–$U$ curve when rotary condenser is installed, (c) $P$–$U$ curve when PSVR is installed.

Figure 1.27 Voltage distribution when one of the circuits of 500 kV transmission system is cut off.
Table 1.2  System-wide reactive power balance when one of the circuits of 500 kV transmission system is cut off.

<table>
<thead>
<tr>
<th>Control mode</th>
<th>Balance (Mvar)</th>
<th>PSVR mode (Mvar)</th>
<th>Conventional AVR mode (Mvar)</th>
<th>Difference (Mvar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains side</td>
<td>Genernator</td>
<td>14.080</td>
<td>16.540</td>
<td>−2.460</td>
</tr>
<tr>
<td></td>
<td>Rotary condenser</td>
<td>13.730</td>
<td>13.010</td>
<td>+0.720</td>
</tr>
<tr>
<td>Load side</td>
<td>Load</td>
<td>12.140</td>
<td>12.140</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Transmission loss</td>
<td>15.670</td>
<td>17.410</td>
<td>−1.740</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>27.810</td>
<td>29.550</td>
<td>−1.740</td>
</tr>
</tbody>
</table>

1.5.3 Composition of PSVR

1.5.3.1 Basic Control of PSVR
There are multiple schemes of PSVR control. Figure 1.28a shows a simple control scheme. In the scheme, additional signals are supplied by the transmission high voltage side to compensate for the generator voltage benchmark value $U_g$. The degree of compensation, that is, the slope of the generator voltage on the external characteristic curve of the reactive power is $(0.5–5)\%U_H/Q_{g_{max}}$, where $Q_{g_{max}}$ is the maximum allowable reactive power, as shown in Figure 1.28b.

1.5.3.2 Basic Equation of PSVR Control
The PSVR control system block diagram is shown in Figure 1.29.

Figure 1.28 PSVR control mode: (a) diagram of control system, (b) generator voltage control characteristics.

Figure 1.29 PSVR control system block diagram.
For the PSVR control system shown in Figure 1.29, it is assumed that the normal gain of the AVR is infinite and decreases to $\beta = 1$ after the compensation. The following equations can be obtained:

$$n(U_g - X_i I_q) = U_H$$ \hspace{1cm} (1.41)

$$(r_h - U_H)K_H = U_c$$ \hspace{1cm} (1.42)

$$U_g = r_g + U_c$$ \hspace{1cm} (1.43)

If $U_c$ in Eq. (1.42) is substituted into Eq. (1.43) and then $U_g$ is substituted into Eq. (1.41), the basic equation into which $U_H$ is substituted can be obtained:

$$n(r_g + (r_h - U_H)K_H - X_i I_q) = U_H$$ \hspace{1cm} (1.44)

Through calculation, the following is obtained:

$$U_H = \frac{n(r_g + r_h K_H)}{1 + nK_H} - \frac{nX_i}{1 + nK_H} I_q = \frac{n(r_g + r_h K_H)}{1 + nK_H} - \alpha_v I_q$$ \hspace{1cm} (1.45)

where

$\alpha_v$ – voltage slope coefficient;

$K_H$ – voltage gain coefficient.

If $U_H$ in Eq. (1.45) is substituted into Eq. (1.41), the expression for $U_g$ can be obtained:

$$U_g = \frac{r_g + r_h K_H}{1 + nK_H} + \frac{K_H nX_i}{1 + nK_H} I_q = \frac{r_g + r_h K_H}{1 + nK_H} + K_H \alpha_v I_q$$ \hspace{1cm} (1.46)

As can be seen from Eq. (1.44), a drop in the system voltage will cause an increase in the generator reactive current $I_q$. The degree of the drop depends on $\alpha_v$.

As can be seen from Eq. (1.45), as $I_q$ increases, the generator terminal voltage will increase. The magnitude of the increase depends on $K_H$ and $\alpha_v$. If the gain reduction set for the generator AVR measurement circuit is taken into account, that is, the gain reduction factor $\beta$ is not equal to 1, Eq. (1.43) can be rewritten as

$$U_g = r_g + U_c/\beta$$ \hspace{1cm} (1.47)

With simultaneous Eqs. (1.41), (1.42), and (1.47), $U_H$ and $U_g$ can be obtained:

$$U_H = \frac{n(\beta r_g + r_h K_H)}{\beta + nK_H} - \frac{\beta nX_i}{\beta + nK_H} I_q = \frac{n(\beta r_g + r_h K_H)}{\beta + nK_H} - \alpha_{\beta} I_q$$ \hspace{1cm} (1.48)

$$\alpha_{\beta} = \frac{\beta nX_i}{\beta + nK_H}$$

$$U_g = \frac{\beta r_g + r_h K_H}{\beta + nK_H} + K_H \alpha_{\beta} I_q$$ \hspace{1cm} (1.49)

where

$\alpha_{\beta}$ – voltage gain slope coefficient with gain reduction coefficient $\beta$ factored in.
### 1.5.4 Comparison between PSVR and AVR in Control Characteristics

For the AVR mode, the high-voltage-side feedback coefficient \( K_H \) can be made equal to 0. In this case, Eqs. (1.45) and (1.46) can be rewritten as

\[
U_{HA} = nr_g - nx_t I_q = nr_g - \alpha_v (1 + nK_H)I_q \tag{1.50}
\]

\[
U_{gA} = r_g \tag{1.51}
\]

For the PSVR mode, when \( K_H \neq 0 \), Eqs. (1.45) and (1.46) can be rewritten as

\[
U_{HP} = nr_g \frac{1 + r_h K_H}{1 + nK_H} - \alpha_v I_q \tag{1.52}
\]

\[
U_{gP} = r_g \frac{1 + r_h K_H}{1 + nK_H} + K_H \alpha_v I_q \tag{1.53}
\]

If it is assumed that \( n = r_h/r_g \), Eqs. (1.52) and (1.53) can be written as

\[
U_{HP} = nr_g - \alpha_v I_q \tag{1.54}
\]

\[
U_{gP} = r_g + K_H \alpha_v I_q \tag{1.55}
\]

As can be seen from these two equations, compared with the AVR mode, the PSVR control can reduce the voltage drop on the high-voltage side to \( 1/(1 + nK_H) \) while the generator-side voltage increases only by \( K_H \alpha_v \).

### 1.5.5 Basic Functions of PSVR

Figure 1.30 shows the basic composition of the PSVR control circuit. In order to achieve AVR control by the high-voltage-side line voltage, PSVR can automatically determine the target value of the output voltage by the time program and detect anomalies. The relevant functions are as follows.

#### 1.5.5.1 Basic Control

PSVR can quickly and accurately take samples at a sampling frequency of 600 Hz or more and an accuracy of ±0.2% or less and measure the generator three-phase voltage RMS and average. In order to ensure the generator excitation system regulation stability, it provides phase compensation and gain reduction circuits. It can achieve generator voltage stability and reactive power balance settings with the regulation gain \( K_H \).

#### 1.5.5.2 Program Voltage Setting

It can achieve control of up to 16 ladder benchmark values with different models of working and rest days.

#### 1.5.5.3 Output Limit

It provides a voltage limiting circuit at the PSVR output terminal.

#### 1.5.5.4 Anomaly Self-Detection

It can self-detect operation anomalies.

#### 1.5.5.5 Control Stability

In the conventional AVR control mode, its deviation signal is added with the system voltage-related deviation and amplified for operation control. The result is that the gain selected by the AVR is too large, so that the
Figure 1.30 Basic composition of PSVR control circuit.

damping system power oscillation capacity declines if any system transmission line failure occurs. To improve the damping capacity, the following measures can be taken:

1. Provide a gain reduction \((1-\beta)\) circuit in the AVR control circuit;
2. Provide phase compensation (advanced first order and lagged second order);
3. Increase the limit on the PSS.

Figure 1.31 shows signal operation and phase compensation coordination in the PSVR control system. The generator voltage is determined by the sum of the reference voltage value \(r_g\) of the AVR and the output voltage of the PSVR. When the output voltage of the generator exceeds the allowable value, the output voltage of the PSVR will be limited. If only the gain of the AVR is reduced and connected to the limited output terminal of the PSVR, the transient gain of the AVR will be reduced when a major disturbance event occurs on the transmission line. For this reason, if the gain reduction \(\beta (\beta \leq 1)\) of the AVR is connected to the input terminal of the phase compensation circuit with a greater lag time as shown in Figure 1.31, under the action of a large transient disturbance, the gain reduction of the AVR can give rise to the same response ability as before.
1.5 Power System Voltage Regulator (PSVR)

1.5.6 PSVR Simulation Test

The PSVR simulation test is shown in Figure 1.32. The digital simulation test is conducted by a single generator in an infinite system.

The test includes a steady-state test and a transient test, with the results shown in Figure 1.33. The test in Figure 1.33a is carried out without phase compensation. During the test, the generator voltage and the active power both produced slight oscillations. The test in Figure 1.33b is carried out with phase compensation, without a generator voltage and active power oscillation. In Figure 1.33c, the gain is increased, so that $\beta = 1$. The voltage closed circuit system unstably oscillates. Figure 1.33d shows the limit action under the generator inverse time limit voltage limit. It maintains the stability of the voltage closed-loop system.
PSVRs can comprehensively improve the voltage stability of trunk lines of transmission systems. In Japan, PSVRs have been applied to 500 kV transmission systems of hydro, thermal, and nuclear power generating units since the early 1990s. Nowadays their effectiveness has been achieved in actual operation, and their effect in improvement of system stability has been confirmed.