appendix A

Trigonometric Identities for Three-Phase Systems

In solving problems involving three-phase systems, the engineer encounters a large number of trigonometric functions involving the angles $\pm 120°$. Some of these are listed here to save the time and effort of computing these same quantities over and over. Although the symbol (°) has been omitted from angles $\pm 120°$, it is always implied.

$$\sin(\theta \pm 120) = -1/2 \sin\theta \pm \sqrt{3}/2 \cos\theta \tag{A.1}$$

$$\cos(\theta \pm 120) = -1/2 \cos\theta \mp \sqrt{3}/2 \sin\theta \tag{A.2}$$

$$\begin{aligned}\sin^2(\theta \pm 120) &= 1/4 \sin^2\theta + 3/4 \cos^2\theta \mp \sqrt{3}/2 \sin\theta\cos\theta \\ &= 1/2 + 1/4 \cos 2\theta \mp \sqrt{3}/4 \sin 2\theta\end{aligned} \tag{A.3}$$

$$\begin{aligned}\cos^2(\theta \pm 120) &= 1/4 \cos^2\theta + 3/4 \sin^2\theta \pm \sqrt{3}/2 \sin\theta\cos\theta \\ &= 1/2 - 1/4 \cos 2\theta \pm \sqrt{3}/4 \sin 2\theta\end{aligned} \tag{A.4}$$

$$\begin{aligned}\sin\theta \sin(\theta \pm 120) &= -1/2 \sin^2\theta \pm \sqrt{3}/2 \sin\theta\cos\theta \\ &= -1/4 + 1/4 \cos 2\theta \pm \sqrt{3}/4 \sin 2\theta\end{aligned} \tag{A.5}$$

$$\begin{aligned}\cos\theta \cos(\theta \pm 120) &= -1/2 \cos^2\theta \mp \sqrt{3}/2 \sin\theta\cos\theta \\ &= -1/4 - 1/4 \cos 2\theta \mp \sqrt{3}/4 \sin 2\theta\end{aligned} \tag{A.6}$$

$$\begin{aligned}\sin\theta \cos(\theta \pm 120) &= -1/2 \sin\theta\cos\theta \mp \sqrt{3}/2 \sin^2\theta \\ &= -1/4 \sin 2\theta \pm \sqrt{3}/4 \cos 2\theta \mp \sqrt{3}/4\end{aligned} \tag{A.7}$$

$$\begin{aligned}\cos\theta \sin(\theta \pm 120) &= -1/2 \sin\theta\cos\theta \pm \sqrt{3}/2 \cos^2\theta \\ &= -1/4 \sin 2\theta \pm \sqrt{3}/4 \cos 2\theta \pm \sqrt{3}/4\end{aligned} \tag{A.8}$$

$$\begin{aligned}\sin(\theta + 120)\cos(\theta + 120) &= -1/2 \sin\theta\cos\theta - \sqrt{3}/4 \cos^2\theta + \sqrt{3}/4 \sin^2\theta \\ &= -1/4 \sin 2\theta - \sqrt{3}/4 \cos 2\theta\end{aligned} \tag{A.9}$$

$$\sin(\theta + 120)\cos(\theta - 120) = \sin\theta\cos\theta - \sqrt{3}/4 = 1/2 \sin 2\theta - \sqrt{3}/4 \tag{A.10}$$

$$\sin(\theta - 120)\cos(\theta + 120) = \sin\theta\cos\theta + \sqrt{3}/4 = 1/2 \sin 2\theta + \sqrt{3}/4 \tag{A.11}$$

$$\begin{aligned}\sin(\theta - 120)\cos(\theta - 120) &= -1/2 \sin\theta\cos\theta + \sqrt{3}/4 \cos^2\theta - \sqrt{3}/4 \sin^2\theta \\ &= -1/4 \sin 2\theta + \sqrt{3}/4 \cos 2\theta\end{aligned} \tag{A.12}$$

$$\sin(\theta + 120)\sin(\theta - 120) = 1/4 \sin^2\theta - 3/4 \cos^2\theta = -1/4 - 1/2 \cos 2\theta \tag{A.13}$$

$$\cos(\theta + 120)\cos(\theta - 120) = 1/4 \cos^2\theta - 3/4 \sin^2\theta = -1/4 + 1/2 \cos 2\theta \tag{A.14}$$

$$\sin(2\theta \pm 120) = -1/2 \sin 2\theta \pm \sqrt{3}/2 \cos 2\theta \tag{A.15}$$

$$\cos(2\theta \pm 120) = -1/2 \cos 2\theta \mp \sqrt{3}/2 \sin 2\theta \tag{A.16}$$

$$\sin\theta + \sin(\theta - 120) + \sin(\theta + 120) = 0 \tag{A.17}$$

$$\cos\theta + \cos(\theta - 120) + \cos(\theta + 120) = 0 \tag{A.18}$$

$$\sin^2\theta + \sin^2(\theta - 120) + \sin^2(\theta + 120) = 3/2 \tag{A.19}$$

$$\cos^2\theta + \cos^2(\theta - 120) + \cos^2(\theta + 120) = 3/2 \tag{A.20}$$

$$\sin\theta\cos\theta + \sin(\theta - 120)\cos(\theta - 120) + \sin(\theta + 120)\cos(\theta + 120) = 0 \tag{A.21}$$

In addition to the above, the following commonly used identities are often required:

$$\begin{aligned}\sin^2\theta + \cos^2\theta &= 1 \\ \sin\theta\cos\theta &= 1/2 \sin 2\theta \\ \cos^2\theta - \sin^2\theta &= \cos 2\theta \\ \cos^2\theta &= (1 + \cos 2\theta)/2 \\ \sin^2\theta &= (1 - \cos 2\theta)/2\end{aligned}$$

appendix B

Some Computer Methods for Solving Differential Equations

The solution of dynamic systems of any kind involves the integration of differential equations. Some physical systems, such as power systems, are described by a large number of differential equations. Hand computation of such large systems of equations is exceedingly cumbersome, and computer solutions are usually called for.

Computer solutions fall into two categories, analog and digital, with hybrid systems as a combination of the two. The purpose of this appendix is to reinforce the material of the text by providing some of the fundamentals of computer solutions. This material is divided into two parts: analog computer fundamentals and digital computer solutions of ordinary differential equations. A short bibliography of references on analog and digital solutions is included at the end of this appendix.

B.1 Analog Computer Fundamentals

The analog computer is a device designed to solve differential equations. This is done by means of electronic components that perform the functions usually required in such problems. These include summation, integration, multiplication, division, multiplication by a constant, and other special functions.

The purpose of this appendix is to acquaint the beginner with the basic fundamentals of analog computation. As such it may be a valuable aid to the understanding of some of the text material and may be helpful in attempting an actual analog simulation. It should be used as a supplement to the many excellent books on the subject. In particular, the engineer who attempts an actual simulation will surely need the instruction manual for the computer actually used.

B.1.1 Analog computer components

Here we consider the most important analog computer components. Later, we will connect several components to solve a simple differential equation. We discuss these components using the common symbolic language of analog computation and omit entirely the electronic means of accomplishing these ends.

The summer. The first important component is the summer or summing amplifier shown in Figure B.1, where both the analog symbol and the mathematical operation are indicated. Note that the amplifier inverts (changes the sign) of the input sum and multiplies each input voltage by a gain constant k_i selected by the user. On most computers k_i may have values of 1 or 10, but some models have other gains available. Usually V_4 is limited to 100 V (10 V on some computers).

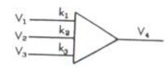

Fig. B.1. The summer; $V_4 = -(k_1V_1 + k_2V_2 + k_3V_3)$.

The integrator. It is necessary to be able to perform integration if differential equations are to be solved. Fortunately, integration may be done rapidly and very reliably by electronic means, as shown in Figure B.2, where V_0 is the initial value (at $t = 0$) of the output variable V_4. Gain constants k_i are chosen by the operator and are restricted to values available on the computer, usually 1 and 10. The output voltage is limited, usually to 100 V.

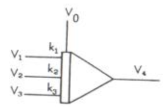

Fig. B.2. The integrator; $V_4 = -[V_0 + \int_0^t (k_1V_1 + k_2V_2 + k_3V_3)dt]$.

The potentiometer. The potentiometer is used to scale down a voltage by an exact amount as shown in Figure B.3, where the signal is implied as going from left to right. Potentiometers are usually 10-turn pots and can be reliably set to three decimals with excellent accuracy.

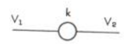

Fig. B.3. The potentiometer; $V_2 = kV_1, 0 \leq k \leq 1$.

The function generator. The function generator is a device used to simulate a nonlinear function by straight-line segments. Function generators are represented by the "pointed box" shown in Figure B.4 where the function f is specified by the user, and this function is set according to the instructions for the particular computer used. This feature makes it possible to simulate with reasonable accuracy certain nonlinear functions such as generator saturation. The function f must be single valued.

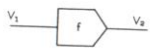

Fig. B.4. The function generator; $V_2 = f(V_1)$.

The high-gain amplifier. On some analog computers it is necessary to use high-gain amplifiers to simulate certain operations such as multiplication. The symbol usually used for this is shown in Figure B.5, although it should be mentioned that this symbol is not used by all manufacturers of analog equipment. Note that the gain of the amplifiers is very high, usually being greater than 10^4 and often greater than 10^6. This

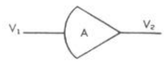

Fig. B.5. The high-gain amplifier; $V_2 = -AV_1, A > 10^4$.

means that the input voltage of such amplifiers is essentially zero since the output is always limited to a finite value (often 100 V).

The multiplier. The multiplier used on modern analog computers is an electronic quarter-square multiplier that operates on the following principle. Suppose v and i are to be multiplied to find the instantaneous power; i.e., $p = vi$. To do this, we begin with two voltages, one proportional to v, the other proportional to i. Then we form sum and difference signals, which in turn are squared and subtracted; i.e.,

$$M = (v + i)^2 - (v - i)^2 = (v^2 + 2vi + i^2) - (v^2 - 2vi + i^2) = 4vi$$

and $p = (1/4)M$, or one *quarter* of the difference of the *squared* signals.

The symbol used for multiplication varies with the actual components present in the computer multiplier section, but in its simplest form it may be represented as shown in Figure B.6. Note that it is usually necessary to supply both the positive and negative of one signal, say V_1. The multiplier inverts and divides the result by 100 (on a 100-V computer).

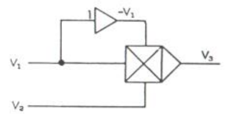

Fig. B.6. The multiplier; $V_3 = -V_1 V_2/100\ \text{V} = -V_1 V_2$ pu.

Other components. Most full-scale analog computers have other components not described here, including certain logical elements to control the computer operation. These specialized devices are left for the interested reader to discover for himself.

B.1.2 Analog computer scaling

Two kinds of scaling are necessary in analog computation, time scaling and amplitude scaling. Time scaling can be illustrated by means of a simple example. Consider the first-order equation

$$T\frac{dv}{dt} = f(v, t) \tag{B.1}$$

where v is the dependent variable that is desired, T is a constant, and f is a nonlinear function of v and t. The constant T would appear to be merely an amplitude scale factor, but such is not the case. Suppose we write

$$T\frac{dv}{dt} = \frac{dv}{d(t/T)} = \frac{dv}{d\tau} = f(v, t) \tag{B.2}$$

where $\tau = t/T$. Thus replacing the constant T by unity as in (B.2) amounts to time scaling the equation. In an analog computation the integration time must be chosen so

that the computed results may be conveniently plotted or displayed. For example, if the output plotter has a frequency limit of 1.0 kHz, the computer should be time scaled to plot the results more slowly than this limit.

Analog computers must also be amplitude scaled so that no variables will exceed the rating of the computer amplifiers (usually 100 V). This requires that the user estimate the maximum value of all variables to be represented and scale the values of these variables so that the maximum excursion is well below the computer rating.

Actually, it is convenient to scale time and amplitude simultaneously. One reason for this is that the electronic integrator is unable to tell the difference between the two scale factors. Moreover, this makes one equation suffice for both kinds of scaling. We begin with the following definitions. Let the time scaling constant a be defined as follows:

$$\tau = \text{computer time} \qquad t = \text{real time} \qquad a = \frac{\tau}{t} = \frac{\text{computer time}}{\text{real time}} \tag{B.3}$$

For example, if $a = 100$, this means that it will take the computer 100 times as long to solve the problem as the real system would require. It also means that 100 s on the output plotter corresponds to 1 s of real time.

Also define L as the *level* of a particular variable in volts, corresponding to 1.0 pu of that variable. For example, suppose the variable v in (B.1) ordinarily does not go above 5.0 pu. If the computer is rated 100 V, we could set $L = 20$ V on the amplifier supplying v. Then if v goes to 5.0 pu, the amplifier would reach 100 V, its maximum safe value. The scaling procedure follows:

1. Choose a time scale a that is compatible with plotting equipment and will give reasonable computation times (a few minutes at most).
2. Choose levels for all variables at the output of all summers and integrators.

Fig. B.7. Time and amplitude scaling.

3. Apply the following formula to all potentiometer settings (see Figure B.7):

$$PG = KL_{out}/aL_{in} \tag{B.5}$$

where a = time scale factor
P = potentiometer setting, $0 \le P \le 1$
G = amplifier or integrator gain
K = physical constant computed for this potentiometer
L_{out} = assigned output level, V
L_{in} = assigned input level, V

B.1.3 Analog computation

Example B.1

Suppose the integrator in Figure B.7 is to integrate $-\dot{\delta}$ (in pu) to get the torque angle δ in radians. Then we write

$$\delta = -\delta_0 - \omega_R \int_0^t \dot{\delta}\, dt \tag{B.6}$$

Thus the constant K in Figure B.7 and (B.5) is ω_R, which is required to convert from $\dot{\delta}$ in pu to $\dot{\delta}$ in rad/s. In our example let $\omega_R = 377$.

Solution

Let $a = 50$. Then the levels are computed as follows: $\delta_{max} = 100° = 1.745$ rad, so let $L_{out} = 50$ V, $(1.745 \times 50 < 100)$. Also estimate $\dot{\delta}_{max} = 1.25$ pu, so let $L_{in} = 75$ V, $(1.25 \times 75 < 100)$. Then compute

$$PG = KL_{out}/aL_{in} = (377 \times 50)/(50 \times 75) = 5.03$$

Since $0 \leq P \leq 1$ let $G = 10$ = gain of integrator and $P = 0.503$ = potentiometer setting.

Example B.2

Compute the buildup curve of a dc exciter by analog computer and compare with the method of formal integration used in Chapter 7. Use numerical data from Examples 7.4, 7.5, and 7.6.

Solution

For this problem we have the first-order differential equation

$$\dot{v}_F = (v - Ri)/T \tag{B.7}$$

where $v = v_p$ when separately excited
$= v_F$ when self-excited
$= v_R + v_F$ when boost-buck excited

where both v_p and v_R are constants. Thus the analog computer diagram is that shown in Figure B.8, where $v_{F0} = v_F(0)$.

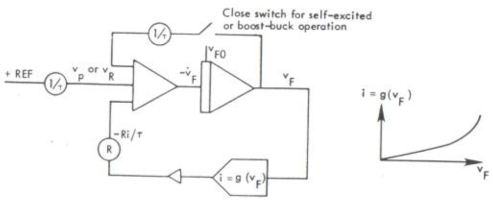

Fig. B.8. Solution diagram for dc exciter buildup.

An alternate solution utilizing the Frohlich approximation to the magnetization curve is described by the equation

$$\tau_E \dot{v}_F = v - \frac{bRv_f}{a - v_f} \tag{B.8}$$

Solving this equation should exactly duplicate the results of Chapter 7 where this same equation was solved by formal integration.

Using numerical data from Example 7.4 we have

$$\tau_E = 0.25 \text{ s} \quad a = 279.9 \quad b = 5.65$$

The values of R and v depend upon the type of buildup curve being simulated. From Examples 7.4, 7.5, and 7.6 we have

Separately excited: $v = v_p = 125$ V $\quad R = 34\ \Omega$
Self excited: $v = v_F \quad R = 30\ \Omega$
Boost-buck excited: $v = v_F + 50$ V $\quad R = 43.6\ \Omega$

and these values will give a ceiling of 110.3 V in all cases. Also, from Table 7.5 we note that the derivative of v_F can be greater than 100 V/s. This will help us scale the voltage level of $\dot{v}_F$.

Rewriting equation (B.8) with numerical values, we have

$$0.25\, \dot{v}_F = v - 5.65\, Rv_F/(279.9 - v_F) \text{ V} \tag{B.9}$$

where R and v depend on the type of system being simulated. Suppose we choose a base voltage of 100 V. Then dividing (B.9) by the base voltage we have the pu equation

$$0.25\, \dot{v}_F = v - 0.0565\, Rv_F/(2.799 - v_F) \tag{B.10}$$

where v_F and v are now in pu.

A convenient time scale factor is obtained by writing

$$\tau_E \dot{v}_F = \tau_E \frac{dv_F}{dt} = \frac{dv_F}{d(t/\tau_E)} = \frac{dv_F}{d\tau}$$

or $a = \tau/t = 1/\tau_E = 4.0\ \text{s}^{-1}$
Then the factor 0.25 in front of (B.10) becomes unity, and 4 s on the computer corresponds to 1.0 s of real time.

The analog computer solution for (B.10) is shown in Figure B.9, and the potentiometer settings are given in Table B.1. By moving the three switches simultaneously to positions R, C, and L, the same computer setup solves the separately excited, self-excited, and boost-buck buildup curves respectively. Voltage levels are assumed for

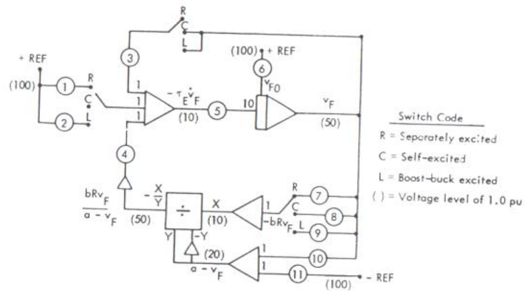

Fig. B.9. Solution diagram for Frohlich approximated buildup.

each amplifier and are noted in parentheses. These values are substituted into (B.5) to compute the PG products given in Table B.1. For example, for potentiometer 5

$$PG = (K/a)(L_{out}/L_{in}) = (1.0/4)(50/10) = 1.25 = 0.125 \times 10$$

or for potentiometer 7

$$PG = (1.92/1)(10/50) = 0.384 = 0.384 \times 1$$

Other table entries are similarly computed.

Table B.1. Potentiometer and Gain Calculations for Figure B.9

Potentiometer	Function	K	PG	P	G
1	v_P	1.25	0.125	0.125	1
2	v_R	0.50	0.050	0.050	1
3	scale	1.0	0.20	0.20	1
4	scale	1.0	0.20	0.20	1
5	time scale	1.0	1.25	0.125	10
6	initial value, v_{F0}	0.45	...	0.45	...
7	bR (separately)	1.92	0.384	0.384	1
8	bR (self)	1.695	0.339	0.339	1
9	bR (boost-buck)	2.46	0.492	0.492	1
10	scale	1.0	0.40	0.40	1
11	a	2.799	0.56	0.56	1

The computed results are shown in Examples 7.4, 7.5, and 7.6.

B.2 Digital Computer Solution of Ordinary Differential Equations

The purpose of this section is to present a brief introduction to the solution of ordinary differential equations by numerical techniques. The treatment here is simple and is intended to introduce the subject of numerical analysis to the reader who wishes to see how equations can be solved numerically.

One effective method of introducing a subject is to turn immediately to a simple example that can be solved without getting completely immersed in details. We shall use this technique. Our sample problem is the dc exciter buildup equation from Chapter 7, which was solved by integration in Examples 7.4–7.6. Since the solution is known, our numerical exercise will serve as a check on the work of Chapter 7. However, the real reason for choosing this example is that it is a scalar (one-dimensional) system that we can solve numerically with relative ease. Larger n-dimensional systems of equations are more challenging, but the principles are the same. The nonlinear differential equation here is

$$\dot{v}_F = \frac{dv_F}{dt} = \frac{1}{\tau_E}(v - Ri) \tag{B.11}$$

which we will solve by numerical techniques using a digital computer. Such problems are generally called "initial value problems" because the dependent variable v_F is known to have the initial value (at $t = 0$) of $v_F(0) = v_{F0}$.

B.2.1 Brief survey of numerical methods

There are several well-documented methods for solving the initial value problem by numerical integration. All methods divide the time domain into small segments Δt long

and solve for the value of v_F at the end of each segment. In doing this there are three problems: getting the integration started, the speed of computation, and the generation of errors. Some methods are self-starting and others are not; therefore, a given computation scheme may start the integration using one method and then change to another method for increased speed or accuracy. Speed is important because, although the digital computer may be fast, any process that generates a great deal of computation may be expensive. Thus, for example, choosing Δt too small may greatly increase the cost of a computed result and may not provide enough improvement in accuracy to be worth the extra cost.

A brief outline of some known methods of numerical integration is given in Table B.2. Note that the form of equation is given in each case as an nth-order equation. However, it is easily shown that any nth-order equation can be written as n first-order equations. Thus instead of

$$v^{(n)} = f(v, t) \tag{B.12}$$

we may write

$$\begin{aligned} \dot{x}_1 &= f_1(v, t) \\ \dot{x}_2 &= f_2(v, t) \\ &\cdots\cdots \\ \dot{x}_n &= f_n(v, t) \end{aligned}$$

or in matrix form

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, t) \tag{B.13}$$

Thus we concern ourselves primarily with the solution of a first-order equation.

Table B.2. Some Methods of Numerical Integration of Differential Equations

Method	Form of equation	Order of errors	Remarks
Direct integration, trapezoidal rule, Simpson's rule	$v^{(n)} = f(t)$	Δt	Must know $n-1$ derivatives to solve for $v^{(n)}$
Euler	$v^{(n)} = f(v, t)$	$(\Delta t)^2$	Self-starting
Modified Euler (Heun)	$v^{(n)} = f(v, t)$	$(\Delta t)^3$	Self-starting predictor-corrector
Runge-Kutta	$v^{(n)} = f(v, t)$	$(\Delta t)^3$	Self-starting, slow
Milne	$v^{(n)} = f(v, t)$	$(\Delta t)^5$	Start by Runge-Kutta or Taylor series
Hamming	$v^{(n)} = f(v, t)$	...	Imposes maximum condition on Δt for stable solution
Crane	$v^{(n)} = f(v, t)$	...	Varies size of Δt to control error

A complete analysis of every method in Table B.2 is beyond the scope of this appendix and the interested reader is referred to the many excellent references on the subject. Instead, we will investigate only the modified Euler method in enough detail to be able to work a simple problem.

B.2.2 Modified Euler method

Consider the first-order differential equation

$$\dot{v} = f(v, t) \tag{B.14}$$

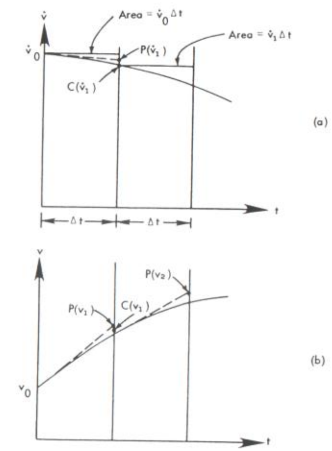

Fig. B.10. Graphical interpretation of the predictor-corrector routine: (a) $\dot{v}$ versus t, (b) v versus t.

where v is known for $t = 0$ (the initial value). Suppose the curves for v and $\dot{v}$ are as shown in Fig. B.10, where the time base has been divided into finite intervals Δt wide. Now define

$$\dot{v}_0 = f(v_0, 0) \tag{B.15}$$

which gives the initial slope of the v versus t curve. Next a *predicted* value for v at the end of the first interval is computed. If we define $v = v_1$ when $t = \Delta t$, we compute the *predicted* value v_1 as

$$P(v_1) = v_0 + \dot{v}_0 \Delta t \tag{B.16}$$

which is an extension of the initial slope out to the end of the first interval, as shown in Figure B.10(b). But $\dot{v}_0 \Delta t$ is the rectangular area shown in Figure B.10(a) and is obviously larger than the true area under the $\dot{v}$ versus t curve, so we conclude that $P(v_1)$ is too large [also see Figure B.10(b)].

Suppose we now approximate the value of $\dot{v}_1$ by substituting $P(v_1)$ into the given differential equation (B.14). Calling this value $P(\dot{v}_1)$, we compute

$$P(\dot{v}_1) = f[P(v_1), \Delta t] \tag{B.17}$$

Now approximate the true area under the $\dot{v}$ versus t curve between 0 and Δt by a trapezoid whose top is the straight line from $\dot{v}_0$ to $P(\dot{v}_1)$, as shown by the dashed line in Figure B.10(a). Using this area rather than the rectangular area, we compute a corrected value of v_1, which we call $C(v_1)$,

$$C(v_1) = v_0 + \{[\dot{v}_0 + P(\dot{v}_1)]/2\} \Delta t \tag{B.18}$$

We call (B.18) the corrector equation. Now we substitute the corrected value of v_1, $C(v_1)$, into the original equation to get a corrected $\dot{v}_1$.

$$C(\dot{v}_1) = f[C(v_1), \Delta t] \tag{B.19}$$

We now repeat this operation, using $C(\dot{v}_1)$ in (B.18) rather than $P(\dot{v}_1)$ to obtain an even better value for $C(v_1)$. This is done over and over again until successive values of $C(v_1)$ differ from one another by less than some prescribed precision index or until

$$C(v_1)^k - C(v_1)^{k-1} \leqq \epsilon \tag{B.20}$$

where k is the iteration number and ϵ is some convenient, small precision index (10^{-6}, for example). Once v_1 is determined as above, we use it as the starting point to find v_2 by the same method.

The general form of predictor and corrector equations is

$$P(v_{i+1}) = v_i + \dot{v}_i(\Delta t) \tag{B.21}$$

$$C(v_{i+1}) = v_i + \{[\dot{v}_i + P(\dot{v}_{i+1})]/2\} \Delta t \tag{B.22}$$

B.2.3 Use of the modified Euler method

Example B.3

Solve the separately excited buildup curve by the predictor-corrector method of numerical integration. Use numerical values from Example 7.4.

Solution

The equation requiring solution is

$$\tau_E \dot{v}_F = v_p - Ri \tag{B.23}$$

where i as a function of v_F is known from Table 7.3. We could proceed in two different ways at this point. We could store the data of Table 7.3 in the computer and use linear (or other means) interpolation to compute values of i for v_F between given data points. Thus using linear interpolation, we have for any value of v between v_1 and v_2

$$i = i_1 + (i_2 - i_1)(v - v_1)/(v_2 - v_1) \tag{B.24}$$

In this way we can compute the value of i corresponding to any v_F and substitute in (B.23) to find $\dot{v}_F$. An alternative method is to use an approximate formula to represent the nonlinear relationship between v_F and i. Thus, by the Frohlich equation,

$$i = bv_F/(a - v_F) \tag{B.25}$$

where a and b may be found as in Example 7.2.

Let us proceed using the latter of the two methods, where from Example 7.2 we have

$$a = 279.9 \qquad b = 5.65$$

Thus (B.23) becomes

$$\dot{v}_F = \frac{v_p}{\tau_E} - \frac{Rbv_F}{\tau_E(a - v_F)} \tag{B.26}$$

or

$$\dot{v}_F = 500 - 282.5\, v_F/(279.9 - v_F) \tag{B.27}$$

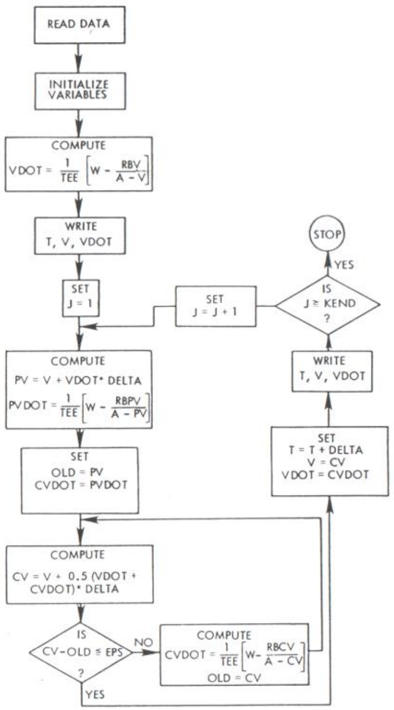

Fig. B.11. Computer flow diagram, separately excited case.

To avoid confusion in programming, we drop the subscript on v_F, represent v_p by a constant W, and replace τ by T to write

$$\dot{v} = W/T - (Rb/T)[v/(a - v)] \tag{B.28}$$

The data that must be input to begin the solution is shown in Table B.3 with certain additional variables that must be defined.

The computer flow diagram is shown in Figure B.11 for the separately excited case. The FORTRAN coding is given in Figure B.12. The solution is printed in tabular form in Table B.4 for values of t from 0 to 0.8 s. Note that both v_F and $\dot{v}_F$ are given. The derivative may not be needed, but it is known and can just as well be printed. The computed results agree almost exactly with the results of Example 7.4 and are therefore not plotted.


```
      VDOT1(W,V) = (W-R*B*V/(A-V))/TEE
      READ(1,101)W,TEE,R,B,A,VO,DELTA,KEND,EPS
101   FORMAT (F5.2,F4.3,F5.2,F5.3,F6.3,F5.2,F5.4,I3,F7.7)
      V = VO
      VDOT = 0.0
      PV = 0.0
      CV = 0.0
      PVDOT = 0.0
      CVDOT = 0.0
      T = 0.0
      VDOT = VDOT1 (W,V)
      WRITE(3,110)T,V,VDOT
      DO 200 J = 1, KEND
105   PV = V + VDOT*DELTA
      PVDOT = VDOT1 (W,PV)
102   OLD = PV
103   CVDOT = PVDOT
104   CV = V + 0.5*(VDOT + CVDOT)*DELTA
      IF(CV-OLD-EPS) 107,107,106
106   CVDOT = VDOT1(W,CV)
      OLD = CV
      GO TO 104
107   T = T + DELTA
      V = CV
      VDOT = CVDOT
      WRITE(3,110)T,V,VDOT
110   FORMAT(' ',F10.3,F10.2,F10.2)
200   CONTINUE
      STOP
      END
```

Fig. B.12. FORTRAN coding for the separately excited case.

Table B.3. Data and Variable Symbols, Names, and Formats

Symbol	Name	Format	Constant	Variable
v_p	W	F5.2	x	
T	TEE	F4.3	x	
R	R	F5.2	x	
b	B	F5.3	x	
a	A	F6.3	x	
$v(0)$	VO	F5.2	x	
Δt	DELTA	F5.4	x	
—	KEND	I3	x	
ϵ	EPS	F7.7	x	
v	V	F5.2		x
$\dot{v}$	VDOT	F6.2		x
$P(v_{i+1})$	PVDOT			x
$C(v_{i+1})$	CVDOT			x
$P(\dot{v}_{i+1})$	PV			x
$C(\dot{v}_{i+1})$	CV			x
t	T	F5.3		x

Table B.4. Separately Excited Results in Tabular Form

t	v_F	$\dot{v}_F$	t	v_F	$\dot{v}_F$
			0.400	158.55	130.72
0.0	40.00	452.90	0.410	159.82	123.82
0.010	44.50	446.55	0.420	161.02	117.15
0.020	48.93	440.10	0.430	162.16	110.72
0.030	53.30	433.50	0.440	163.24	104.52
0.040	57.60	426.75	0.450	164.26	98.58
0.050	61.83	419.84	0.460	165.21	92.87
0.060	66.00	412.78	0.470	166.11	87.42
0.070	70.09	405.57	0.480	166.96	82.20
0.080	74.11	398.20	0.490	167.76	77.23
0.090	78.05	390.69	0.500	168.51	72.50
0.100	81.92	383.03	0.510	169.21	68.00
0.110	85.71	375.23	0.520	169.87	63.73
0.120	89.42	367.29	0.530	170.49	59.68
0.130	93.06	359.21	0.540	171.06	55.85
0.140	96.61	351.01	0.550	171.60	52.23
0.150	100.08	342.68	0.560	172.11	48.82
0.160	103.46	334.24	0.570	172.58	45.59
0.170	106.76	325.70	0.580	173.02	42.56
0.180	109.97	317.05	0.590	173.43	39.71
0.190	113.10	308.32	0.600	173.82	37.03
0.200	116.14	299.52	0.610	174.17	34.51
0.210	119.09	290.65	0.620	174.51	32.15
0.220	121.95	281.74	0.630	174.82	29.94
0.230	124.72	272.79	0.640	175.11	27.87
0.240	127.41	263.82	0.650	175.38	25.93
0.250	130.00	254.84	0.660	175.63	24.12
0.260	132.50	245.88	0.670	175.86	22.43
0.270	134.92	236.94	0.680	176.08	20.85
0.280	137.24	228.05	0.690	176.28	19.37
0.290	139.48	219.21	0.700	176.46	18.00
0.300	141.63	210.46	0.710	176.64	16.72
0.310	143.69	201.80	0.720	176.80	15.52
0.320	145.66	193.26	0.730	176.95	14.41
0.330	147.56	184.84	0.740	177.09	13.38
0.340	149.36	176.57	0.750	177.22	12.41
0.350	151.09	168.45	0.760	177.34	11.52
0.360	152.73	160.51	0.770	177.45	10.68
0.370	154.30	152.76	0.780	177.55	9.91
0.380	155.79	145.20	0.790	177.65	9.19
0.390	157.20	137.85	0.800	177.73	8.52

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appendix C

Normalization

There are many ways that equations can be normalized, and no one system is clearly superior to the others [1, 2, 3]. For the study of system dynamic performance it is important to choose a normalization scheme that provides a convenient *simulation* of the equations. At the same time it is also important to consider the traditions that have been established over the years [1, 2] and either comply wholly or provide a clear transition to a new system.

Having carefully considered a number of normalization schemes for synchronous machines and weighed the merits of each, the authors have adopted the following guidelines against which any normalization system should be measured.

1. *The system voltage equations must be exactly the same whether the equations are in* pu *or* MKS *units.* This means that the equations are symbolically always the same and no normalization constants are required in the pu equations.
2. *The system power equation must be exactly the same whether the equation is in* pu *or* MKS *units.* This means that power is invariant in undergoing the normalization. Thus both before and after normalization we may write

$$p = kv^t i \tag{C.1}$$

and k is the same both before and after normalization.

3. *All mutual inductances must be capable of representation as tee circuits after normalization.* This requirement is included to simplify the *simulation* of the pu equations.
4. *The major* pu *impedances traditionally provided by the manufacturers must be maintained in the adopted system for the convenience of the users.* Other pu impedances must be related to and easily derived from the data supplied by the manufacturer.

The normalization scheme used by U.S. manufacturers does not satisfy requirement 2. The manufacturers use the original Park's transformation, as given by (4.22), which is different from the transformation used in this book, as given by (4.5). However, the pu system is to be developed so that *the same* pu *stator and rotor impedance values are obtained.*

C.1 Normalization of Mutually Coupled Coils

Consider the ideal transformer shown in Figure C.1. First we write the equations in MKS quantities, i.e., volts, amperes, ohms, and henrys.

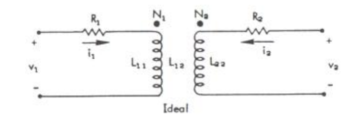

Fig. C.1. Schematic diagram of an ideal transformer.

$$v_1 = R_1 i_1 + L_{11}\frac{di_1}{dt} + L_{12}\frac{di_2}{dt}\ \text{V}$$

$$v_2 = R_2 i_2 + L_{22}\frac{di_2}{dt} + L_{21}\frac{di_1}{dt}\ \text{V} \tag{C.2}$$

where, in terms of the mutual permeance $\mathcal{P}_m$ and the coil turns N, $L_{jk} = \mathcal{P}_m N_j N_k$ for $j, k = 1, 2$. Now choose base values for voltage, current, and time in each circuit, i.e.,

For circuit 1: $V_{1B} I_{1B} t_{1B}$

For circuit 2: $V_{2B} I_{2B} t_{2B}$

Then since any quantity is the product of its per unit and base quantities, we have, using the subscript u to clearly distinguish pu quantities,

$$V_{1B} v_{1u} = R_1 I_{1B} i_{1u} + \frac{L_{11} I_{1B}}{t_{1B}}\frac{di_{1u}}{dt_{1u}} + \frac{L_{12} I_{2B}}{t_{2B}}\frac{di_{2u}}{dt_{2u}}\ \text{V}$$

$$V_{2B} v_{2u} = R_2 I_{2B} i_{2u} + \frac{L_{22} I_{2B}}{t_{2B}}\frac{di_{2u}}{dt_{2u}} + \frac{L_{21} I_{1B}}{t_{1B}}\frac{di_{1u}}{dt_{1u}}\ \text{V} \tag{C.3}$$

Dividing each equation by its base voltage, we have the pu (normalized) voltage equations

$$v_{1u} = \frac{R_1}{V_{1B}/I_{1B}} i_{1u} + \frac{L_{11} I_{1B}}{V_{1B} t_{1B}}\frac{di_{1u}}{dt_{1u}} + \frac{L_{12} I_{2B}}{V_{1B} t_{2B}}\frac{di_{2u}}{dt_{2u}}$$

$$v_{2u} = \frac{R_2}{V_{2B}/I_{2B}} i_{2u} + \frac{L_{22} I_{2B}}{V_{2B} t_{2B}}\frac{di_{2u}}{dt_{2u}} + \frac{L_{21} I_{1B}}{V_{2B} t_{1B}}\frac{di_{1u}}{dt_{1u}} \tag{C.4}$$

We can define

$$R_{1u} = \frac{R_1}{V_{1B}/I_{1B}} = \frac{R_1}{R_{1B}} \qquad R_{2u} = \frac{R_2}{V_{2B}/I_{2B}} = \frac{R_2}{R_{2B}}$$

$$L_{11u} = \frac{L_{11}}{V_{1B} t_{1B}/I_{1B}} = \frac{L_{11}}{L_{1B}} \qquad L_{22u} = \frac{L_{22}}{V_{2B} t_{2B}/I_{2B}} = \frac{L_{22}}{L_{2B}} \tag{C.5}$$

Now examine the mutual inductance coefficients. To preserve reciprocity, we require that

$$L_{12} I_{2B}/V_{1B} t_{2B} = L_{21} I_{1B}/V_{2B} t_{1B}$$

and since $L_{12} = L_{21}$ H, we compute

$$V_{1B} I_{1B}/t_{1B} = V_{2B} I_{2B}/t_{2B}$$

or

$$S_{1B}/t_{1B} = S_{2B}/t_{2B} \tag{C.6}$$

The ideal transformer is also characterized as having the following constraints on primary and secondary quantities:

$$n = i_2/i_1 = v_1/v_2 \tag{C.7}$$

where $n = N_1/N_2$. Rewriting in terms of base and pu values, we have

$$n = I_{2B}i_{2u}/I_{1B}i_{1u} = V_{1B}v_{1u}/V_{2B}v_{2u}$$

Thus the pu turns ratio n_u must be

$$n_u = i_{2u}/i_{1u} = nI_{1B}/I_{2B} = v_{1u}/v_{2u} = nV_{2B}/V_{1B} \tag{C.8}$$

and base quantities are often chosen to make $n_u = 1$. From (C.8) we compute

$$I_{1B}/I_{2B} = V_{2B}/V_{1B}$$

or

$$V_{1B}I_{1B} = V_{2B}I_{2B} \qquad S_{1B} = S_{2B} \triangleq S_B \tag{C.9}$$

Combining with (C.6), it is apparent that we must have

$$t_{1B} = t_{2B} \triangleq t_B \tag{C.10}$$

and the mutual inductance terms of the voltage equation (C.4) become

$$L_{12u} = \frac{L_{12}}{V_{1B}t_B/I_{2B}} = \frac{L_{12}}{L_{12B}} \qquad L_{21u} = \frac{L_{21}}{V_{2B}t_B/I_{1B}} = \frac{L_{21}}{L_{21B}} = \frac{L_{12}}{L_{12B}} \tag{C.11}$$

Then the voltage equation is exactly the same in pu as in volts, and the first requirement is satisfied. Furthermore, if this identical relationship exists between currents and voltages, the power is also invariant and the second requirement is also met.

C.2 Equal Mutual Flux Linkages

To adapt the voltage equations to a pu tee circuit, we divide the coil inductances into a leakage and a magnetizing inductance; i.e.,

$$L_{11} = \ell_1 + L_{m1} \qquad L_{22} = \ell_2 + L_{m2} \quad \text{H} \tag{C.12}$$

From the flux linkage equations we write (in MKS units)

$$\begin{bmatrix}\lambda_1\\ \lambda_2\end{bmatrix} = \begin{bmatrix}L_{11} & L_{12}\\ L_{21} & L_{22}\end{bmatrix}\begin{bmatrix}i_1\\ i_2\end{bmatrix} = \begin{bmatrix}\ell_1 & 0\\ 0 & \ell_2\end{bmatrix}\begin{bmatrix}i_1\\ i_2\end{bmatrix} + \begin{bmatrix}L_{m1} & L_{12}\\ L_{21} & L_{m2}\end{bmatrix}\begin{bmatrix}i_1\\ i_2\end{bmatrix} \tag{C.13}$$

Injecting a base current in circuit 1 with circuit 2 open, i.e., with $i_1 = I_{1B}$ and $i_2 = 0$, gives the following mutual flux linkages

$$\lambda_{m1} = L_{m1}I_{1B} \qquad \lambda_{m2} = L_{21}I_{1B} \quad \text{Wb turns} \tag{C.14}$$

In pu these flux linkages are

$$\lambda_{m1u} = \lambda_{m1}/\lambda_{1B} = L_{m1}I_{1B}/L_{1B}I_{1B} = L_{m1}/L_{1B} \tag{C.15}$$

$$\lambda_{m2u} = \lambda_{m2}/\lambda_{2B} = L_{21}I_{1B}/L_{2B}I_{2B} \tag{C.16}$$

Equal pu mutual flux linkages require that

$$\lambda_{m1u} = \lambda_{m2u} \tag{C.17}$$

or

$$L_{m1}/L_{1B} = L_{m1u} = L_{21}I_{1B}/L_{2B}I_{2B} \tag{C.18}$$

Following a similar procedure, we can show that injecting a base current in circuit 2 with circuit 1 open (i.e., with $i_2 = I_{2B}$ and $i_1 = 0$) gives the following pu flux linkages:

$$\lambda_{m1u} = L_{12}I_{2B}/L_{1B}I_{1B} \qquad \lambda_{m2u} = L_{m2}/L_{2B} \tag{C.19}$$

Again equal pu flux linkages give

$$L_{m2}/L_{2B} = L_{m2u} = L_{12}I_{2B}/L_{1B}I_{1B} \tag{C.20}$$

From $S_{1B} = S_{2B}$

$$I_{1B}^2L_{1B} = I_{2B}^2L_{2B} \tag{C.21}$$

and from (C.20) and (C.21)

$$L_{m2}/L_{2B} = L_{m2u} = L_{12}I_{1B}/L_{2B}I_{2B} \tag{C.2}$$

Comparing (C.18) and (C.22),

$$L_{m1u} = L_{m2u} \triangleq L_{mu} \tag{C.2}$$

Now using (C.12), (C.20), (C.22), and (C.23) in the voltage equation (C.4),

$$v_{1u} = R_{1u}i_{1u} + \ell_1\dot{i}_{1u} + L_{mu}(\dot{i}_{1u} + \dot{i}_{2u})$$
$$v_{2u} = R_{2u}i_{2u} + \ell_2\dot{i}_{2u} + L_{mu}(\dot{i}_{1u} + \dot{i}_{2u}) \tag{C.2}$$

which is represented schematically by the tee circuit shown in Figure C.2. Thus t third requirement is satisfied.

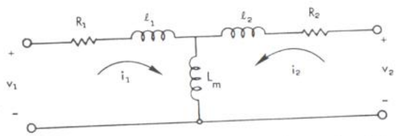

Fig. C.2. Tee circuit representation of a transformer.

An interesting point to be made here is that the requirement for equal pu mu flux linkages is the same as equal base MMF's.

$$S_B(L_{m1}/L_{1B}) = S_B(L_{m2}/L_{2B})$$

or

$$(L_{m1}/L_{1B})(I_{1B}^2L_{1B}) = (L_{m2}/L_{2B})(I_{2B}^2L_{2B})$$
$$L_{m1}I_{1B}^2 = L_{m2}I_{2B}^2 \quad (\text{C}$$

or in terms of the mutual permeance $\mathcal{P}_m$

$$\mathcal{P}_mN_1^2I_{1B}^2 = \mathcal{P}_mN_2^2I_{2B}^2 \quad (\text{C}$$

or

$$N_1^2I_{1B}^2 = N_2^2I_{2B}^2 \quad ($$

or in terms of MMF

$$F_{1B} = F_{2B} \quad ($$

The ideal transformer is also characterized as having the following constraints on primary and secondary quantities:

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where $n = N_1/N_2$. Rewriting in terms of base and pu values, we have

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Thus the pu turns ratio n_u must be

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$$I_{1B}/I_{2B} = V_{2B}/V_{1B}$$

or

$$V_{1B}I_{1B} = V_{2B}I_{2B} \qquad S_{1B} = S_{2B} \triangleq S_B \tag{C.9}$$

Combining with (C.6), it is apparent that we must have

$$t_{1B} = t_{2B} \triangleq t_B \tag{C.10}$$

and the mutual inductance terms of the voltage equation (C.4) become

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Then the voltage equation is exactly the same in pu as in volts, and the first requirement is satisfied. Furthermore, if this identical relationship exists between currents and voltages, the power is also invariant and the second requirement is also met.

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From the flux linkage equations we write (in MKS units)

$$\begin{bmatrix}\lambda_1\\ \lambda_2\end{bmatrix} = \begin{bmatrix}L_{11} & L_{12}\\ L_{21} & L_{22}\end{bmatrix}\begin{bmatrix}i_1\\ i_2\end{bmatrix} = \begin{bmatrix}\ell_1 & 0\\ 0 & \ell_2\end{bmatrix}\begin{bmatrix}i_1\\ i_2\end{bmatrix} + \begin{bmatrix}L_{m1} & L_{12}\\ L_{21} & L_{m2}\end{bmatrix}\begin{bmatrix}i_1\\ i_2\end{bmatrix} \tag{C.13}$$

Injecting a base current in circuit 1 with circuit 2 open, i.e., with $i_1 = I_{1B}$ and $i_2 = 0$, gives the following mutual flux linkages

$$\lambda_{m1} = L_{m1}I_{1B} \qquad \lambda_{m2} = L_{21}I_{1B} \quad \text{Wb turns} \tag{C.14}$$

In pu these flux linkages are

$$\lambda_{m1u} = \lambda_{m1}/\lambda_{1B} = L_{m1}I_{1B}/L_{1B}I_{1B} = L_{m1}/L_{1B} \tag{C.15}$$

$$\lambda_{m2u} = \lambda_{m2}/\lambda_{2B} = L_{21}I_{1B}/L_{2B}I_{2B} \tag{C.16}$$

Equal pu mutual flux linkages require that

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$$L_{m1}/L_{1B} = L_{m1u} = L_{21}I_{1B}/L_{2B}I_{2B} \tag{C.18}$$

Following a similar procedure, we can show that injecting a base current in circuit 2 with circuit 1 open (i.e., with $i_2 = I_{2B}$ and $i_1 = 0$) gives the following pu flux linkages:

$$\lambda_{m1u} = L_{12}I_{2B}/L_{1B}I_{1B} \qquad \lambda_{m2u} = L_{m2}/L_{2B} \qquad \text{(C.19}$$

Again equal pu flux linkages give

$$L_{m2}/L_{2B} = L_{m2u} = L_{12}I_{2B}/L_{1B}I_{1B} \qquad \text{(C.20}$$

From $S_{1B} = S_{2B}$

$$I_{1B}^2L_{1B} = I_{2B}^2L_{2B} \qquad \text{(C.21}$$

and from (C.20) and (C.21)

$$L_{m2}/L_{2B} = L_{m2u} = L_{12}I_{1B}/L_{2B}I_{2B} \qquad \text{(C.2:}$$

Comparing (C.18) and (C.22),

$$L_{m1u} = L_{m2u} \triangleq L_{mu} \qquad \text{(C.2}$$

Now using (C.12), (C.20), (C.22), and (C.23) in the voltage equation (C.4),

$$v_{1u} = R_{1u}i_{1u} + \ell_1\dot{i}_{1u} + L_{mu}(\dot{i}_{1u} + \dot{i}_{2u})$$
$$v_{2u} = R_{2u}i_{2u} + \ell_2\dot{i}_{2u} + L_{mu}(\dot{i}_{1u} + \dot{i}_{2u}) \qquad \text{(C.2}$$

which is represented schematically by the tee circuit shown in Figure C.2. Thus t third requirement is satisfied.

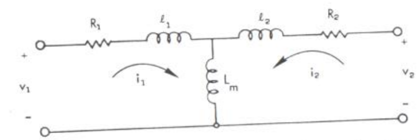


Fig. C.2. Tee circuit representation of a transformer.

An interesting point to be made here is that the requirement for equal pu mu flux linkages is the same as equal base MMF's.

$$S_B(L_{m1}/L_{1B}) = S_B(L_{m2}/L_{2B})$$

or

$$(L_{m1}/L_{1B})(I_{1B}^2L_{1B}) = (L_{m2}/L_{2B})(I_{2B}^2L_{2B})$$
$$L_{m1}I_{1B}^2 = L_{m2}I_{2B}^2 \qquad \text{(C}$$

or in terms of the mutual permeance $\mathcal{P}_m$

$$\mathcal{P}_m N_1^2 I_{1B}^2 = \mathcal{P}_m N_2^2 I_{2B}^2 \qquad \text{((}$$

or

$$N_1^2I_{1B}^2 = N_2^2I_{2B}^2 \qquad \text{((}$$

or in terms of MMF

$$F_{1B} = F_{2B} \qquad \text{(}$$

C.2.1 Summary

The first three normalization specifications require that

1. All circuits must have the same VA base (C.9).
2. All circuits must have the same time base (C.6), (C.9), and (C.10).
3. The requirement of a common pu tee circuit means equal pu magnetizing inductance in all circuits (C.23). This requires equal pu mutual flux linkages (C.17), which in turn requires that the base MMF be the same in all circuits (C.28).

C.3 Comparison with Manufacturers' Impedances

We now select the base stator and rotor quantities to satisfy the fourth requirement, namely, to give the same pu impedances as those supplied by the manufacturers.

The choice of the stator base voltage V_{1B} and the stator base current I_{1B} determines the base stator impedance. Because of a certain awkwardness in the original Park's transformation resulting from the fact that the transformation is not power invariant, a system of stator base quantities is used by U.S. manufacturers that facilitates the choice of rotor base quantities. For this reason it is customary to use a stator base voltage equal to the *peak* line-to-neutral voltage and a stator base current equal to the *peak* line current. Such a choice, along with the requirement of equal base ampere turns (or equal pu mutuals), leads to a rotor VA base equal to the three-phase stator VA base.

Since the transformation used in this book is power invariant, the awkwardness referred to above is not encountered. A variety of possible stator base quantities can be chosen to satisfy the condition of having the same pu stator impedances as supplied by the manufacturers. For example, among the possible choices for the stator base: peak line-to-neutral voltage and peak line current (same as the manufacturers), rms line-to-neutral voltage and rms line current, or rms line voltage and $\sqrt{3}$ times rms line current. Note that in all these choices the base stator impedance is the same. However, the other three requirements stated in the previous sections may not be satisfied.

To illustrate, it would appear that adoption of stator base quantities of rated rms line voltage and $\sqrt{3}$ times line current would be attractive. The factor of $\sqrt{3}$ appearing in the d and q axis equations of Chapter 4 would be eliminated. Careful examination, however, would reveal that the requirement of having the same identical equation hold for the MKS and the pu systems would be violated. For example, if the phase voltage $v_a = \sqrt{2}V\cos(\omega_R t + \alpha)$, the d and q axis voltages are obtained by a relation similar to that of (4.146)

$$v_d = -\sqrt{3}V\sin(\delta - \alpha) \qquad v_q = \sqrt{3}V\cos(\delta - \alpha) \quad \text{V} \tag{C.29}$$

where V = rms voltage to neutral. Choosing $V_{1B} = \sqrt{3}V_{LN}$ (rated), we get

$$v_{du} = -\frac{\sqrt{3}V\sin(\delta - \alpha)}{\sqrt{3}V_{LN}} = -(V/V_{LN})\sin(\delta - \alpha) \quad \text{pu}$$
$$v_{qu} = (V/V_{LN})\cos(\delta - \alpha) \quad \text{pu} \tag{C.30}$$

Note that (C.29) and (C.30) are not identical, and hence this choice of stator base quantities does not meet requirement number 1.

In this book the stator base quantities selected to meet the requirements stated above are

$$\begin{aligned} S_{1B} &= \text{rated per phase voltampere, VA} \\ V_{1B} &= \text{rated rms voltage to neutral, V} \\ I_{1B} &= \text{rated rms line current, A} \\ t_{1B} &= 1/\omega_R,\ \text{s} \end{aligned} \tag{C.31}$$

The rotor base quantities are selected to meet the conditions of equal S_B, t_B, and F_B (or λ_m). Equal VA base gives

$$V_{1B}I_{1B} = V_{2B}I_{2B} \quad \text{VA} \tag{C.32}$$

(The subscript 2 is used to indicate *any* rotor circuit. The same derivation applies to a field circuit or to an amortisseur circuit.) Equal mutual flux linkages require that the mutual flux linkage in the d axis stator produced by a base stator current would be the same as the d axis stator flux linkage produced by a d axis rotor base current. Thus in MKS units,

$$I_{1B}L_{m1} = I_{2B}\mathrm{k}M_F \qquad \mathrm{k} = \sqrt{3/2}$$

or

$$I_{2B} = (L_{m1}/\mathrm{k}M_F)I_{1B} = (1/k_F)I_{1B} \quad \text{A} \tag{C.33}$$

where $k_F = \mathrm{k}M_F/L_{m1}$.

From (C.32) and (C.33) we obtain for the rotor circuit base voltage

$$V_{2B} = V_{1B}I_{1B}/I_{2B} = k_F V_{1B} \tag{C.34}$$

From (C.33) and (C.34) for the rotor resistance base

$$R_{2B} = V_{2B}/I_{2B} = k_F^2(V_{1B}/I_{1B}) = k_F^2 R_{1B} \quad \Omega \tag{C.35}$$

The inductance base for the rotor circuit is then given by

$$L_{2B} = V_{2B}t_B/I_{2B} = (\mathrm{k}M_F/L_{m1})^2(V_{1B}/I_{1B})\left(\frac{1}{\omega_R}\right) = k_F^2 L_{1B} \tag{C.36}$$

The base for the mutual inductance is obtained from (C.11) and (C.33)

$$L_{12B} = \frac{V_{1B}t_B}{I_{2B}} = \frac{V_{1B}\left(\frac{1}{\omega_R}\right)}{(L_{m1}/\mathrm{k}M_F)I_{1B}} = k_F L_{1B} \tag{C.37}$$

The pu d axis mutual inductance is then given by

$$\mathrm{k}M_{Fu} = \frac{\mathrm{k}M_F}{L_{12B}} = \frac{\mathrm{k}M_F}{(\mathrm{k}M_F/L_{m1})L_{1B}} = \frac{L_{m1}}{L_{1B}} = L_{m1u} \tag{C.38}$$

Thus the value of the pu d axis mutual inductance of *any* rotor circuit is the same as the pu magnetizing inductance of the stator.

$$\mathrm{k}M_{Fu} = \mathrm{k}M_{Du} = M_{Ru} = L_{m1u} \tag{C.39}$$

A comparison between the pu system derived in this book and that used by U.S. manufacturers is given in the Table C.1. Note that the base inductances and resistances are the same in both systems.

Table C.3. Direct Axis Parameters in pu and MKS

Symbol	pu value	MKS value	Units
L_d	1.700	6.341 329 761	mH
L'_d	0.245		
L''_d	0.185		
L_{md}	1.550	5.781 800 664	mH
ℓ_d	0.150	0.559 529 097	mH
L_F	1.651 202 749	2.189 475 759	H
L_{mF}	1.550	2.055 282 084	H
ℓ_F	0.101 202 749	0.134 193 675	H
L_D	1.605 416 667		
L_{mD}	1.550		
ℓ_D	0.055 416 667		
M_F	1.265 5697	0.089 006 484	H
kM_F	1.550	0.109 010 235	H
M_D	1.265 5697		
kM_D	1.550		
M_R	1.550		
L_{MD}	0.028 378 3784		
r_a 25°C	0.791 607 397 × 10^{-3}	1.113	mΩ
r_a 125°C	1.096 463 455 × 10^{-3}	1.541 901 734	mΩ
r_F 25°C	...	0.2687 (not used)	Ω
r_F Hot	0.742 364 295 × 10^{-3}	0.371 097 586	Ω
r_D	13.099 135 90 × 10^{-3}		
τ_a	90.477 868 44	0.24	s
τ'_{d0}	2224.247 599	5.90	s
τ'_d	320.442 450 7	0.85	s
τ''_{d0}	11.482 945 69	0.030 459	s
τ''_d	8.670 795 726	0.023	s

Table C.4. Quadrature Axis Parameters in pu and MKS

Symbol	pu value	MKS value	Units
L_q	1.640	6.117 518 122	mH
L'_q	0.380 (not used)		
L''_q	0.185		
L_{mq}	1.490	5.557 989 025	mH
ℓ_q	0.150	0.559 529 097	mH
L_Q	1.525 808 581		
L_{mQ}	1.490		
ℓ_Q	0.035 808 581		
M_Q	1.216 579 905		
kM_Q	1.490		
L_{MQ}	0.028 357 4715		
r_a 25°C	0.791 607 397 × 10^{-3}	1.113	mΩ
r_a 125°C	1.096 463 455 × 10^{-3}	1.541 901 734	mΩ
r_Q	0.053 955 165		
τ'_{q0}	203.575 204	0.54	s
τ''_{q0}	28.274 333 89	0.075	s
τ''_q	3.189 482 785	8.460 365 85	ms

References

1. Rankin, A. W. Per unit impedances of synchronous machines. *AIEE Trans.* 64:569–841, 1945.
2. Lewis, W. A. A basic analysis of synchronous machines, Pt. 1. *AIEE Trans.* 77:436–56, 1958.
3. Harris, M. R., Lawrenson, P. J., and Stephenson, J. M. *Per Unit Systems: With Special Reference to Electrical Machines.* IEE Monogr. Ser. 4. Cambridge Univ. Press, 1970.
4. General Electric Co. Power system stability. Electric Utility Engineering Seminar, Section on Synchronous Machines. Schenectady, N.Y., 1973.

appendix D

Typical System Data

In studying system control and stability, it is often helpful to have access to typical system constants. Such constants help the student or teacher become acquainted with typical system parameters, and they permit the practicing engineer to estimate values for future installations.

The data given here were chosen simply because they were available to the authors and are probably typical. A rather complete set of data is given for various sizes of machines driven by both steam and hydraulic turbines. In most cases such an accumulation of information is not available without special inquiry. For example, data taken from manufacturers' bids are limited in scope, and these are often the only known data for a machine. Thus it is often necessary for the engineer to estimate or calculate the missing information.

Data are also provided that might be considered typical for certain prime mover systems. This is helpful in estimating simulation constants that can be used to represent other typical medium to large units. Finally, data are provided for typical transmission lines of various voltages. (See Tables D.1–D.8 at the end of this appendix.)

D.1 Data for Generator Units

Included here are all data normally required for dynamic simulation of the synchronous generator, the exciter, the turbine-governor system, and the power system stabilizer. The items included in the tabulations are specified in Table D.1.

Certain items in Table D.1 require explanation. Table references on these items are given in parentheses following the identifying symbol. An explanation of these referenced items follows.

(1) Short circuit ratio

The SCR is the "short circuit ratio" of a synchronous machine and is defined as the ratio of the field current required for rated open circuit voltage to the field current required for rated short circuit current [1]. Referring to Figure D.1, we compute

$$\mathrm{SCR} = I_B/I_S \ \text{pu} \tag{D.1}$$

It can be shown that

$$\mathrm{SCR} \simeq 1/x_d \ \text{pu} \tag{D.2}$$

where x_d is the saturated d axis synchronous reactance.

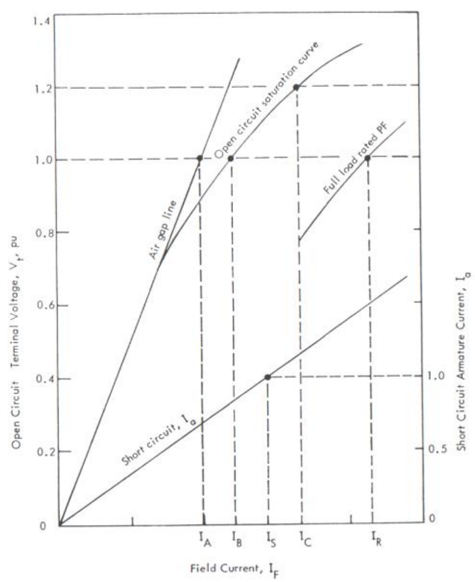


Fig. D.1. Open circuit, full load, and short circuit characteristics of a synchronous generator.

(2) Generator saturation

Saturation of the generator is often specified in terms of a pu saturation function S_G, which is defined in terms of the open circuit terminal voltage versus field current characteristic shown in Figure D.2. We compute

$$S_G \text{ at } V_{t1} = (I_{F2} - I_{F1})/I_{F1} \tag{D.3}$$

where (D.3) is valid for any point V_{t1} [2, 3]. With use of this definition, it is common to specify two values of saturation at V_t = 1.0 and 1.2 pu. These values are given under open circuit conditions so that V_t is actually the voltage behind the leakage reactance and is the voltage across L_{AD}, the pu saturated magnetizing inductance. Thus we can easily determine two saturation values from the generator saturation curve to use as the basis for defining a saturation function. From Figure D.1 we arbitrarily define

$$S_{G1.0} = (I_B - I_A)/I_A \tag{D.4}$$
$$S_{G1.2} = (I_C - 1.2I_A)/1.2I_A \tag{D.5}$$

and will use these two values to generate a saturation function.

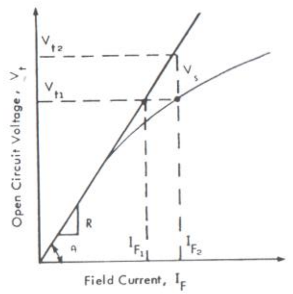


Fig. D.2. Construction used for computing saturation.

There are several ways to define a saturation function, one of which is given in Section 5.10.1 where we define

$$S_G = A_G e^{B_G V_\Delta} \tag{D.6}$$

where

$$V_\Delta = V_t - 0.8 \tag{D.7}$$

is the difference between the open circuit terminal voltage and the assumed saturation threshold of 0.8 pu. Since (D.6) contains two unknowns and the quantities S_G and V_Δ are known at two points, we can solve for A_G and B_G explicitly.

From the given data we write

$$S_{G1.0} = A_G e^{0.2B_G} \qquad 1.2S_{G1.2} = A_G e^{0.4B_G} \tag{D.8}$$

Rearranging and taking logarithms,

$$\ln(S_{G1.0}/A_G) = 0.2\,B_G \qquad \ln(1.2S_{G1.2}/A_G) = 0.4\,B_G \tag{D.9}$$

Then,

$$(S_{G1.0}/A_G)^2 = 1.2S_{G1.2}/A_G$$

or

$$A_G = S_{G1.0}^2/1.2S_{G1.2} \qquad B_G = 5\ln(1.2S_{G1.2}/S_{G1.0}) \tag{D.10}$$

Example D.1

Suppose that measurements on a given generator saturation curve provide the following data:

$$S_{G1.0} = 0.20 \qquad S_{G1.2} = 0.80$$

Then we compute, using (D.10),

$$A_G = (0.20)^2/1.2(0.80) = 0.04167 \qquad B_G = 5\ln(1.2 \times 0.8/0.20) = 7.843$$

This gives an idea of the order of magnitude of these constants; A_G is usually less than 0.1 and B_G is usually between 5 and 10.

The value of S_G determined above may be used to compute the open circuit voltage (or flux linkage) in terms of the *saturated* value of field current (or MMF). Referring again to Figure D.1, we write the voltage on the air gap line as

$$V_t = RI_F \tag{D.11}$$

Refer to Figure D.2. When saturation is present, current I_{F2} does not give $V_{t2} = RI_{F2}$ but only produces V_{F1}, or

$$V_{t1} = V_{t2} - V_s = RI_{F2} - V_s \tag{D.12}$$

where V_s is the drop in voltage due to saturation. But from Figure D.2

$$\tan\theta = R = V_s/(I_{F2} - I_{F1}) \tag{D.13}$$

From (D.3) we write

$$S_G = (I_{F2} - I_{F1})/I_{F1} = V_s/RI_{F1} = V_s/V_{t1} \tag{D.14}$$

Then from (D.12)

$$V_{t1} = RI_{F2} - S_G V_{t1} \tag{D.15}$$

where S_G is clearly a function of V_{t1}. Equation (D.15) describes how V_{t1} is reduced by saturation below its air gap value RI_{F2} at no load. Usually, we assume a similar reduction occurs under load.

Note that the exponential saturation function does not satisfy the definition (D.3) in the neighborhood of $V_t = 0.8$, where we assume that saturation begins. The computed saturation function has the shape shown in Figure D.3. Note that $S_G > 0$ for any V_Δ. The error is small, however, and the approximation solution is considered adequate in the neighborhood of 1.0 pu voltage. Note that A_G is usually a very small number, so the saturation computed for $V_t < 0.8$ is negligible.

Other methods of treating saturation are found in the literature [1, 2, 4, 5, 6, 7].

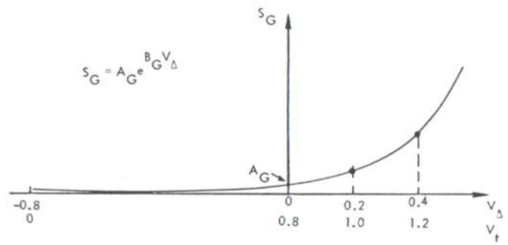


Fig. D.3. The approximate saturation function, S_G.

(3) Damping

It is common practice in stability studies to provide a means of adding damping that is proportional to speed or slip. This concept is discussed in Sections 2.3, 2.4, 2.9, 4.10, and 4.15 and is treated in the literature [8–12]. The method of introducing the damping is by means of a speed or slip feedback term similar to that shown in Figure 3.4, where D is the pu damping coefficient used to compute a damping torque T_d

defined as

$$T_d = D\omega_{\Delta u} \text{ pu} \tag{D.16}$$

where all quantities are in pu. The value used for D depends greatly on the kind of generator model used and particularly on the modeling of the amortisseur windings. For example, a damping of 1–3 pu is often used to represent damping due to turbine windage and load effects [2]. A much higher value, up to 25 pu is sometimes used as a representation of amortisseur damping if this important source of damping is omitted from the machine model.

The value of D also depends on the units of (D.16). In some simulations the torque is computed in megawatts. Then with the slip ω_Δ in pu

$$T_d = (S_{B3}D)\omega_{\Delta u} \text{ MW} \tag{D.17}$$

It is also common to see the slip computed in hertz, i.e., f_Δ Hz. Then (D.17) becomes

$$T_d = (S_{B3}D/f_R)f_\Delta = D'f_\Delta \text{ MW} \tag{D.18}$$

where S_{B3} is the three-phase MVA base, f_R is the base frequency in Hz, and f_Δ is the slip in Hz. A value sometimes used for D' in (D.18) is

$$D' = P_G/f_R \text{ MW/Hz} \tag{D.19}$$

wnere P_G is the scheduled power generated in MW for this unit. This corresponds to $D = P_G/S_{B3}$ pu.

(4) Voltage regulator type

The type of voltage regulator system is tabulated using an alphabetical symbol that corresponds to the block diagrams shown in Figures D.4–D.11. Excitation systems have undergone significant changes in the past decade, both in design and in the models for representing the various designs. The models proposed by the IEEE committee in 1968 [3] have been largely superseded by newer systems and alternate models for certain older systems. The approach used here is the alphabetic labeling adopted by the Western Systems Coordinating Council (WSCC), provided through private communication. The need for expanded modeling and common format for exchange of modeling data is under study by an IEEE working group at the time of publication of this book.

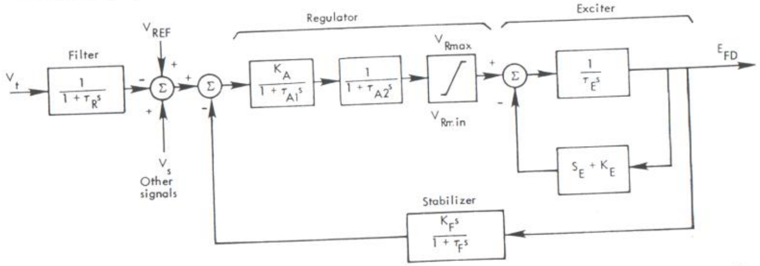


Fig. D.4. Type A—continuously acting dc rotating excitation system. Representative systems: (1) $T_R = 0$: General Electric NA143, NA108; Westinghouse Mag-A-Stat, WMA; Allis Chalmers Regulux; (2) $T_R \neq 0$: General Electric NA 101; Westinghouse Rototrol, Silverstat, TRA.

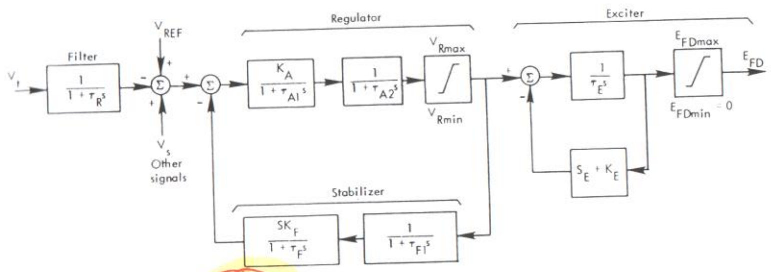


Fig. D.5. Type B—Westinghouse pre-1967 brushless.

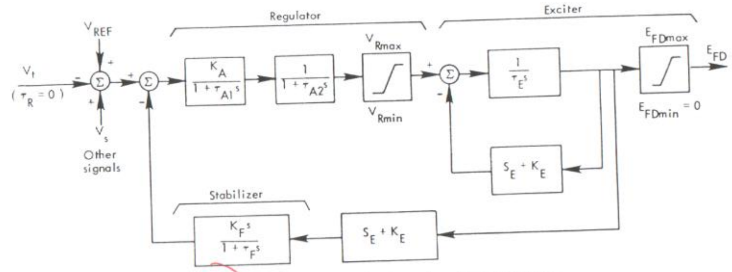


Fig. D.6. Type C—Westinghouse brushless since 1966.

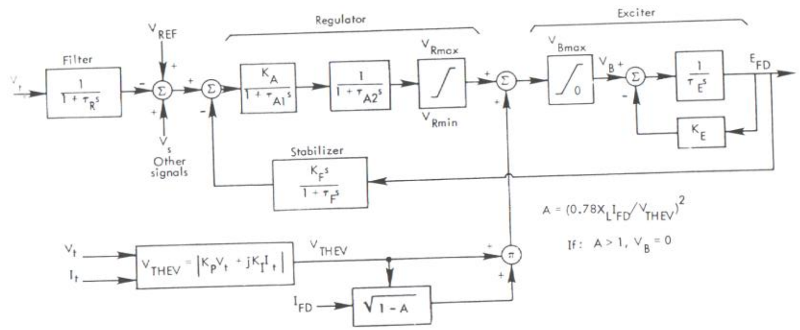


Fig. D.7. Type D—SCPT system.

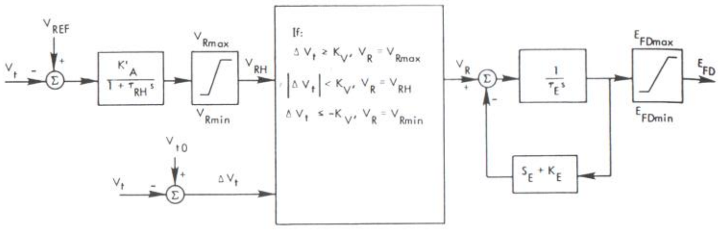


Fig. D.8. Type E—noncontinuously acting rheostatic excitation system. Representative systems: General Electric GFA4, Westinghouse BJ30.

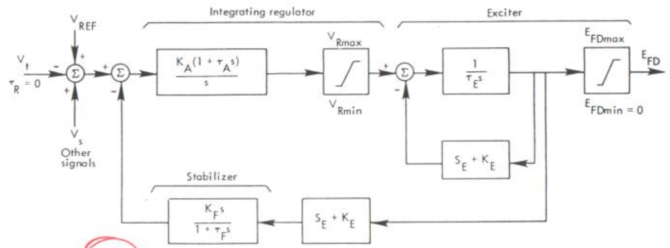


Fig. D.9. Type F—Westinghouse continuously acting brushless rotating alternator excitation system.

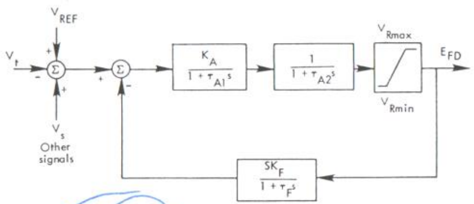


Fig. D.10. Type G—General Electric SCR excitation system.

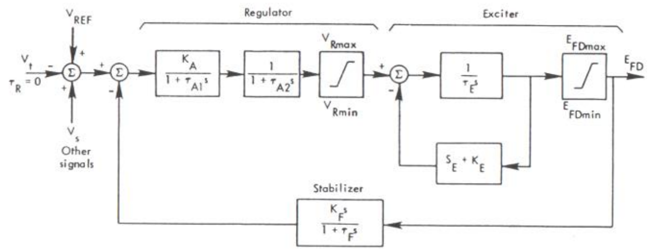


Fig. D.11. Type K—General Electric Alterrex.

Note that the regulator base voltage used to normalize V_R may be chosen arbitrarily. Since the exciter input signal is usually $V_R - (S_E + K_E)E_{FD}$, choosing a different base affects the constant S_E and K_E and also the gain K_A.

(5) Exciter saturation

The saturation of dc generator exciters is represented by an exponential model derived to fit the actual saturation curve at the exciter ceiling (max) voltage (zero field rheostat setting) and at 75% of ceiling. Referring to Figure D.12, we define the following constants at ceiling, 0.75 of ceiling and full load.

$$S_{E\max} = (A - B)/B \qquad S_{E.75\max} = (E - F)/F \qquad S_{EFL} = (C - D)/D \tag{D.20}$$

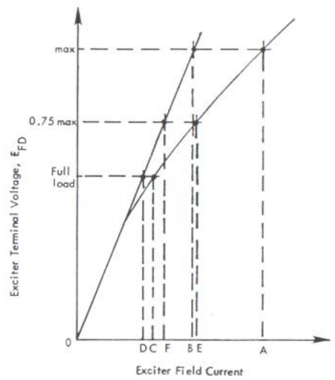


Fig. D.12. A dc exciter saturation curve.

Then in pu with E_{FDFL} as a base (actually, any convenient base may be used),

$$E_{FD\max} = E_{FD\max}(\mathrm{V})/E_{FDFL}(\mathrm{V}) = B/D \quad \mathrm{pu}$$

or

$$B = DE_{FD\max} \tag{D.21}$$

We can also compute

$$B/F = 4/3 = DE_{FD\max}/F$$

or

$$F = 0.75DE_{FD\max} \tag{D.22}$$

Combining (D.20)–(D.22) we can write

$$\begin{aligned} S_{E\max} &= (A - B)/B = (A - B)/DE_{FD\max} \\ S_{E.75\max} &= (E - F)/F = (E - F)/0.75DE_{FD\max} = (4/3)(E - F)/DE_{FD\max} \end{aligned} \tag{D.23}$$

Now define the saturation function

$$S_E \triangleq A_{EX}e^{B_{EX}E_{FD}} \tag{D.24}$$

which gives the approximate saturation for any E_{FD}. Suppose we are given the numerical values of saturation at $E_{FD\max}$ and $0.75E_{FD\max}$. These values are called $S_{E\max}$ and $S_{E.75\max}$ respectively. Using these two saturation values, we compute the two unknowns A_{EX} and B_{EX} as follows. At $E_{FD} = E_{FD\max}$

$$S_E = S_{E\max} = (A - B)/DE_{FD\max} = A_{EX}e^{B_{EX}E_{FD\max}} \tag{D.25}$$

and at $E_{FD} = 0.75E_{FD\max}$

$$S_E = S_{E.75\max} = (4/3)(E - F)/DE_{FD\max} = A_{EX}e^{B_{EX}(0.75E_{FD\max})} \tag{D.26}$$

We then solve (D.25) and (D.26) simultaneously to find

$$A_{EX} = S^4_{E.75\max}/S^3_{E\max} \qquad B_{EX} = (4/E_{FD\max})\ln(S_{E\max}/S_{E.75\max}) \tag{D.27}$$

(6) Governor representation

Three types of governor representation are specified in this appendix: a general governor model that can be used for both steam and hydro turbines, a cross-compound governor model, and a hydraulic governor model. The appropriate model is identified by the letters G, C, and H in the tabulation. The governor block diagrams are given in Figures D.13–D.15. The regulation R is the steady-state regulation or droop and is usually factory set at 5% for U.S. units.

R statitičnost turbinskog regulatora (obično je 5%)!

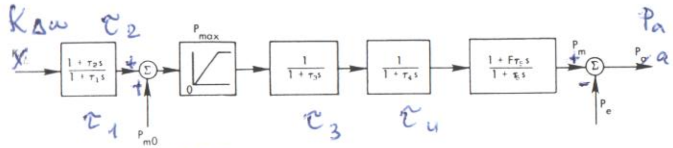
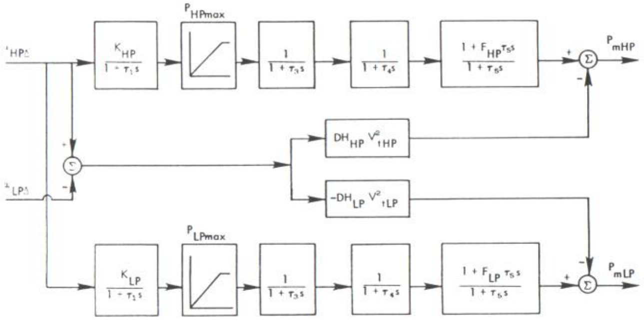


Fig. D.13. General purpose governor block diagram.



$$DH = 1/2\left[\frac{(x_d' - x_d'')\tau_{d0}''}{(x_d' + x_T)} + \frac{(x_q - x_q'')\tau_{q0}''}{(x_q + x_T)}\right]$$

Fig. D.14. Cross-compound governor block diagram.

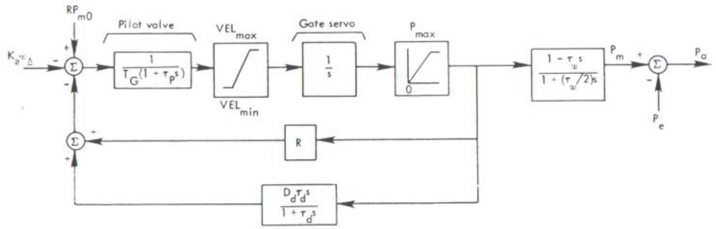


Fig. D.15. Hydroturbine governor block diagram.

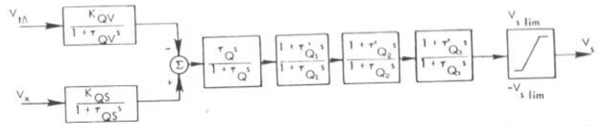


Fig. D.16. Power system stabilizer block diagram. Stabilizer types: (1) V_x = rotor slip = ω_Δ, (2) V_x = frequency deviation = f_Δ, (3) V_x = accelerating power = P_a.

(7) Power system stabilizer

The constants used for power system stabilizer (PSS) settings will always depend on the location of a unit electrically in the system, the dynamic characteristics of the system, and the dynamic characteristics of the unit. Still there is some merit in having approximate data that can be considered typical of stabilizer settings. Values given in Tables D.2–D.5 are actual settings used at certain locations and may be used as a rough estimate for stabilizer adjustment studies. The PSS block diagram is given in Figure D.16.

D.2 Data for Transmission Lines

Data are provided in Table D.8 for estimating the impedance of transmission lines. Usually, accurate data are available for transmission circuits, based on actual utility line design information. Table D.8 provides data for making rough estimates of transmission line impedances for a variety of common 60-Hz ac transmission voltages.

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Table D.1. Definitions of Tabulated Generator Unit Data

GENERATOR		
Unit no.		Arbitrary reference number
Rated MVA		Machine-rated MVA; base MVA for impedances
Rated kV		Machine-rated terminal voltage in kV; base kV for impedances
Rated PF		Machine-rated power factor
SCR	(1)	Machine short circuit ratio
x''_d	pu	Unsaturated *d* axis subtransient reactance
x'_d	pu	Unsaturated *d* axis transient reactance
x_d	pu	Unsaturated *d* axis synchronous reactance
x''_q	pu	Unsaturated *q* axis subtransient reactance
x'_q	pu	Unsaturated *q* axis transient reactance
x_q	pu	Unsaturated *q* axis synchronous reactance
r_a	pu	Armature resistance
x_ℓ or x_p	pu	Leakage or Potier reactance
r_2	pu	Negative-sequence resistance
x_2	pu	Negative-sequence reactance
x_0	pu	Zero-sequence reactance
τ''_d	s	*d* axis subtransient short circuit time constant
τ'_d	s	*d* axis transient short circuit time constant
τ''_{d0}	s	*d* axis subtransient open circuit time constant
τ'_{d0}	s	*d* axis transient open circuit time constant
τ''_q	s	*q* axis subtransient short circuit time constant
τ'_q	s	*q* axis transient short circuit time constant
τ''_{q0}	s	*q* axis subtransient open circuit time constant
τ'_{q0}	s	*q* axis transient open circuit time constant
τ_a	s	Armature time constant
W_R	MW·s	Kinetic energy of turbine + generator at rated speed in MJ or MW·s
r_F	Ω	Machine field resistance in Ω
$S_{G1.0}$	(2)	Machine saturation at 1.0 pu voltage in pu
$S_{G1.2}$	(2)	Machine saturation at 1.2 pu voltage in pu
E_{FDFL}	(2)	Machine full load excitation in pu
D	(3)	Machine load damping coefficient
EXCITER		
VR Type	(4)	Excitation system type
Name		Excitation system name
RR	(4)	Exciter response ratio (formerly ASA response)
τ_R	s	Regulator input filter time constant
K_A	pu	Regulator gain (continuous acting regulator) or fast raise-lower contact setting (rheostatic regulator)
τ_A or τ_{A1}	s	Regulator time constant (#1)
τ_{A2}	s	Regulator time constant (#2)
EXCITER (*continued*)		
$V_{R\,max}$	pu (4)	Maximum regulator output, starting at full load field voltage
$V_{R\,min}$	pu (4)	Minimum regulator output, starting at full load field voltage
K_E	pu	Exciter self-excitation at full load field voltage
τ_E	s	Exciter time constant
$S_{E.75\,max}$	(5)	Rotating exciter saturation at 0.75 ceiling voltage, or K_I for SCPT exciter
$S_{E\,max}$	(5)	Rotating exciter saturation at ceiling voltage, or K_p for SCPT exciter
A_{EX}	(5)	Derived saturation constant for rotating exciters
B_{EX}	(5)	Derived saturation constant for rotating exciters
$E_{FD\,max}$	pu (5)	Maximum field voltage or ceiling voltage, pu
$E_{FD\,min}$	pu	Minimum field voltage
K_F	pu	Regulator stabilizing circuit gain
τ_F or τ_{F1}	s	Regulator stabilizing circuit time constant (#1)
τ_{F2}	s	Regulator stabilizing circuit time constant (#2)
TURBINE-GOVERNOR		
GOV	(6)	Governor type: G = general, C = cross-compound, H = hydraulic
R	(6)	Turbine steady-state regulation setting or droop
P_{max}	MW	Maximum turbine output in MW
τ_1	s	Control time constant (governor delay) or governor response time (type H)
τ_2	s	Hydro reset time constant (type G) or pilot valve time (type H)
τ_3	s	Servo time constant (type G or C), or hydro gate time constant (type G) or dashpot time constant (type H)
τ_4	s	Steam valve bowl time constant (zero for type G hydrogovernor) or ($\tau_W/2$ for type H)
τ_5	s	Steam reheat time constant or 1/2 hydro water starting time constant (type C or G) or minimum gate velocity in MW/s (type H)
F	(6)	pu shaft output ahead of reheater or −2.0 for hydro units (types C or G), or maximum gate velocity in MW/s (type H)
STABILIZER		
PSS	(7)	PSS feedback: F = frequency, S = speed, P = accelerating power
K_{QV}	(7)	PSS voltage gain, pu
K_{QS}	(7)	PSS speed gain, pu
τ_Q	s	PSS reset time constant
τ'_{Q1}	s	First lead time constant
τ_{Q1}	s	First lag time constant
τ'_{Q2}	s	Second lead time constant
τ_{Q2}	s	Second lag time constant
τ'_{Q3}	s	Third lead time constant
τ_{Q3}	s	Third lag time constant
$V_{S\,lim}$	pu	PSS output limit setting, pu

Table D.2. Typical Data for Hydro (H) Units

GENERATOR										
Unit no.		$H1$	$H2$	$H3$	$H4$	$H5$	$H6$	$H7$	$H8$	$H9$
Rated MVA		9.00	17.50	25.00	35.00	40.00	54.00	65.79	75.00	86.00
Rated kV		6.90	7.33	13.20	13.80	13.80	13.80	13.80	13.80	13.80
Rated PF		0.90	0.80	0.95	0.90	0.90	0.90	0.95	0.95	0.90
SCR	(1)	1.250	...	2.280	1.167	1.180	1.18	1.175	2.36	1.18
x''_d	pu	0.329	0.330	0.310	0.235	0.288	0.340	0.240	0.140	0.258
x'_d	pu	0.408	...	...	0.260	0.318	0.380	0.260	0.174	0.320
x_d	pu	0.911	1.070	1.020	1.000	0.990	1.130	0.900	0.495	1.050
x''_q	pu	...	...	...	0.264	0.306	0.340	...	0.135	0.306
x'_q	pu	0.580	0.660	0.650	0.620	0.615	0.680	0.540	...	0.670
x_q	pu	0.580	0.660	0.650	0.620	0.615	0.680	0.540	0.331	0.670
r_a	pu	...	0.003	0.0032	0.004	0.0029	0.0049	0.0022	0.0041	0.0062
x_ℓ or x_p	pu	...	0.310	0.924	0.170	0.224	0.2100	...	0.120	0.140
r_2	pu	...	0.030	0.030	0.040	...	...	0.014	...	0.060
x_2	pu	...	0.490	0.460	0.270	0.297	0.340	0.260	0.130	0.312
x_0	pu	...	0.200	0.150	0.090	0.125	0.180	0.130	0.074	0.130
τ''_d	s	...	0.035	0.035	0.035	...	...	...	...	0.044
τ'_d	s	...	1.670	2.190	2.300	1.700	3.000	1.600	1.850	2.020
τ''_{d0}	s	...	...	...	...	...	...	...	...	0.051
τ'_{d0}	s	4.200	5.400	7.200	7.100	5.300	8.500	5.500	8.400	4.000
τ''_q	s	...	0.035	0.035	0.035	...	...	...	...	0.017
τ'_q	s	...	0.835	1.100	1.150	...	...	...	...	...
τ''_{q0}	s	...	...	...	...	...	...	...	...	0.033
τ'_{q0}	s	...	...	...	...	...	...	...	...	...
τ_a	s	0.1800	...	...	...	...	...	...	...	0.286
W_R	MW·s	23.50	117.00	183.00	254.00	107.90	168.00	176.00	524.00	233.00
r_F	Ω	...	...	...	...	0.269	0.301	0.199	0.155	0.332
$S_{G1.0}$	(2)	0.160	0.064	0.064	0.064	0.194	0.3127	0.1827	0.170	0.245
$S_{G1.2}$	(2)	0.446	1.018	1.018	1.018	0.685	0.7375	0.507	0.440	0.770
E_{FDFL}	(2)	2.080	2.130	2.130	2.130	2.030	2.320	1.904	1.460	2.320
D	(3)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
EXCITER										
VR type	(4)	E	E	E	E	A	A	A	A	A
Name		RHEO	AJ23	GFA4	WMA	NA108	REGULUX	WMA	NA108	NA143
RR	(4)	0.88	0.5	0.5	0.5	0.5	0.5	1.85	0.5	0.5
τ_R	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K_A	pu	0.050	0.050	0.050	0.050	65.200	25.000	37.300	180.000	242.000
τ_A or τ_{A1}	s	20.000	20.000	20.000	20.000	0.200	0.200	0.120	1.000	0.060
τ_{A2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.000	0.000
$V_{R\max}$	pu (4)	4.320	5.940	4.390	5.940	2.607	1.000	1.410	3.000	5.320
$V_{R\min}$	pu (4)	0.000	1.210	0.000	1.210	−2.607	−1.000	−1.410	−3.000	−5.320
K_E	pu	1.000	1.000	1.000	1.000	−0.111	−0.057	−0.137	−0.150	−0.1219
τ_E	s	2.019	0.760	1.970	0.760	1.930	0.646	0.560	2.000	2.700
$S_{E.75\max}$	(5)	0.099	0.220	0.096	0.220	0.176	0.0885	0.328	0.623	0.450
$S_{E\max}$	(5)	0.385	0.950	0.375	0.950	0.610	0.3480	0.687	1.327	1.500
A_{EX}	(5)	0.0017	0.0027	0.0016	0.0027	0.0042	0.0015	0.0357	0.0645	0.0121
B_{EX}	(5)	1.7412	1.9185	1.7059	1.9185	0.9488	1.5738	1.1507	1.1861	1.3566
$E_{FD\max}$	pu (5)	3.120	3.050	3.195	3.050	5.240	3.480	2.570	2.550	3.550
$E_{FD\min}$	pu	0.000	1.210	0.000	1.210	−5.240	−3.480	−2.570	−2.550	−3.550
K_F	pu	0.000	0.000	0.000	0.000	0.120	0.103	0.055	0.150	0.100
τ_F or τ_{F1}	s	0.000	0.000	0.000	0.000	1.000	1.000	1.000	1.000	1.000
τ_{F2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table D.2 *(continued)*

TURBINE-GOVERNOR										
GOV	(6)	G	G	G	G	G	G	G	G	G
R	(6)	0.050	0.050	0.050	0.050	0.056	0.050	0.050	0.050	0.050
$P_{\max}$	MW	8.60	14.00	23.80	40.00	40.00	52.50	65.50	90.00	86.00
τ_1	s	48.440	16.000	16.000	16.000	0.000	0.000	25.600	20.000	12.000
τ_2	s	4.634	2.400	2.400	2.400	0.000	0.000	2.800	4.000	3.000
τ_3	s	0.000	0.920	0.920	0.920	0.500	0.000	0.500	0.500	0.500
τ_4	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
τ_5	s	0.579	0.300	0.300	0.300	0.430	0.785	0:350	0.850	1.545
F	(6)	−2.000	−2.000	−2.000	−2.000	−2.000	−2.000	−2.000	−2.000	−2.000
STABILIZER										
PSS	(7)	...	...	...	...	...	...	F	F	F
K_{QV}	(7)	...	...	...	...	...	...	0.000	0.000	0.000
K_{QS}	(7)	...	...	...	...	...	...	1.000	4.000	3.150
τ_Q	s	...	...	...	...	...	...	30.000	30.000	10.000
τ'_{Q1}	s	...	...	...	...	...	...	0.500	0.700	0.758
τ_{Q1}	s	...	...	...	...	...	...	0.030	0.100	0.020
τ'_{Q2}	s	...	...	...	...	...	...	0.500	0.700	0.758
τ_{Q2}	s	...	...	...	...	...	...	0.030	0.050	0.020
τ'_{Q3}	s	...	...	...	...	...	...	0.000	0.000	0.000
τ_{Q3}	s	...	...	...	...	...	...	0.000	0.000	0.000
$V_{s\lim}$	pu	...	...	...	...	...	...	0.100	0.100	0.095

Table D.2. (*cont.*)

Table D.2 *(continued)*

GENERATOR										
Unit no.		*H10*	*H11*	*H12*	*H13*	*H14*	*H15*	*H16*	*H17*	*H18*
Rated MVA		100.10	115.00	125.00	131.00	145.00	158.00	231.60	250.00	615.00
Rated kV		13.80	12.50	13.80	13.80	14.40	13.80	13.80	18.00	15.00
Rated PF		0.90	0.85	0.90	0.90	0.90	0.90	0.95	0.85	0.975
SCR	(1)	1.20	1.05	1.155	1.12	1.20	...	1.175	1.050	...
x_d''	pu	0.280	0.250	0.205	0.330	0.273	0.220	0.245	0.155	0.230
x_d'	pu	0.314	0.315	0.300	0.360	0.312	0.300	0.302	0.195	0.2995
x_d	pu	1.014	1.060	1.050	1.010	0.953	0.920	0.930	0.995	0.8979
x_q''	pu	0.375	0.287	0.221	0.330	0.402	0.290	0.270	0.143	0.2847
x_q'	pu	0.770	0.610	0.686	0.570	0.573	0.510	...	0.568	0.646
x_q	pu	0.770	0.610	0.686	0.570	0.573	0.510	0.690	0.568	0.646
r_a	pu	0.0049	0.0024	0.0023	0.004	...	0.002	0.0021	0.0014	...
x_ℓ or x_p	pu	0.163	0.147	0.218	0.170	0.280	0.130	0.340	0.160	0.2396
r_2	pu	...	0.027	0.008	...	...	0.045	...	...	...
x_2	pu	0.326	0.269	0.211	0.330	...	0.255	0.258	...	...
x_0	pu	...	0.161	0.150	0.150	...	0.120	0.135	...	...
τ_d''	s	0.035	...	...	0.030	...	0.024	0.020	...	...
τ_d'	s	1.810	2.260	1.940	2.700	...	1.600	3.300	...	...
τ_{d0}''	s	0.039	0.040	...	0.030	0.041	0.029	0.030	...	...
τ_{d0}'	s	6.550	8.680	6.170	7.600	7.070	5.200	8.000	9.200	7.400
τ_q''	s	...	...	...	0.030	...	0.028	0.020	...	...
τ_q'	s	...	...	...	...	...	...	...	...	...
τ_{q0}''	s	0.071	0.080	...	0.040	0.071	0.034	0.060	...	...
τ_{q0}'	s	...	...	...	...	...	...	...	...	...
τ_a	s	0.278	0.330	...	0.180	...	0.360	0.200	...	...
W_R	MW-s	312.00	439.00	392.09	458.40	469.00	502.00	786.00	1603.00	3166.00
r_F	Ω	0.332	0.156	0.379	0.182	...	0.206	0.181	...	...
$S_{G1.0}$	(2)	0.219	0.178	0.200	0.113	0.220	0.1642	0.120	0.0769	0.180
$S_{G1.2}$	(2)	0.734	0.592	0.612	0.478	0.725	0.438	0.400	0.282	0.330
E_{FDFL}	(2)	2.229	2.200	2.220	1.950	2.230	1.990	1.850	1.88	...
D	(3)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000

EXCITER										
VR type	(4)	*A*	*A*	*A*	*G*	*A*	*A*	*A*	*A*	*J*
Name		WMA	WMA	NA143A	SCR	WMA	NA143	SIEMEN	ASEA	...
RR	(4)	1.0	1.5	1.5	0.5	1.0	0.5	1.0	1.0	...
τ_R	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K_A	pu	400.000	276.000	54.000	272.000	400.000	17.800	50.000	100.000	200.000
τ_A or τ_{A1}	s	0.050	0.060	0.105	0.020	0.050	0.200	0.060	0.020	0.020
τ_{A2}	s	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.000	0.000
$V_{R\max}$	pu (4)	4.120	1.960	3.850	2.730	4.120	0.710	1.000	5.990	7.320
$V_{R\min}$	pu (4)	−4.120	−1.960	−3.850	−2.730	−4.120	−0.710	−1.000	−5.990	0.000
K_E	pu	−0.243	−0.184	−0.062	1.000	−0.243	−0.295	−0.080	−0.020	1.000
τ_E	s	0.950	1.290	0.732	0.000	0.950	0.535	0.405	0.100	0.000
$S_{E.75\max}$	(5)	0.484	0.270	0.410	0.000	0.480	0.333	0.200	0.127	0.000
$S_{E\max}$	(5)	1.308	0.560	1.131	0.000	1.310	0.533	0.407	0.300	0.000
A_{EX}	(5)	0.0245	0.0303	0.0195	0.000	0.0236	0.0812	0.0237	0.0096	0.000
B_{EX}	(5)	1.0276	0.5612	1.1274	0.000	1.0377	0.6303	0.9227	1.1461	0.000
$E_{FD\max}$	pu (5)	3.870	5.200	3.600	2.730	3.870	2.985	3.080	3.000	7.320
$E_{FD\min}$	pu	−3.870	−5.200	−3.600	0.000	−3.870	−2.985	−3.080	−3.000	0.000
K_F	pu	0.040	0.0317	0.140	0.0043	0.040	0.120	0.0648	0.000	0.010
τ_F or τ_{F1}	s	1.000	0.480	1.000	0.060	1.000	1.000	1.000	0.000	1.000
τ_{F2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table D.2 *(continued)*

TURBINE-GOVERNOR										
GOV	(6)	*G*	*G*	*G*	*G*	*G*	*G*	*G*	*G*	*G*
R	(6)	0.030	0.051	0.050	0.050	0.038	0.050	0.050	0.050	0.050
$P_{\max}$	MW	133.00	115.00	171.00	120.00	160.00	155.00	267.00	250.00	603.30
τ_1	s	52.100	...	31.00	27.500	65.300	...	124.470	30.000	36.000
τ_2	s	4.800	...	4.120	3.240	6.200	...	8.590	3.500	6.000
τ_3	s	0.500	...	0.393	0.500	0.500	...	0.250	0.520	0.000
τ_4	s	0.000	...	0.000	0.000	0.000	...	0.000	0.000	0.000
τ_5	s	0.498	...	0.515	0.520	0.650	...	0.740	0.415	0.900
F	(6)	−2.000	−2.000	−2.000	−2.000	−2.000	−2.000	−2.000	−2.000	−2.000

STABILIZER										
PSS	(7)	*F*	*F*	*F*	...	...	...	*F*	*F*	*F*
K_{QV}	(7)	0.000	0.000	0.000	...	...	...	0.000	0.000	0.000
K_{QS}	(7)	1.000	0.300	8.000	...	...	...	4.000	10.000	5.000
τ_Q	s	10.000	10.000	30.000	...	...	...	55.000	15.000	10.000
τ_{Q1}'	s	0.700	0.431	0.600	...	...	...	1.000	0.000	0.380
τ_{Q1}	s	0.020	0.020	0.100	...	...	...	0.020	0.053	0.020
τ_{Q2}'	s	0.700	0.431	0.600	...	...	...	1.000	0.000	0.380
τ_{Q2}	s	0.020	0.020	0.040	...	...	...	0.020	0.053	0.020
τ_{Q3}'	s	0.000	0.000	0.000	...	...	...	0.000	0.000	0.000
τ_{Q3}	s	0.000	0.000	0.000	...	...	...	0.000	0.000	0.000
$V_{s\lim}$	pu	0.050	0.100	0.100	...	...	...	0.090	0.050	0.050

Table D.3. Typical Data for Fossil Steam (F) Units

GENERATOR												
Unit no.		$F1$	$F2$	$F3$	$F4$	$F5$	$F6$	$F7$	$F8$	$F9$	$F10$	$F11$
Rated MVA		25.00	35.29	51.20	75.00	100.00	125.00	147.10	160.00	192.00	233.00	270.00
Rated kV		13.80	13.80	13.80	13.80	13.80	15.50	15.50	15.00	18.00	20.00	18.00
Rated PF		0.80	0.85	0.80	0.80	0.80	0.85	0.85	0.85	0.85	0.85	0.85
SCR	(1)	0.80	0.80	0.90	1.00	0.90	0.90	0.64	0.64	0.64	0.64	0.6854
x''_d	pu	0.120	0.118	0.105	0.130	0.145	0.134	0.216	0.185	0.171	0.249	0.185
x'_d	pu	0.232	0.231	0.209	0.185	0.220	0.174	0.299	0.245	0.232	0.324	0.256
x_d	pu	1.250	1.400	1.270	1.050	1.180	1.220	1.537	1.700	1.651	1.569	1.700
x''_q	pu	0.120	...	0.116	0.130	0.145	0.134	0.216	0.185	0.171	0.248	0.147
x'_q	pu	0.715	...	0.850	0.360	0.380	0.250	0.976	0.380	0.380	0.918	0.245
x_q	pu	1.220	1.372	1.240	0.980	1.050	1.160	1.520	1.640	1.590	1.548	1.620
r_a	pu	0.0014	...	...	0.0031	0.0035	0.004	0.0034	0.0031	0.0026	0.0016	0.0016
x_ℓ or x_p	pu	0.134	...	0.108	0.070	0.075	0.078	0.133	0.110	0.102	0.204	0.155
r_2	pu	0.0082	...	...	0.016	0.020	0.017	0.0284	0.016	0.023	...	...
x_2	pu	0.120	0.118	0.105	0.085	0.095	0.134	0.216	0.115	0.171	0.248	0.140
x_0	pu	0.0215	0.077	0.116	0.070	0.065	...	0.093	0.100	...	0.143	0.060
τ''_d	s	0.035	...	...	...	...	0.023	0.035	...	0.023	0.350	0.027
τ'_d	s	0.882	...	0.882	...	...	1.280	...	...	0.829	0.950	0.620
τ''_{d0}	s	0.059	...	...	0.038	0.042	0.033	0.0484	0.033	0.033	0.0437	...
τ'_{d0}	s	4.750	5.500	6.600	6.100	5.900	8.970	4.300	5.900	5.900	5.140	4.800
τ''_q	s	0.035	...	...	...	...	0.023	0.0072	...	0.023	...	...
τ'_q	s	...	...	...	...	...	0.640	...	...	0.415	...	...
τ''_{q0}	s	0.210	...	...	0.099	0.092	0.070	0.218	0.076	0.078	0.141	...
τ'_{q0}	s	1.500	...	...	0.300	0.300	0.500	1.500	0.540	0.535	1.500	0.500
τ_a	s	0.177	...	...	0.140	0.140	0.390	0.470	0.240	0.254	0.420	0.297
W_R	MW·s	125.40	154.90	260.00	464.00	498.50	596.00	431.00	634.00	634.00	960.50	1115.00
r_F	Ω	0.375	...	0.295	0.290	0.215	...	...	0.370	...	...	0.166
$S_{G1.0}$	(2)	0.279	0.210	0.2067	0.100	0.0933	0.1026	0.057	0.1251	0.105	0.0987	0.125
$S_{G1.2}$	(2)	0.886	0.805	0.724	0.3928	0.4044	0.4320	0.364	0.7419	0.477	0.303	0.450
E_{FDFL}	(2)	2.500	3.000	2.310	2.120	2.292	2.220	2.670	2.680	2.640	2.580	2.300
D	(3)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
EXCITER												
VR type		E	A	A	E	A	A	A	A	A	C	A
Name	(4)	BJ30	NA143A	WMA	GFA4	NA101	NA101	WMA	NA101	NA101	BRLS	BBC
RR	(4)	0.50	0.50	1.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
τ_R	s	0.000	0.000	0.000	0.000	0.060	0.060	0.000	0.060	0.060	0.000	0.000
K_A	pu	0.050	57.140	400.000	0.050	25.000	25.000	175.000	25.000	25.000	250.000	30.000
τ_A or τ_{A1}	s	20.000	0.050	0.050	20.000	0.200	0.200	0.050	0.200	0.200	0.060	0.400
τ_{A2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$V_{R\max}$	pu (4)	6.812	1.000	0.6130	4.380	1.000	1.000	3.120	1.000	1.000	4.420	4.590
$V_{R\min}$	pu (4)	1.395	−1.000	−0.6130	0.000	−1.000	−1.000	−3.120	−1.000	−1.000	−4.420	−4.590
K_E	pu	1.000	−0.0445	−0.0769	1.000	−0.0582	−0.0601	−0.170	−0.0497	−0.0505	1.000	−0.020
τ_E	s	0.700	0.500	1.370	1.980	0.6544	0.6758	0.952	0.560	0.5685	0.613	0.560
$S_{E.75\max}$	(5)	0.414	0.0684	0.1120	0.0967	0.0895	0.0924	0.220	0.0765	0.0778	0.010	0.730
$S_{E\max}$	(5)	0.908	0.2667	0.2254	0.3774	0.349	0.3604	0.950	0.2985	0.303	0.270	1.350
A_{EX}	(5)	0.0392	0.0012	0.0137	0.0016	0.0015	0.0016	0.0027	0.0013	0.0013	0.000	0.1154
B_{EX}	(5)	0.8807	1.2096	0.6774	1.7128	1.5833	1.6349	1.4628	1.3547	1.3733	3.7884	0.7128
$E_{FD\max}$	pu (5)	3.567	4.500	4.130	3.180	3.438	3.330	4.000	4.020	3.960	3.480	3.450
$E_{FD\min}$	pu	1.417	−4.500	−4.130	0.000	−3.438	−3.330	−4.000	−4.020	−3.960	0.000	−3.450
K_F	pu	0.000	0.080	0.040	0.000	0.105	0.108	0.030	0.0896	0.091	0.053	0.050
τ_F or τ_{F1}	s	0.000	1.000	1.000	0.000	0.350	0.350	1.000	0.350	0.350	0.330	1.300
τ_{F2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TURBINE GOVERNOR												
GOV	(6)	G	G	G	G	G	G	G	G	G	G	G
R	(6)	0.050	0.050	0.078	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
$P_{\max}$	MW	22.50	36.10	53.00	75.00	105.00	132.00	121.00	142.30	175.00	210.00	230.00
τ_1	s	0.200	0.200	0.200	0.090	0.090	0.083	0.200	0.100	0.083	0.150	0.100
τ_2	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
τ_3	s	0.300	0.300	0.300	0.200	0.200	0.200	0.300	0.200	0.200	0.100	0.259
τ_4	s	0.090	0.200	0.090	0.300	0.300	0.050	0.090	0.050	0.050	0.300	0.100
τ_5	s	0.000	0.000	0.000	0.000	0.000	5.000	10.000	8.000	8.000	10.000	10.000
F	(6)	1.000	1.000	1.000	1.000	1.000	0.280	0.250	0.300	0.271	0.237	0.272
STABILIZER												
PSS	(7)	...	...	F	...	...	...	...	...	S	...	...
K_{QV}	(7)	...	...	0.000	...	...	...	...	...	0.000	...	...
K_{QS}	(7)	...	...	0.700	...	...	...	...	...	15.000	...	...
τ_Q	s	...	...	10.000	...	...	...	...	...	10.000	...	...
τ'_{Q1}	s	...	...	0.300	...	...	...	...	...	1.000	...	...
τ_{Q1}	s	...	...	0.020	...	...	...	...	...	0.020	...	...
τ'_{Q2}	s	...	...	0.300	...	...	...	...	...	0.750	...	...
τ_{Q2}	s	...	...	0.020	...	...	...	...	...	0.020	...	...
τ'_{Q3}	s	...	...	0.000	...	...	...	...	...	0.000	...	...
τ_{Q3}	s	...	...	0.000	...	...	...	...	...	0.000	...	...
$V_{s\lim}$	pu	...	...	0.100	...	...	...	...	...	0.050	...	...

Table D.3 (continued)

		F12	F13	F14	F15	F16	F17	F18	F19	F20	F21
GENERATOR											
Unit no.		F12	F13	F14	F15	F16	F17	F18	F19	F20	F21
Rated MVA		330.00	384.00	410.00	448.00	512.00	552.00	590.00	835.00	896.00	911.00
Rated kV		20.00	24.00	24.00	22.00	24.00	24.00	22.00	20.00	26.00	26.00
Rated PF		0.90	0.85	0.90	0.85	0.90	0.90	0.95	0.90	0.90	0.90
SCR	(1)	0.580	0.580	0.580	0.580	0.580	0.580	0.500	0.500	0.52	0.64
x''_d	pu	...	0.260	0.2284	0.205	0.200	0.198	0.215	0.339	0.180	0.193
x'_d	pu	0.317	0.324	0.2738	0.265	0.270	0.258	0.280	0.413	0.220	0.266
x_d	pu	1.950	1.798	1.7668	1.670	1.700	1.780	2.110	2.183	1.790	2.040
x''_q	pu	...	0.255	0.2239	0.205	...	0.172	0.215	0.332	...	0.191
x'_q	pu	1.120	1.051	1.0104	0.460	0.470	0.247	0.490	0.285	0.400	0.262
x_q	pu	1.920	1.778	1.7469	1.600	1.650	1.770	2.020	2.157	1.715	1.960
r_a	pu	...	0.0014	0.0019	0.0043	0.004	0.0047	0.0046	0.0019	0.001	0.001
x_ℓ or x_p	pu	0.199	0.1930	0.1834	0.150	0.160	...	0.155	0.246	0.135	0.154
r_2	pu	...	0.0054	...	0.023	...	0.013	0.026	...	0.019	...
x_2	pu	...	0.2374	0.2261	0.175	...	0.167	0.215	0.309	0.135	0.192
x_0	pu	...	0.1320	0.1346	0.140	...	0.112	0.150	0.174	0.130	0.105
τ''_d	s	...	0.035	...	0.023	...	0.030	0.0225	...	0.035	...
τ'_d	s	...	0.159	...	1.070	...	0.550	...	...	0.596	...
τ''_{d0}	s	...	0.042	0.042	0.032	...	...	0.032	0.041	0.032	...
τ'_{d0}	s	6.000	5.210	5.432	3.700	3.800	3.650	4.200	5.690	4.300	6.000
τ''_q	s	...	0.035	...	...	...	...	0.0225	...	0.035	...
τ'_q	s	...	0.581	...	...	...	...	...	...	0.298	...
τ''_{q0}	s	...	0.042	0.158	0.060	...	...	0.062	0.144	...	...
τ'_{q0}	s	1.500	1.500	1.500	0.470	0.480	1.230	0.565	1.500	...	0.900
τ''_a	s	...	0.450	...	0.150	...	...	0.140	...	0.160	...
W_R	MW·s	992.00	1006.50	1518.70	1190.00	1347.20	3010.00	1368.00	2206.40	2625.00	2265.00
r_F	Ω	...	0.1245	...	0.1357	...	0.0711	0.1094	...	...	...
$S_{G1.0}$	(2)	0.082	0.162	0.2632	0.0910	0.090	0.111	0.079	0.134	0.090	0.340
$S_{G1.2}$	(2)	0.290	0.508	0.5351	0.400	0.400	0.518	0.349	0.617	0.402	1.120
E_{FDFL}	(2)	...	3.053	2.7895	2.870	2.700	3.000	2.980	3.670	3.330	3.670
D	(3)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
EXCITER											
VR type		A	C	C	A	G	A	G	C	G	A
Name	(4)	WMA	BRLS	BRLS	NA143A	ALTHYREX	BBC	ALTHYREX	WTA	ALTHYREX	BBC
RR	(4)	0.50	0.50	0.50	0.50	1.50	0.50	3.50	2.00	2.50	0.50
τ_R	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K_A	pu	400.000	400.000	400.000	50.000	200.000	30.000	200.000	400.000	250.000	50.000
τ_A or τ_{A1}	s	0.050	0.020	0.020	0.060	0.3950	0.400	0.3575	0.020	0.200	0.060
τ_{A2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$V_{R\max}$	pu (4)	3.810	8.130	5.270	1.000	3.840	5.990	5.730	18.300	5.150	1.000
$V_{R\min}$	pu (4)	−3.810	−8.130	−5.270	−1.000	−3.840	−5.990	−5.730	−18.300	−5.150	−1.000
K_E	pu	−0.170	1.000	1.000	−0.0465	1.000	−0.020	1.000	1.000	1.000	−0.0393
τ_E	s	0.950	0.812	0.920	0.520	0.000	0.560	0.000	0.942	0.000	0.440
$S_{E.75\max}$	(5)	0.220	0.459	0.435	0.071	0.000	0.730	0.000	0.813	0.000	0.064
$S_{E\max}$	(5)	0.950	0.656	0.600	0.278	0.000	1.350	0.000	2.670	0.000	0.235
A_{EX}	(5)	0.0027	0.1572	0.1658	0.0012	0.000	0.1154	0.000	0.023	0.000	0.0013
B_{EX}	(5)	0.3857	0.2909	0.3910	1.2639	0.000	0.5465	0.000	0.9475	0.000	1.1562
$E_{FD\max}$	pu (5)	4.890	4.910	3.290	4.320	3.840	4.500	5.730	5.020	5.150	4.500
$E_{FD\min}$	pu	−4.890	0.000	0.000	−4.320	−3.840	−4.500	−5.730	0.000	−5.150	−4.500
K_F	pu	0.040	0.060	0.030	0.0832	0.0635	0.050	0.0529	0.030	0.036	0.070
τ_F or τ_{F1}	s	1.000	1.000	1.000	1.000	1.000	1.300	1.000	1.000	1.000	1.000
τ_{F2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TURBINE GOVERNOR											
GOV	(6)	G	G	G	G	G	G	G	G	G	G
R	(6)	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
$P_{\max}$	MW	347.00	360.00	367.00	390.00	460.00	497.00	553.00	766.29	810.00	820.00
τ_1	s	0.100	0.220	0.180	0.100	0.150	0.100	0.080	0.180	0.100	0.100
τ_2	s	0.000	0.000	0.000	0.000	0.050	0.000	0.000	0.030	0.000	0.000
τ_3	s	0.400	0.200	0.040	0.300	0.300	0.300	0.150	0.200	0.200	0.200
τ_4	s	0.050	0.250	0.250	0.050	0.260	0.100	0.050	0.000	0.100	0.100
τ_5	s	8.000	8.000	8.000	10.000	8.000	10.000	10.000	8.000	8.720	8.720
F	(6)	0.250	0.270	0.267	0.250	0.270	0.300	0.280	0.300	0.300	0.300
STABILIZER											
PSS	(7)	...	...	...	S	S	...	S	F	S	...
K_{QV}	(7)	...	...	...	0.000	0.000	...	0.000	0.000	0.000	...
K_{QS}	(7)	...	...	...	4.000	26.000	...	24.400	0.400	24.000	...
τ_Q	s	...	...	...	10.000	3.000	...	3.000	10.000	10.000	...
τ'_{Q1}	s	...	...	...	0.230	0.150	...	0.150	0.650	0.200	...
τ_{Q1}	s	...	...	...	0.020	0.050	...	0.050	0.020	0.060	...
τ'_{Q2}	s	...	...	...	0.230	0.150	...	0.150	0.650	0.150	...
τ_{Q2}	s	...	...	...	0.020	0.050	...	0.050	0.020	0.020	...
τ'_{Q3}	s	...	...	...	0.000	0.000	...	0.000	0.000	0.000	...
τ_{Q3}	s	...	...	...	0.000	0.000	...	0.000	0.000	0.000	...
$V_{s\lim}$	pu	...	...	...	0.100	0.050	...	0.050	0.100	0.050	...

Table D.4. Typical Data for Cross-Compound Fossil Steam (CF) Units

GENERATOR											
Unit no.		*CF1-HP*	*CF1-LP*	*CF2-HP*	*CF2-LP*	*CF3-HP*	*CF3-LP*	*CF4-HP*	*CF4-LP*	*CF5-HP*	*CF5-LP*
Rated MVA		128.00	128.00	192.00	192.00	278.30	221.70	445.00	375.00	483.00	426.00
Rated kV		13.80	13.80	18.00	18.00	20.00	20.00	22.00	22.00	22.00	22.00
Rated PF		0.85	0.85	0.85	0.85	0.90	0.90	0.90	0.90	0.90	0.90
SCR	(1)	0.64	0.64	0.64	0.64	0.58	0.58	0.64	0.64	0.604	0.645
x''_d	pu	0.171	0.250	0.225	0.225	0.231	0.252	0.205	0.180	0.220	0.205
x'_d	pu	0.232	0.369	0.315	0.315	0.311	0.380	0.260	0.250	0.285	0.285
x_d	pu	1.680	1.660	1.670	1.670	1.675	1.581	1.650	1.500	1.800	1.750
x''_q	pu	0.171	0.250	0.224	0.224	0.229	0.248	0.205	0.181	0.220	0.205
x'_q	pu	0.320	0.565	0.958	0.958	0.979	0.955	0.460	0.440	0.490	0.485
x_q	pu	1.610	1.590	1.640	1.640	1.648	1.531	1.590	1.400	1.720	1.580
r_a	pu	0.0024	0.003	0.0036	0.0036	0.0043	0.0039	0.0043	0.0045	0.0027	0.0036
x_ℓ or x_p	pu	0.095	0.140	0.186	0.186	0.304	0.291	0.150	0.140	0.160	0.155
r_2	pu	0.026	0.020	0.028	0.028	0.029	0.028	0.022	0.022	0.025	0.025
x_2	pu	0.171	0.250	0.224	0.224	0.229	0.249	0.175	0.145	0.220	0.205
x_0	pu	...	...	0.101	0.101	...	...	0.140	0.135	0.150	0.150
τ''_d	s	0.023	0.023	...	...	0.023	0.023	0.020	0.020	0.023	0.023
τ'_d	s	0.815	1.130	0.820	0.820	1.000	1.292	...	...	0.586	1.360
τ''_{d0}	s	0.034	0.037	0.043	0.043	0.047	0.053	0.032	0.036	0.032	0.035
τ'_{d0}	s	5.890	5.100	5.000	5.000	5.400	5.390	4.800	8.000	3.700	8.400
τ''_q	s	0.023	0.023	...	...	0.023	0.023	0.020	0.020	0.023	0.023
τ'_q	s	0.410	0.570	...	...	0.500	0.650	...	...	0.293	0.680
τ''_{q0}	s	0.080	0.070	0.150	0.150	0.150	0.135	0.060	0.070	0.060	0.070
τ'_{q0}	s	0.600	0.326	1.500	1.500	1.500	1.500	0.470	0.410	0.480	0.460
τ_a	s	0.171	0.205	0.390	0.390	0.390	0.330	0.150	0.110	0.150	0.110
W_R	MW·s	305.00	787.00	596.70	650.70	464.00	1418.00	639.50	3383.50	633.00	2539.00
r_F	Ω	...	...	0.141	0.141	...	...	0.1357	0.3958	0.1259	0.343
$S_{G1.0}$	(2)	0.121	0.1122	0.0982	0.0982	0.1249	0.0905	0.0926	0.1333	0.0866	0.177
$S_{G1.2}$	(2)	0.610	0.433	0.4161	0.4161	0.500	0.345	0.4139	0.5555	0.410	0.532
E_{FDFL}	(2)	2.640	2.640	2.840	2.840	2.570	2.500	2.730	2.560	2.900	2.915
D	(3)	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
EXCITER											
VR type		*A*	*A*	*A*	*A*	*A*	*A*	*A*	*A*	*G*	*G*
Name	(4)	NA101	NA101	WMA	WMA	WMA	WMA	NA143A	NA143A	ALTHYREX	ALTHYREX
RR	(4)	0.50	0.50	0.50	0.50	0.50	0.50	2.00	2.00	2.50	2.50
τ_R	s	0.060	0.060	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K_A	pu	25.000	25.000	275.000	275.000	245.000	245.000	592.000	312.000	250.000	250.000
τ_A or τ_{A1}	s	0.200	0.200	0.060	0.060	0.050	0.050	0.053	0.050	0.140	0.060
τ_{A2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$V_{R\max}$	pu (4)	1.000	1.000	0.984	0.984	2.780	2.780	13.050	10.770	5.150	4.910
$V_{R\min}$	pu (4)	−1.000	−1.000	−0.984	−0.984	−2.780	−2.780	−13.050	−10.770	−5.150	−4.910
K_E	pu	−0.051	−0.051	−0.0667	−0.0667	−0.170	−0.170	−0.591	−0.4035	1.000	1.000
τ_E	s	0.5685	0.5685	1.230	1.230	1.370	1.370	0.512	1.080	0.000	0.000
$S_{E.75\max}$	(5)	0.0778	0.0778	0.1688	0.1688	0.220	0.220	1.094	0.647	0.000	0.000
$S_{E\max}$	(5)	0.3035	0.3035	0.2978	0.2978	0.950	0.950	3.048	2.545	0.000	0.000
A_{EX}	(5)	0.0013	0.0013	0.0307	0.0307	0.0027	0.0027	0.0506	0.0106	0.000	0.000
B_{EX}	(5)	1.3750	1.3750	0.5331	0.5331	1.639	1.639	0.7719	1.0891	0.000	0.000
$E_{FD\max}$	pu (5)	3.960	3.960	4.260	4.260	3.570	3.570	5.310	5.030	5.150	4.910
$E_{FD\min}$	pu	−3.960	−3.960	−4.260	−4.260	−3.570	−3.570	−5.310	−5.030	−5.150	−4.910
K_F	pu	0.091	0.091	0.033	0.033	0.040	0.040	0.070	0.090	0.062	0.025
τ_F or τ_{F1}	s	0.350	0.350	0.330	0.330	1.000	1.000	1.880	2.250	1.000	1.000
τ_{F2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TURBINE GOVERNOR											
GOV	(6)	*G*	*G*	*G*	*G*	*G*	*G*	*G*	*G*	*G*	*G*
R	(6)	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
$P_{\max}$	MW	107.50	107.50	172.50	172.50	267.00	213.00	411.00	339.00	436.00	382.00
τ_1	s	0.100	0.100	0.100	0.100	0.250	0.250	0.100	0.100	0.100	0.100
τ_2	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
τ_3	s	0.150	0.150	0.150	0.150	0.000	0.000	0.200	0.200	0.300	0.300
τ_4	s	0.300	0.300	0.300	0.300	0.050	0.300	0.100	0.100	0.050	0.050
τ_5	s	10.000	10.000	4.160	4.160	12.000	12.000	8.720	8.720	14.000	14.000
F	(6)	0.606	0.000	0.560	0.000	0.549	0.000	0.540	0.000	0.580	0.000
STABILIZER											
PSS	(7)	*S*	*S*	*F*	*F*	*S*	*S*	*F*	*F*	*S*	*S*
K_{QV}	(7)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K_{QS}	(7)	12.000	8.000	0.600	0.600	10.000	10.000	1.170	1.170	24.000	24.000
τ_Q	s	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000
τ'_{Q1}	s	1.000	1.000	0.490	0.455	0.250	0.700	0.265	0.640	0.200	0.200
τ_{Q1}	s	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.050	0.070
τ'_{Q2}	s	0.750	0.250	0.490	0.455	0.400	0.450	0.265	0.640	0.200	0.300
τ_{Q2}	s	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
τ'_{Q3}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
τ_{Q3}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$V_{s\lim}$	pu	0.050	0.050	0.080	0.080	0.050	0.050	0.060	0.080	0.050	0.050

Table D.5. Typical Data for Nuclear Steam (N) Units

GENERATOR									
Unit no.		$N1$	$N2$	$N3$	$N4$	$N5$	$N6$	$N7$	$N8$
Rated MVA		76.80	245.5	500.00	920.35	1070.00	1280.00	1300.00	1340.00
Rated kV		13.8	14.4	18.00	18.00	22.00	22.00	25.00	25.00
Rated PF		0.85	0.85	0.90	0.90	0.90	0.95	0.90	0.90
SCR	(1)	0.650	0.640	0.580	0.607	0.500	0.500	0.480	0.480
x_d''	pu	0.190	0.210	0.283	0.275	0.312	0.237	0.315	0.281
x_d'	pu	0.320	0.320	0.444	0.355	0.467	0.358	0.467	0.346
x_d	pu	1.660	1.710	1.782	1.790	1.933	2.020	2.129	1.693
x_q''	pu	0.120	0.210	0.277	0.275	...	0.237	0.308	0.281
x_q'	pu	0.470	0.510	1.201	0.570	1.144	0.565	1.270	0.991
x_q	pu	1.580	1.630	1.739	1.660	1.743	1.860	2.074	1.636
r_a	pu	...	0.0032	0.0041	0.0048	0.360	0.0019	0.0029	0.0021
x_ℓ or x_p	pu	0.150	0.125	0.275	0.215	...	0.205	0.251	0.228
r_2	pu	...	0.025	0.029	0.028	...	0.029	...	...
x_2	pu	0.125	0.160	0.280	0.230	0.284	0.215	...	0.228
x_0	pu	0.450	0.110	...	0.195	...	0.195	...	...
τ_d''	s	...	0.230	0.035	...	...	...	...	...
τ_d'	s	...	...	1.512	...	...	...	...	...
τ_{d0}''	s	0.032	0.038	0.055	0.032	...	0.034	0.052	0.043
τ_{d0}'	s	4.780	7.100	6.070	7.900	6.660	9.100	6.120	6.580
τ_q''	s	...	...	0.035	...	...	...	...	...
τ_q'	s	...	...	0.756	...	...	...	...	...
τ_{q0}''	s	...	0.073	0.152	0.055	...	0.059	0.144	0.124
τ_{q0}'	s	...	0.380	1.500	0.41	...	0.460	1.500	1.500
τ_a	s	...	0.210	0.310	0.19	...	0.180	...	...
W_R	MW·s	281.70	1136.00	1990.00	3464.00	3312.00	4690.00	4580.00	4698.00
r_F	Ω	...	0.217	...	0.0901	...	0.0979	0.0576	0.0576
$S_{G1.0}$	(2)	0.0857	0.1309	0.0900	0.0816	...	0.0779	0.0714	0.0769
$S_{G1.2}$	(2)	0.3244	0.5331	0.3520	0.3933	...	0.3055	0.3100	0.4100
E_{FDFL}	(2)	2.587	2.730	2.710	2.870	...	2.945	3.340	2.708
D	(3)	2.000	...	2.000	...	2.000	2.000	2.000	2.000
EXCITER									
VR type		A	A	A	A	C	A	C	C
Name	(4)	NA101	NA101	WMA	NA143	BRLS	EA210	BRLS	BRLS
RR	(4)	0.50	0.50	0.50	0.50	2.00	1.50	2.23	2.00
τ_R	s	0.060	0.060	0.000	0.000	0.000	0.000	0.000	0.000
K_A	pu	25.000	25.000	256.000	25.000	400.000	50.000	400.000	400.000
τ_A or τ_{A1}	s	0.200	0.200	0.050	0.200	0.020	0.020	0.020	0.020
τ_{A2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$V_{R\max}$	pu (4)	1.000	1.000	2.858	1.000	10.650	1.000	6.960	6.020
$V_{R\min}$	pu (4)	−1.000	−1.000	−2.858	−1.000	−10.650	−1.000	−6.960	−6.020
K_E	pu	−0.0516	−0.0489	−0.170	−0.0464	1.000	−0.0244	1.000	1.000
τ_E	s	0.579	0.550	2.150	0.522	1.000	0.1455	0.015	0.015
$S_{E.75\max}$	(5)	0.0794	0.0752	0.2200	0.0714	0.375	0.0863	0.3400	0.3900
$S_{E\max}$	(5)	0.3093	0.2932	0.9500	0.2784	1.220	0.2148	0.5600	0.5630
A_{EX}	(5)	0.0013	0.0016	0.0027	0.0016	...	0.0056	0.0761	0.1296
B_{EX}	(5)	1.4015	1.6120	1.5966	1.5330	...	0.6818	0.4475	0.3814
$E_{FD\max}$	pu (5)	3.881	4.090	3.665	4.310	4.800	5.350	4.460	3.850
$E_{FD\min}$	pu	−3.881	−4.090	−3.665	−4.310	0.000	0.000	0.000	0.000
K_F	pu	0.093	0.088	0.040	0.084	0.060	0.0233	0.040	0.040
τ_F or τ_{F1}	s	0.350	0.350	1.000	1.000	1.000	0.7750	0.050	0.050
τ_{F2}	s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table D.5. *(continued)*

TURBINE GOVERNOR									
GOV	(6)	G	G	G	G	G	G	G	G
R	(6)	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
$P_{\max}$	MW	65.00	208.675	450.00	790.18	951.00	1216.00	1090.00	1205.00
τ_1	s	...	...	0.250	...	0.180	0.150	0.180	0.180
τ_2	s	...	...	0.000	...	0.030	0.000	0.000	0.000
τ_3	s	...	...	0.000	...	0.100	0.210	0.040	0.040
τ_4	s	...	...	0.300	...	0.200	0.814	0.200	0.200
τ_5	s	...	...	5.000	...	6.280	2.460	5.000	5.000
F	(6)	...	...	0.320	...	0.330	0.340	0.300	0.300
STABILIZER									
PSS	(7)	S	...	...	...	F	S	F	F
K_{QV}	(7)	0.000	...	...	...	0.000	0.000	0.000	0.000
K_{QS}	(7)	0.200	...	...	...	10.000	1.530	20.000	20.000
τ_Q	s	10.000	...	...	...	10.000	3.000	10.000	10.000
τ_{Q1}'	s	1.330	...	...	...	0.080	0.150	0.300	0.300
τ_{Q1}	s	0.020	...	...	...	0.020	0.050	0.020	0.020
τ_{Q2}'	s	1.330	...	...	...	0.080	0.150	0.000	0.000
τ_{Q2}	s	0.020	...	...	...	0.020	0.050	0.000	0.000
τ_{Q3}'	s	0.000	...	...	...	0.000	0.000	0.000	0.000
τ_{Q3}	s	0.000	...	...	...	0.000	0.000	0.000	0.000
$V_{s\lim}$	pu	0.100	...	...	...	0.100	0.100	0.100	0.100

Table D.6. Typical Data for Synchronous Condensor (SC) Units

GENERATOR						
Unit no.		$SC1$	$SC2$	$SC3$	$SC4$	$SC5$
Rated MVA		25.00	40.00	50.00	60.00	75.00
Rated kV		13.80	13.80	12.70	13.80	13.80
Rated PF		0.00	0.00	0.00	0.00	0.00
SCR	(1)	...	0.558	1.004	0.477	0.800
x''_d	pu	0.2035	0.231	0.141	0.257	0.170
x'_d	pu	0.304	0.343	0.244	0.385	0.320
x_d	pu	1.769	2.373	1.083	2.476	1.560
x''_q	pu	0.199	...	0.170	0.261	0.200
x'_q	pu	0.5795	1.172	0.720	1.180	1.000
x_q	pu	0.855	1.172	0.720	1.180	1.000
r_a	pu	0.0025	...	0.006	0.0024	0.0017
x_ℓ or x_p	pu	0.1045	0.132	...	0.146	0.0987
r_2	pu	0.0071	...	0.160	...	0.180
x_2	pu	0.177	...	...	0.225	0.185
x_0	pu	0.115	...	0.058	0.165	0.128
τ''_d	s	...	0.035	0.041	0.035	0.041
τ'_d	s	...	...	0.858	...	3.230
τ''_{d0}	s	0.0525	0.058	0.050	0.058	0.039
τ'_{d0}	s	8.000	11.600	6.000	12.350	16.000
τ''_q	s	...	...	...	...	0.0473
τ'_q	s	...	...	...	...	...
τ''_{q0}	s	0.0151	0.201	...	0.188	0.235
τ'_{q0}	s	...	...	0.150	...	...
τ_a	s	...	0.159	0.200	0.290	0.288
W_R	MW·s	30.00	60.80	105.00	60.60	89.98
r_F	Ω	0.4407	...	0.0631	0.274	0.279
$S_{G1.0}$	(2)	0.304	0.295	0.0873	0.180	0.150
$S_{G1.2}$	(2)	0.666	0.776	0.310	0.708	0.500
E_{FDFL}	(2)	3.560	4.180	2.338	4.224	3.730
D	(3)	...	...	...	...	...
EXCITER						
VR type		A	A	A	A	A
Name	(4)	WMA	WMA	...	WMA	NA143
RR	(4)	0.50	1.00	3.85	1.00	2.00
τ_R	s	0.000	0.000	0.000	0.000	0.000
K_A	pu	400.000	400.000	200.000	400.000	18.000
τ_A or τ_{A1}	s	0.050	0.050	0.050	0.050	0.200
τ_{A2}	s	0.000	0.000	0.000	0.000	0.000
$V_{R\max}$	pu (4)	4.407	6.630	11.540	5.850	1.000
$V_{R\min}$	pu (4)	−4.407	−6.630	−11.540	−5.850	−1.000
K_E	pu	−0.170	−0.170	−0.170	−0.170	−0.0138
τ_E	s	0.950	0.950	1.000	0.950	0.0669
$S_{E.75\max}$	(5)	0.220	0.220	0.220	0.220	0.0634
$S_{E\max}$	(5)	0.950	0.950	0.950	0.950	0.1512
A_{EX}	(5)	0.0027	0.0027	0.0027	0.0027	0.0047
B_{EX}	(5)	1.0356	0.6884	0.3956	0.7802	0.4782
$E_{FD\max}$	pu (5)	5.650	8.500	14.790	7.500	7.270
$E_{FD\min}$	pu	−5.650	−8.500	−14.790	−7.500	−7.270
K_F	pu	0.040	0.040	0.070	0.040	0.0153
τ_F or τ_{F1}	s	1.000	1.000	1.000	1.000	1.000
τ_{F2}	s	0.000	0.000	0.000	0.000	0.000

Table D.7. Typical Data for Combustion Turbine (CT) Units

GENERATOR			
Unit no.		CT1	CT2
Rated MVA		20.65	62.50
Rated kV		13.80	13.80
Rated PF		0.85	0.85
SCR	(1)	0.580	0.580
x''_d	pu	0.155	0.102
x'_d	pu	0.225	0.159
x_d	pu	1.850	1.640
x''_q	pu	...	0.100
x'_q	pu	...	0.306
x_q	pu	1.740	1.575
r_a	pu	...	0.034
x_ℓ or x_p	pu	...	0.113
r_2	pu	...	0.352
x_2	pu	...	0.102
x_0	pu	...	0.051
τ''_d	s	...	0.035
τ'_d	s	...	0.730
τ''_{d0}	s	...	0.054
τ'_{d0}	s	4.610	7.500
τ''_q	s	...	0.035
τ'_q	s	...	0.188
τ''_{q0}	s	...	0.107
τ'_{q0}	s	...	1.500
τ_a	s	...	0.350
W_R	MW·s	183.30	713.50
r_F	Ω	...	0.261
$S_{G1.0}$	(2)	...	0.0870
$S_{G1.2}$	(2)	...	0.2681
E_{FDFL}	(2)	2.640	2.4348
D	(3)	...	2.000

EXCITER			
VR type		D	C
Name	(4)	SCPT	BRLS
RR	(4)	...	0.50
τ_R	s	0.000	0.000
K_A	pu	120.000	400.000
τ_A or τ_{A1}	s	0.050	0.020
τ_{A2}	s	0.000	0.000
$V_{R\max}$	pu (4)	1.200	7.300
$V_{R\min}$	pu (4)	−1.200	−7.300
K_E	pu	1.000	1.000
τ_E	s	0.500	0.253
$S_{E.75\max}$	(5)	...	0.500
$S_{E\max}$	(5)	...	0.860
A_{EX}	(5)	...	0.0983
B_{EX}	(5)	...	0.2972
$E_{FD\max}$	pu (5)	...	7.300
$E_{FD\min}$	pu	...	0.000
K_F	pu	0.020	0.030
τ_F or τ_{F1}	s	0.461	1.000
τ_{F2}	s	...	0.000
K_P		1.19	
K_I		2.32	

TURBINE GOVERNOR				
GOV	(6)	G		G
R	(6)	0.050		0.040
$P_{\max}$	MW	17.55		82.00
τ_1	s	0.000		0.500
τ_2	s	0.000		1.250
		Fuel: Oil	Gas	
τ_3	s	0.025	0.100	0.700
τ_4	s	0.000	0.000	0.700
τ_5	s	0.025	0.100	0.000
F	(6)	0.5	0.0	1.000

Table D.8. Typical 60-Hz Transmission Line Data

Line-to-line voltage (kV)	Conductors per phase @ 18 in. spacing	ACSR Conductor area (or diam) kCM (in.)	Flat phase spacing (ft)	Geometric mean distance (ft)	60-Hz inductive reactance Ω/mi			60-Hz capacitive reactance MΩ·mi			Surge impedance z_0 (Ω)	Surge impedance loading (MVA)
					x_a	x_d	$x_a + x_d$	x'_a	x'_d	$x'_a + x'_d$		
69	1	226.8	12	15.1	0.465	0.3294	0.7944	0.1074	0.0805	0.1879	386.4	12
115	1	336.4	14	17.6	0.451	0.3480	0.7990	0.1039	0.0851	0.1890	388.6	34
138	1	397.5	16	20.1	0.441	0.3641	0.8051	0.1015	0.0890	0.1905	391.6	49
161	1	477.0	18	22.7	0.430	0.3789	0.8089	0.0988	0.0926	0.1914	393.5	66
230	1	556.5	22	27.7	0.420	0.4030	0.8230	0.0965	0.0985	0.1950	400.6	132
345	1	(1.750)	28	35.3	0.3336	0.4325	0.7761	0.0777	0.1057	0.1834	374.8	318
345	2	(1.246)	28	35.3	0.1677	0.4325	0.6002	0.0379	0.1057	0.1436	293.6	405
500	1	(2.500)	38	47.9	0.2922	0.4694	0.7616	0.0671	0.1147	0.1818	372.1	672
500	2	(1.602)	38	47.9	0.1529	0.4694	0.6223	0.0341	0.1147	0.1488	304.3	822
500	3	(1.165)	38	47.9	0.0988	0.4694	0.5682	0.0219	0.1147	0.1366	278.6	897
500	4	(0.914)	38	47.9	0.0584	0.4694	0.5278	0.0126	0.1147	0.1273	259.2	965
735	3	(1.750)	56	70.6	0.0784	0.5166	0.5950	0.0179	0.1263	0.1442	292.9	1844
735	4	(1.382)	56	70.6	0.0456	0.5166	0.5622	0.0096	0.1263	0.1359	276.4	1955

appendix **E**

Excitation Control System Definitions

There are two important recently published documents dealing with excitation control system definitions. The first [1] appeared in 1961 under the title "Proposed excitation system definitions for synchronous machines" and provided many definitions of basic system elements. The second report [2] was published in 1969 under the same title and, using the first report as a starting point, added the new definitions required by technological change and attempted to make all definitions agree with accepted language of the automatic control community. The definitions that follow are those proposed by the 1969 report.[1]

Reference is also made to the definitions given in ANSI Standard C42.10 on rotating machines [3], ANSI Standard C85.1 on automatic control [4], and the supplement to C85.1 [5]. Finally, reference is made to the IEEE Committee Report "Computer representation of excitation systems" [6], which defines certain time constants and gain factors used in excitation control systems.

Proposed IEEE Definitions

1.0 Systems

1.01 Control system, feedback. A control system which operates to achieve prescribed relationships between selected system variables by comparing functions of these variables and using the difference to effect control.

1.02 Control system, automatic feedback. A feedback control system which operates without human intervention.

1.03 Excitation system [1, definition 4]. The source of field current for the excitation of a synchronous machine and includes the exciter, regulator, and manual control.

1.04 Excitation control system (new). A feedback control system which includes the synchronous machine and its excitation system.

1.05 High initial response excitation system (new). An excitation system having an excitation system voltage response time of 0.1 second or less.

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2.0 Components

2.01 Adjuster [1, definition 40]. An element or group of elements associated with a feedback control system by which adjustment of the level of a controlled variable can be made.

2.02 Amplifier. A device whose output is an enlarged reproduction of the essential features of an input signal and which draws power therefore from a source other than the input signal.

2.03 Compensator [1, definition 44]. A feedback element of the regulator which acts to compensate for the effect of a variable by modifying the function of the primary detecting element.

Notes:

1. Examples are reactive current compensator and active current compensator. A reactive current compensator is a compensator that acts to modify the functioning of a voltage regulator in accordance with reactive current. An active current compensator is a compensator that acts to modify the functioning of a voltage regulator in accordance with active current.
2. Historically, terms such as "equalizing reactor" and "cross-current compensator" have been used to describe the function of a reactive compensator. These terms are deprecated.
3. Reactive compensators are generally applied with generator voltage regulators to obtain reactive current sharing among generators operating in parallel. They function in the following two ways.
   a. Reactive droop compensation is the more common method. It creates a droop in generator voltage proportional to reactive current and equivalent to that which would be produced by the insertion of a reactor between the generator terminals and the paralleling point.
   b. Reactive differential compensation is used where droop in generator voltage is not wanted. It is obtained by a series differential connection of the various generator current transformer secondaries and reactive compensators. The difference current for any generator from the common series current creates a compensating voltage in the input to the particular generator voltage regulator that acts to modify the generator excitation to reduce to minimum (zero) its differential reactive current.
4. Line drop compensators modify generator voltage by regulator action to compensate for the impedance drop from the machine terminals to a fixed point. Action is accomplished by insertion within the regulator input circuit of a voltage equivalent to the impedance drop. The voltage drops of the resistance and reactance portions of the impedance are obtained respectively in pu quantities by an "active compensator" and a "reactive compensator."

2.04 Control, manual (new). Those elements in the excitation control system which provide for manual adjustment of the synchronous machine terminal voltage by open loop (human element) control.

2.05 Elements, feedback. Those elements in the controlling system which change the feedback signal in response to the directly controlled variable.

2.06 Elements, forward. Those elements situated between the actuating signal and the controlled variable in the closed loop being considered.

2.07 Element, primary detecting. That portion of the feedback elements which first either utilizes or transforms energy from the controlled medium to produce a signal which is a function of the value of the directly controlled variable.

2.08 Exciter [1, definition 5]. The source of all or part of the field current for the excitation of an electric machine.

2.09 Exciter, main [1, definition 5]. The source of all or part of the field current for the excitation of an electric machine, exclusive of another exciter.

2.09.1 DC generator commutator exciter. An exciter whose energy is derived from a dc generator. The exciter includes a dc generator with its commutator and brushes. It is exclusive of input control elements. The exciter may be driven by a motor, prime mover, or the shaft of the synchronous machine.

2.09.2 Alternator rectifier exciter. An exciter whose energy is derived from an alternator and converted to dc by rectifiers. The exciter includes an alternator and power rectifiers which may be either noncontrolled or controlled, including gate circuitry. It is exclusive of input control elements. The alternator may be driven by a motor, prime mover, or by the shaft of the synchronous machine. The rectifiers may be stationary or rotating with the alternator shaft.

2.09.3 Compound rectifier exciter. An exciter whose energy is derived from the currents and potentials of the ac terminals of the synchronous machine and converted to dc by rectifiers. The exciter includes the power transformers (current and potential), power reactor, power rectifiers which may be either noncontrolled or controlled, including gate circuitry. It is exclusive of input control elements.

2.09.4 Potential source rectifier exciter. An exciter whose energy is derived from a stationary ac potential source and converted to dc by rectifiers. The exciter includes the power potential transformers, where used, power rectifiers which may be either noncontrolled or controlled, including gate circuitry. It is exclusive of input control elements.

2.10 Exciter, pilot [1, definition 7]. The source of all or part of the field current for the excitation of another exciter.

2.11 Limiter [1, definition 43]. A feedback element of the excitation system which acts to limit a variable by modifying or replacing the function of the primary detector element when predetermined conditions have been reached.

2.12 Regulator, synchronous machine [1, definition 8]. A synchronous machine regulator couples the output variables of the synchronous machine to the input of the exciter through feedback and forward controlling elements for the purpose of regulating the synchronous machine output variables.

Note: In general, the regulator is assumed to consist of an error detector, preamplifier, power amplifier, stabilizers, auxiliary inputs, and limiters. As shown in Figure 7.20, these regulator components are assumed to be self-explanatory, and a given regulator may not have all the items included. Functional regulator definitions describing types of regulators are listed below. The term "dynamic-type" regulator has been omitted as a classification [1, Definition 15].

2.12.1 Continuously acting regulator [1, definition 10]. One that initiates a corrective action for a sustained infinitesimal change in the controlled variable.

2.12.2 Noncontinuously acting regulator [1, definition 11]. One that requires a sustained finite change in the controlled variable to initiate corrective action.

2.12.3 Rheostatic type regulator [1, definition 12]. One that accomplishes the regulating function by mechanically varying a resistance.

Note [1, Definitions 13, 14]: Historically, rheostatic type regulators have been further defined as direct-acting and indirect-acting. An indirect-acting type of regulator is a rheostatic type that controls the excitation of the exciter by acting on an intermediate device not considered part of the regulator or exciter.

A direct-acting type of regulator is a rheostatic type that directly controls the excitation of an exciter by varying the input to the exciter field circuit.

2.13 Stabilizer, excitation control system (new). An element or group of elements which modifies the forward signal by either series or feedback compensation to improve the dynamic performance of the excitation control system.

2.14 Stabilizer, power system (new). An element or group of elements which provides an additional input to the regulator to improve power system dynamic performance. A number of different quantities may be used as input to the power system stabilizer such as shaft speed, frequency, synchronous machine electrical power and other.

3.0 Characteristics and performance

3.01 Accuracy, excitation control system (new). The degree of correspondence between the controlled variable and the ideal value under specified conditions such as load changes, ambient temperature, humidity, frequency, and supply voltage variations. Quantitatively, it is expressed as the ratio of difference between the controlled variable and the ideal value.

3.02 Air gap Line. The extended straight line part of the no-load saturation curve.

3.03 Ceiling voltage, excitation system [1, definition 26]. The maximum dc component system output voltage that is able to be attained by an excitation system under specified conditions.

3.04 Ceiling voltage, exciter [1, definition 24]. Exciter ceiling voltage is the maximum voltage that may be attained by an exciter under specified conditions.

3.05 Ceiling voltage, exciter nominal [1, definition 25]. Nominal exciter ceiling voltage is the ceiling voltage of an exciter loaded with a resistor having an ohmic value equal to the resistance of the field winding to be excited and with this field winding at a temperature of

1. 75°C for field windings designed to operate at rating with a temperature rise of 60°C or less.
2. 100°C for field windings designed to operate at rating with a temperature rise greater than 60°C.

3.06 Compensation. A modifying or supplementary action (also, the effect of such action) intended to improve performance with respect to some specified characteristics.

Note: In control usage this characteristic is usually the system deviation. Compensation is frequently qualified as "series," "parallel," "feedback," etc., to indicate the relative position of the compensating element.

3.07 Deviation, system. The instantaneous value of the ultimately controlled variable minus the command.

3.08 Deviation, transient. The instantaneous value of the ultimately controlled variable minus its steady-state value.

3.09 Disturbance. An undesired variable applied to a system which tends to affect adversely the value of a controlled variable.

3.10 Duty, excitation system (new). Those voltage and current loadings imposed by the synchronous machine upon the excitation system including short circuits and all conditions of loading. The duty cycle will include the action of limiting devices to maintain synchronous machine loading at or below that defined by ANSI C50.13-1965.

3.11 Duty, excitation system (new). An initial operating condition and a subsequent sequence of events of specified duration to which the excitation system will be exposed.

Note: The duty cycle usually involves a three-phase fault of specified duration located electrically close to the synchronous generator. Its primary purpose is to specify the duty that the excitation system components can withstand without incurring maloperation or specified damage.

3.12 Drift [1, definition 36]. An undesired change in output over a period of time, which change is unrelated to input, environment, or load.

Note: The change is a plus or minus variation of short periods that may be superimposed on plus or minus variations of a long time period. On a practical system, drift is determined as the change in output over a specified time with fixed command and fixed load, with specified environmental conditions.

3.13 Dynamic. Referring to a state in which one or more quantities exhibit appreciable change within an arbitrarily short time interval.

3.14 Error. An indicated value minus an accepted standard value, or true value.

Note: ANSI C85 deprecates use of the term as the negative of deviation. See also accuracy, precision in ANSI C85.1.

3.15 Excitation system voltage response [1, definition 21]. The rate of increase or decrease of the excitation system output voltage determined from the excitation system voltage-time response curve, which rate if maintained constant, would develop the same voltage-time area as obtained from the curve for a specified period. The starting point for determining the rate of voltage change shall be the initial value of the excitation system voltage time response curve. Referring to Fig. E-1, the excitation system voltage response is illustrated by line *ac*. This line is determined by establishing the area *acd* equal to area *abd*.

Notes:

1. Similar definitions can be applied to the excitation system major components such as the exciter and regulator.
2. A system having an excitation system voltage response time of 0.1 s or less is defined as a high initial response excitation system (Definition 1.05).

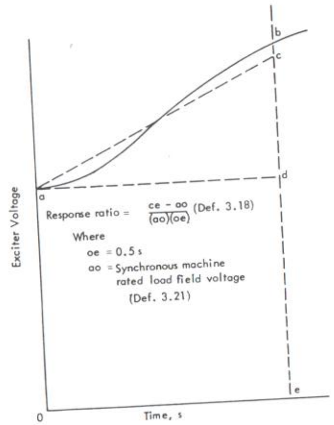

Fig. E.1. Exciter or synchronous machine excitation system voltage response (Def. 3.15).

3.16 Excitation system voltage response time (new). The time in seconds for the excitation voltage to reach 95 percent of ceiling voltage under specified conditions.

3.17 Excitation system voltage time response [1, definition 19]. The excitation system output voltage expressed as a function of time, under specified conditions.

Note: A similar definition can be applied to the excitation system major components: the exciter and regulator separately.

3.18 Excitation system voltage response ratio [1, definition 23]. The numerical value which is obtained when the excitation system voltage response in volts per second, measured over the first half-second interval unless otherwise specified, is divided by the rated-load field voltage of the synchronous machine. Unless otherwise specified, the excitation system voltage response ratio shall apply only to the increase in excitation system voltage. Referring to Fig. E.1 the excitation system voltage response ratio = $(ce - ao)/(ao)(oe)$, where ao = synchronous machine rated load field voltage (Definition 3.21) and oe = 0.5 second, unless otherwise specified.

3.19 Exciter main response ratio; formerly nominal exciter response. The main exciter response ratio is the numerical value obtained when the response, in volts per second, is divided by the rated-load field voltage; which response, if maintained constant, would develop, in one half-second, the same excitation voltage-time area as attained by the actual exciter.

Note: The response is determined with no load on the exciter, with the exciter voltage initially equal to the rated-load field voltage, and then suddenly establishing circuit conditions that would be used to obtain nominal exciter ceiling voltage. For a rotating exciter, response should be determined at rated speed. This definition does not apply to main exciters having one or more series fields (except a light differential series field) nor to electronic exciters.

3.20 Field voltage, base (new). The synchronous machine field voltage required to produce rated voltage on the air gap line of the synchronous machine at field temperatures.

1. 75°C for field windings designed to operate at rating with a temperature rise of 60°C or less.
2. 100°C for field windings designed to operate at rating with a temperature rise greater then 60°C.

Note: This defines one pu excitation system voltage for use in computer representation of excitation systems [6].

3.21 Field voltage, rated-load [1, definition 38]; formerly nominal collector ring voltage. Rated-load field voltage is the voltage required across the terminals of the field winding or an electric machine under rated continuous-load conditions with the field winding at one of the following.

1. 75°C for field windings designed to operate at rating with a temperature rise of 60°C or less.
2. 100°C for field windings designed to operate at rating with a temperature rise greater than 60°C.

3.22 Field voltage, no-load [1, definition 39]. No-load field voltage is the voltage required across the terminals of the field winding of an electric machine under conditions of no load, rated speed, and terminal voltage and with the field winding at 25°C.

3.23 Gain, proportional. The ratio of the change in output due to proportional control action to the change in input. Illustration: $Y = \pm PX$ where P = proportional gain, X = input transform, and Y = output transform.

3.24 Limiting. The intentional imposition or inherent existence of a boundary on the range of a variable, e.g., on the speed of a motor.

3.25 Regulation, load. The decrease of controlled variable (usually speed or voltage) from no load to full load (or other specified limits).

3.26 Regulated voltage, band of [1, definition 37]. Band of regulated voltage is the band or zone, expressed in percent of the rated value of the regulated voltage, within which the excitation system will hold the regulated voltage of an electric machine during steady or gradually changing conditions over a specified range of load.

3.27 Regulated voltage, nominal band of. Nominal band of regulated voltage is the band of regulated voltage for a load range between any load requiring no-load field voltage and any load requiring rated-load field voltage with any compensating means used to produce a deliberate change in regulated voltage inoperative.

3.28 Signal, actuating. The reference input signal minus the feedback signal (Figure 7.19).

3.29 Signal, error. In a closed loop, the signal resulting from subtracting a particular return signal from its corresponding input signal (Figure 7.19).

3.30 Signal, feedback. That return signal which results from the reference input signal (Figure 7.19).

3.31 Signal, input. A signal applied to a system or element.

3.32 Signal, output. A signal delivered by a system or element.

3.33 Signal, rate (new). A signal that is responsive to the rate of change of an input signal.

3.34 Signal, reference input. One external to a control loop which serves as the standard of comparison for the directly controlled variable.

3.35 Signal, return. In a closed loop, the signal resulting from a particular input signal, and transmitted by the loop and to be subtracted from that input signal.

3.36 Stability. For a feedback control system or element, the property such that its output is asymptotic, i.e., will ultimately attain a steady-state, within the linear range and without continuing external stimuli. For certain nonlinear systems or elements, the property that the output remains bounded, e.g., in a limit cycle of continued oscillation, when the input is bounded.

3.37 Stability limit. A condition of a linear system or one of its parameters which places the system on the verge of instability.

3.38 Stability, excitation system. The ability of the excitation system to control the field voltage of the principal electric machine so that transient changes in the regulated voltage are effectively suppressed and sustained oscillations in the regulated voltage are not produced by the excitation system during steady-load conditions or following a change to a new steady-load condition.

Note: It should be recognized that under some system conditions it may be necessary to use power system stabilizing signals as additional inputs to excitation control systems to achieve stability of the power system including the excitation system.

3.39 Steady state. That in which some specified characteristic of a condition, such as value, rate, periodicity, or amplitude, exhibits only negligible change over an arbitrarily long interval of time.

Note: It may describe a condition in which some characteristics are static, others dynamic.

3.40 Transient. In a variable observed during transition from one steady-state operating condition to another that part of the variation which ultimately disappears.

Note: ANSI C85 deprecates using the term to mean the total variable during the transition between two steady states.

3.41 Variable, directly controlled. In a control loop, that variable whose value is sensed to originate a feedback signal.

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