Methods of Determining Regulator Parameters for Power System Dynamic Equivalents

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By

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(Received September 28, 1981)

Abstract

In this paper, two novel methods are proposed for determining the regulator parameters in the construction of power system dynamic equivalents based on coherency. The methods are based on the idea that the governor of the equivalent generator should have the characteristics which are the sum of the characteristics of the governors of the generators belonging to the coherent groups. Also, AVR should have the average characteristics of the AVRs of the coherent generators. The indicial response or the frequency response is used as the representative characteristic, and the equivalent parameters are determined so as to approximate the above ideal characteristics. The methods are applied to the construction of a dynamic equivalent of a sample ten-machine system, and their validity is examined.

1. Introduction

Power systems today continue to increase in size and complexity. The generator capacity and the number of generators are increasing, the interconnection among the power systems tends to be strengthened, and the regulators such as AVRs and governors are becoming to have quick responses. These factors are due to the increasing demand for electric power and the need for economy and reliability of power supply. Accordingly, the stability problem of power systems is becoming more important than ever. In analyzing the stability of such huge and complex power systems, in many cases it is impossible to use the detailed models of the systems. Hence, it becomes indispensable to use dynamic equivalents -the simplified model of the power systems- for the analysis of a dynamic performance. A method for constructing dynamic equivalents is based on coherency, i.e., the generators whose transient behaviors are similar to each other are aggregated into one equivalent generator[1)-3)]. The authors have proposed a method for the coherency recognition in the construction of a dynamic equivalent for the

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calculation of short-term dynamics without the regulators. This method uses the Lyapunov function.[4]

On the other hand, the regulators (AVRs and governors) affect the system performance during the intermediate time domain (2,3–10 sec after the disturbance), resulting from the system swing which occurred during the transient period (1–2 sec after the disturbance). Moreover, due to the recent improvement in the characteristics of the control devices, the regulators (such as the high initial response excitation system etc.) have come to effect the transient stability. Therefore, the regulators can not be ignored in the stability analysis.

In this paper, we investigate the conventional methods for simplifying power systems with regulators. We then propose determining methods of the equivalent regulator parameters which can better retain the original system performance. The proposed method is based on the principle that the governor of the equivalent generator should have the characteristics which are the sum of the characteristics of the governors of the generators belonging to the coherent group. Also, the AVR should have the average characteristics of the AVRs of the coherent generators. The indicial response or frequency response of each regulator is obtained, and the parameters of the equivalent regulator are determined in order that the response may be as close to the above mentioned ideal response as possible. The method is applied to the construction of a dynamic equivalent of a sample ten-machine system, and the transient performances of the equivalent are compared with those obtained by the conventional method.

2. Description of System Model

2-1 Synchronous Machines

In this paper, a synchronous machine is represented by the following fourth order model, considering one winding on each of the direct and quadrature axis of the rotor.

$$
\begin{aligned}
pE_d' &= [-E_d' + (x_q - x_q')i_q]/T_{q0}' \\
pE_q' &= [E_{fd} - E_q' - (x_d - x_d')i_d]\,T_{d0}' \\
p\delta &= \Delta\omega \\
p\Delta\omega &= (P_m - P_e - D\Delta\omega)/M \\
& \qquad P_e = v_d i_d + v_q i_q \\
& \qquad v_t^2 = v_d^2 + v_q^2
\end{aligned}
$$

2-2 AVRs and Governors

A generator is assumed to be equipped with the AVR and governor, the block

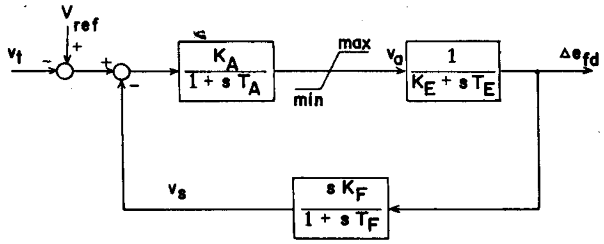

Fig. 1. Block diagram of AVR.

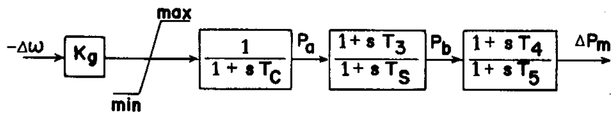

Fig. 2. Block diagram of governor.

diagrams of which are shown in Fig. 1 and Fig. 2, respectively. The characteristics of these regulators are described by the following differential equations:

AVR

$$pv_a = -\frac{1}{T_A}v_a + \frac{K_A}{T_A}(v_{ref} - v_t - v_s)$$

$$p\Delta e_{fd} = -\frac{K_E}{T_E}\Delta e_{fd} + \frac{1}{T_E}v_a$$

$$pv_s = -\frac{1}{T_F}v_s + \frac{K_F}{T_F}p\Delta e_{fd}$$

Governor

$$pP_a = -\frac{1}{T_c}P_a - \frac{K_g}{T_c}\Delta\omega$$

$$pP_b = -\frac{1}{T_s}P_b + \frac{1}{T_s}P_a + \frac{T_3}{T_s}pP_a$$

$$p\Delta P_m = -\frac{1}{T_5}\Delta P_m + \frac{1}{T_5}P_b + \frac{T_4}{T_5}pP_b$$

Accordingly, each generator has ten state-variables, i.e., E_d', E_q', δ, $\Delta\omega$, v_a, Δe_{fd}, v_s, P_a, P_b, and ΔP_m.

3. Methods of Determining Parameters of Dynamic Equivalents

In this section, the determining methods of the parameters of the equivalent generators and transmission systems are first described. Next, regarding the derivation of the equivalent regulator parameters, the conventional method and the novel methods proposed in this paper are presented.

3-1 Determining Method of Parameters of Equivalent Generators and Transmission System

The method which has been long used to determine the parameters of the generators and transmission systems is as follows.

Generator

The inertia constant and damping coefficient are the sum of the values for the coherent generators.

$$M_e = \sum_{i=1}^{n} M_i$$

$$D_e = \sum_{i=1}^{n} D_i$$

where, the subscript e denotes the quantities for the equivalent generator, and n is the number of coherent generators.

The resistances and reactances are the parallel connections of the values for the coherent generators.

$$1/r_e = \sum_{i=1}^{n} (1/r_i)$$

$$1/x_{de} = \sum_{i=1}^{n} (1/x_{di})$$

(The same for x'_d, x_q, x'_q, x_l.)

The time constants are the log average of the values for the coherent generators.

$$\log T'_{doe} = (\sum_{i=1}^{n} \log T'_{doi})/n$$

(The same for T'_{q0}.)

The internally induced voltage is the arithmetical average of the values for the coherent generators.

$$E_e = (\sum_{i=1}^{n} E_i)/n$$

The mechanical input to the generator is the sum of the values for the coherent generators.

$$P_{me} = \sum_{i=1}^{n} P_{mi}$$

Transmission system

The elements of the admittance matrix are the sum of the elements corresponding to the coherent generators.

$$Y_{ee} = \sum_{i,j=1}^{n} Y_{ij}$$

$$Y_{ej} = \sum_{i=1}^{n} Y_{ij}$$

3-2 Determination Method of Equivalent Regulator Parameters

Method I (Conventional Method)

Governor

The gain is the sum of the values for the coherent generator governors.

$$K_{ge} = \sum_{i=1}^{n} K_{gi}$$

The time constants are the log average of the values for the coherent generator governors.

$$\log T_{ce} = \sum_{i=1}^{n} (\log T_{ci})/n$$

(The same for T_3, T_s, T_4, and T_5.)

The upper and lower limits of the limiter are the sum.

AVR

The gain and time constants are the log average of the values for the coherent generator AVRs.

$$\log K_{Ae} = (\sum_{i=1}^{n} \log K_{Ai})/n$$

(The same for K_E, K_F, T_A, T_E and T_F.)

The upper and lower limits of v_a are the log average.

The log average and the parallel connection method works well if the values of the parameters do not differ much among the generators belonging to a coherent group. The generator parameters do not vary so much in their values, if the type of the generators (turbo- or hydro-generator) is the same. Furthermore, it is unlikely that turbo-generators be located electrically close to hydro-generators. Hence, they do not make a coherent group. Therefore, the determination method for the generator described in 3–1 causes little problem.

On the other hand, the parameters of the regulators can take various values if the type of the regulator is not the same. Therefore, it is recommended in Ref. (2) that the aggregation should be limited to those generators which have regulators of the same type. This makes a considerable constraint on the model simplification. If we assume that all generators from a coherent group move in completely the same way in their angular velocities and terminal voltages, then the sum of the outputs from governors (i.e., the mechanical inputs to the generator) which respond to the common angular velocity variation, becomes the variation of the mechanical input to the equivalent generator, and the average of the outputs from AVRs which respond to the common variation of terminal voltage, makes the change of the equivalent generator excitation voltage. These correspond to the facts that the mechanical input to the equivalent generator is the sum of each input, and the internally induced voltage of the equivalent generator is taken as the average of each voltage. Therefore, it is seen that the governor of the equivalent generator (called the equivalent governor, hereafter) should have the summed characteristics of the governors of the coherent generators. Also, the equivalent AVR should have the average characteristics of the coherent generator AVRs. In this paper, we propose and examine the following two methods for determining the equivalent regulator parameters in order to approximate the above mentioned ideal characteristics as well as possible.

Method II (Indicial Response Method)

The equivalent parameters are determined so that the indicial response of the equivalent governor (AVR) approaches the sum (average) of the indicial responses of the coherent generator governors (AVRs) as close as possible. The calculating method is as follows. The sum or the average of the indicial responses are calculated beforehand, and the parameters of the equivalent regulator are obtained, using the trial search method to minimize the root mean square error.

Method III (Frequency Response Method)

The equivalent parameters are determined so that the frequency response (vector loci) of the equivalent governor (AVR) is as close as possible to the sum (average) of the frequency responses of the coherent generator governors (AVRs). As the frequency response can be represented by a rather simple function of the parameters, the equivalent parameters can be obtained by the least-square approximation.

4. Sample System and Coherency Recognition

4-1 Sample System[1)]

Fig. 3 shows the sample ten-machine system. The parameter values of the generators, governors and AVRs are shown in Tables 1–3. The base power of the per unit system is 100MVA, and the No. 1 generator which has the largest capacity is chosen the reference generator. The No. 1 generator has no regulators

Table 1. Synchronous generator data (p.u. on 100 MVA base).

No.	M	r	x_1	x_d	x'_d	x_q	x'_q	T_{do}	T'_{qo}	D
1	500.0	0.0001	0.003	0.02	0.006	0.019	0.008	7.0	0.7	10.0
2	34.5	0.0003	0.0298	0.2106	0.057	0.205	0.0587	4.79	1.96	14.0
3	24.3	0.000686	0.028	0.290	0.057	0.280	0.0911	6.7	0.41	9.0
4	26.4	0.000268	0.0322	0.295	0.049	0.292	0.186	5.66	1.5	8.0
5	34.8	0.00615	0.0224	0.254	0.05	0.241	0.0814	7.3	0.4	10.0
6	26.0	0.00014	0.054	0.67	0.132	0.62	0.166	5.4	0.44	3.0
7	28.6	0.000222	0.0295	0.262	0.0436	0.258	0.166	5.69	1.5	10.0
8	35.8	0.000386	0.0304	0.2495	0.0531	0.237	0.0876	5.7	1.5	10.0
9	30.3	0.00027	0.035	0.295	0.0697	0.282	0.17	6.56	1.5	9.75
10	42.0	0.00014	0.0125	0.1	0.31	0.069	0.01	10.2	0.4	4.0

Table 2. Governor parameters.

No.	K_g	T_c	T_3	T_s	T_4	T_5
1	—	—	—	—	—	—
2	2.76	0.38	0	0.1	1.68	6.0
3	1.79	3.0	0	3.0	0	4.0
4	1.95	0.2	0	0.18	3.75	7.5
5	2.18	3.0	0	5.0	0	5.0
6	2.56	0.121	0	0.154	4.5	9.64
7	1.99	0.24	0	0.18	2.02	10.0
8	0.725	3.0	0	5.0	0	5.0
9	1.835	0.45	0	0.1	13.25	54.0
10	3.5	0.2	9.65	74.4	−1.93	0.965

Table 3. AVR parameters.

No.	K_A	K_E	K_F	T_A	T_E	T_F
1	—	—	—	—	—	—
2	40.0	1.7	0.03	0.02	1.4	1.0
3	5.0	0.13	0.0845	0.02	0.528	1.26
4	40.0	1.6	0.03	0.02	0.73	1.0
5	5.0	0.116	0.754	0.02	0.471	1.246
6	40.0	1.8	0.03	0.02	0.785	1.0
7	5.0	0.15	0.08	0.06	0.50	1.0
8	5.0	0.215	0.08	0.06	0.50	1.0
9	6.2	0.15	0.57	0.05	0.405	0.5
10	5.0	0.12	0.04	0.06	0.25	1.0

and is operated with constant excitation and constant mechanical input. The operating conditions are shown in Table 4. The fault assumed is a three-phase short circuit at point A in Fig. 3, and is cleared 0.19 sec after its occurrence, which

Table 4. Sample system bus data.

bus	volts	load MW	load MVar	gen MW	gen MVar
1	1.0475	0.0	0.0	0.0	0.0
2	1.0489	0.0	0.0	0.0	0.0
3	1.0304	322.0	2.4	0.0	0.0
4	1.0038	500.0	184.0	0.0	0.0
5	1.0050	0.0	0.0	0.0	0.0
6	1.0074	0.0	0.0	0.0	0.0
7	0.9967	233.8	84.0	0.0	0.0
8	0.9957	522.0	176.6	0.0	0.0
9	1.0281	0.0	0.0	0.0	0.0
10	1.0170	0.0	0.0	0.0	0.0
11	1.0125	0.0	0.0	0.0	0.0
12	1.0000	8.5	88.0	0.0	0.0
13	1.0142	0.0	0.0	0.0	0.0
14	1.0117	0.0	0.0	0.0	0.0
15	1.0158	320.0	153.0	0.0	0.0
16	1.0322	329.4	32.3	0.0	0.0
17	1.0339	0.0	0.0	0.0	0.0
18	1.0313	158.0	30.0	0.0	0.0
19	1.0500	0.0	0.0	0.0	0.0
20	0.9909	640.0	103.0	0.0	0.0
21	1.0321	274.0	115.0	0.0	0.0
22	1.0500	0.0	0.0	0.0	0.0
23	1.0455	247.5	84.6	0.0	0.0
24	1.0377	308.6	−92.2	0.0	0.0
25	1.0575	224.0	47.2	0.0	0.0
26	1.0521	139.0	17.0	0.0	0.0
27	1.0379	281.0	75.5	0.0	0.0
28	1.0501	206.0	27.6	0.0	0.0
29	1.0500	283.5	26.9	0.0	0.0
30	1.0475	0.0	0.0	250.0	145.1
31	0.9820	9.2	4.6	563.3	205.5
32	0.9831	0.0	0.0	650.0	205.7
33	0.9972	0.0	0.0	632.0	109.1
34	1.0123	0.0	0.0	508.0	167.0
35	1.0493	0.0	0.0	650.0	211.3
36	1.0635	0.0	0.0	560.0	100.5
37	1.0278	0.0	0.0	540.0	0.7
38	1.0265	0.0	0.0	830.0	22.8
39	1.0300	1104.0	250.0	1000.0	88.0

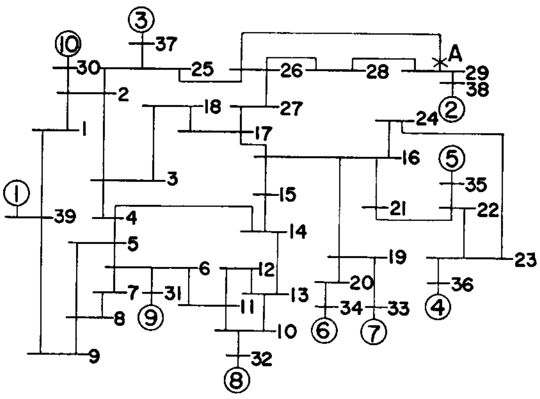

Fig. 3. Sample 10-machine system.

is the critical clearing time for the case without regulators. The reclosing is not considered.

4-2 Coherency Recognition

As mentioned in the Introduction, the authors have reported the coherency recognition method for power systems without regulators by means of the Lyapunov function (V-fn), which is used to assess the transient stability.[4] Roughly speaking, the principle of the method is that, if the value of V-fn for some group of generators is sufficiently less than the value of V-fn for the whole system, then the group is regarded as coherent. In order to use the identical method for the power system with regulators, it is necessary to construct a Lyapunov function which takes the effects of the regulators into account, but it is not an easy task. In this paper, we recognized the coherency using the Lyapunov function without regulators. As for results, we derived two coherent groups: Nos. 4, 5, 7 and Nos. 8, 9 from the eligible generators Nos. 4–9.

Figs. 4 and 5 show the swing curves of the generators to be retained in detail and to be aggregated, respectively. The values of MAE (Maximum Angle Excursion)[1] defined by the following equation are shown in Table 5.

$$\mathrm{MAE} = \max_{t=0\sim T} |\delta_i(t)-\delta_j(t)| - \min_{t=0\sim T} |\delta_i(t)-\delta_j(t)|$$

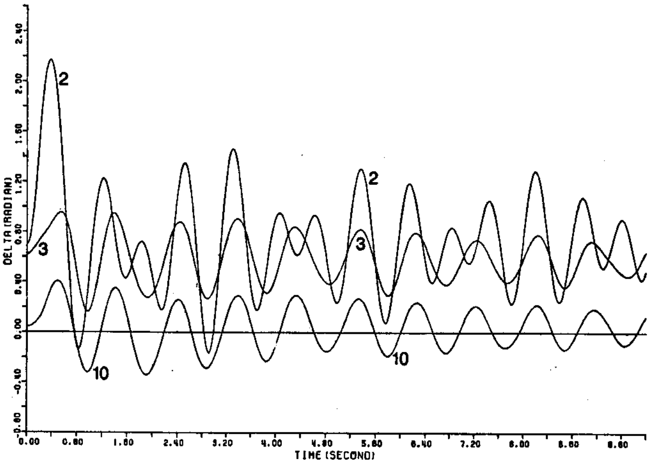

Fig. 4. Swing curves of the original system (retained generators).

The validity of the coherency recognition is ascertained to a certain extent from this table. In the next section, however, a calculation of dynamic response will also be made for the case where the generators Nos. 4–9 are aggregated into one.

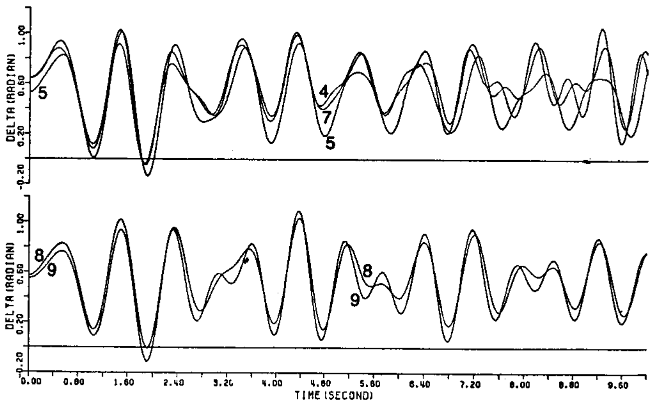

Fig. 5. Swing curves of the original system (coherent groups).

Table 5. Maximum angle excursion (rad.).

No.	2	3	4	5	6	7	8	9	10
1	2.16	0.791	1.01	1.00	0.983	1.05	1.03	1.07	0.406
2		1.32	1.32	1.41	1.25	1.31	1.41	1.46	1.85
3			0.340	0.413	0.494	0.390	0.284	0.392	0.181
4				0.389	0.577	0.232	0.329	0.425	0.519
5					0.586	0.494	0.267	0.339	0.525
6						0.680	0.588	0.683	0.672
7							0.358	0.477	0.688
8								0.153	0.470
9									0.632

5. Results of Simulations Using Dynamic Equivalent

Tables 6 and 7 show the parameter values of the equivalent regulators obtained via each determination method. It is reasonable that the values obtained by Method II and Method III are almost the same. Figs. 6 and 7 show the swing curves of the equivalent system whose regulator parameters are determined by Method I (conventional method). It is obvious from Fig. 6 that the swing curves of the retained generators depart from those of the original system after the second swing. The main reason for this deviation is that the variation of the mechanical input by the equivalent governor is very different from the ideal variation (the sum of the variation for each generator), as is shown in Fig. 8 for the coherent group, Nos. 4, 5 and 7. On the other hand, as shown in Fig. 9, the variation of the field voltage by the equivalent AVR does not differ much from the average of the variation for each generator.

Table 6. Parameters of equivalent governors.

No.	K_g	T_c	T_3	T_s	T_4	T_5
4	1.95	0.2	0.0	0.18	3.75	7.5
5	2.18	3.0	0.0	5.0	0.0	5.0
7	1.99	0.24	0.0	0.18	2.02	10.0
Method I	6.12	0.524	0.0	0.545	0.0	7.21
Method II	4.83	0.218	0.0	0.171	2.77	9.99
Method III	6.12	0.216	0.0	0.175	3.72	16.59
8	0.725	3.0	0.0	5.0	0.0	5.0
9	1.835	0.45	0.0	0.1	13.25	54.0
Method I	2.56	1.16	0.0	0.707	0.0	16.43
Method II	2.284	0.550	0.0	0.105	11.85	55.71
Method III	2.555	0.447	0.0	0.100	13.07	74.64

Table 7. Parameters of equivalent AVRs.

No.	K_A	K_E	K_F	T_A	T_E	T_F
4	40.0	1.6	0.03	0.02	0.73	1.0
5	5.0	0.116	0.0754	0.02	0.471	1.1246
7	5.0	0.15	0.08	0.06	0.50	1.0
Method I	10.0	0.3031	0.0566	0.0288	0.556	1.076
Method II	10.12	0.3031	0.10	0.020	0.4934	1.622
Method III	10.41	0.3031	0.0911	0.0209	0.4410	1.076
8	5.0	0.215	0.08	0.06	0.50	1.0
9	6.2	0.15	0.057	0.05	0.405	0.5
Method I	5.568	0.1796	0.0675	0.0548	0.45	0.7071
Method II	5.737	0.1796	0.0626	0.0555	0.4729	0.699
Method III	5.830	0.1796	0.0682	0.0507	0.4510	0.7071

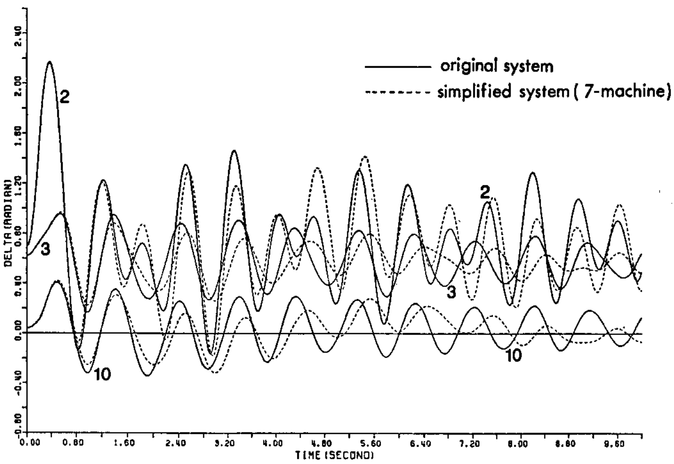

Fig. 6. Swing curves of retained generators (Method I).

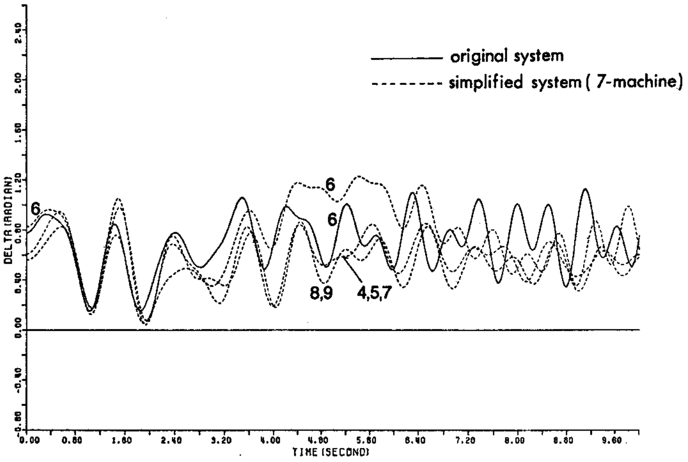

Fig. 7. Swing curves of coherent groups (Method I).

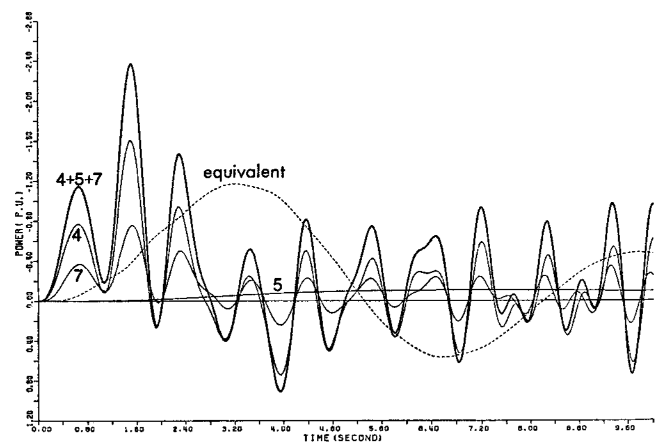

Fig. 8. Output of governor (Method I).

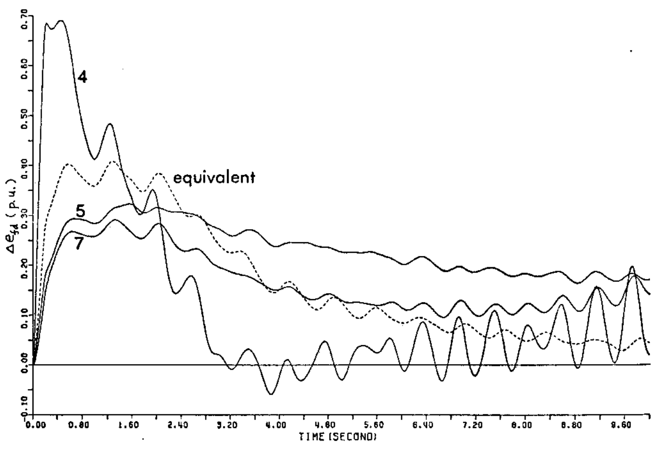

Fig. 9. Output of AVR (Method I).

Figs. 10 and 11 show the swing curves of the equivalent system with the regulator parameters determined by Method II. A comparison of these figures with Figs. 6 and 7 shows that the equivalence is better by Method II than by Method I.

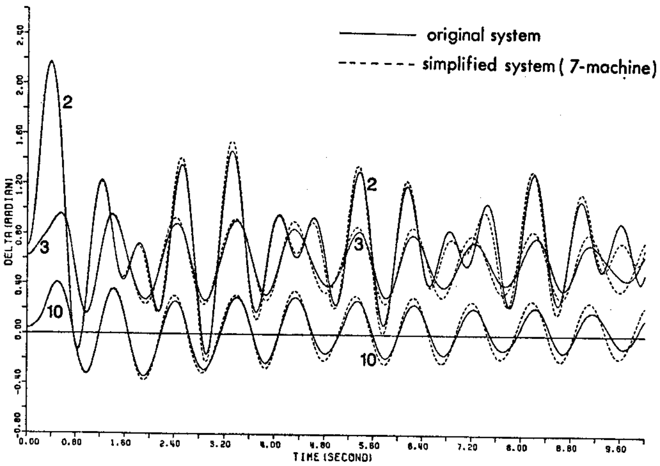

Fig. 10. Swing curves of retained generators (Method II).

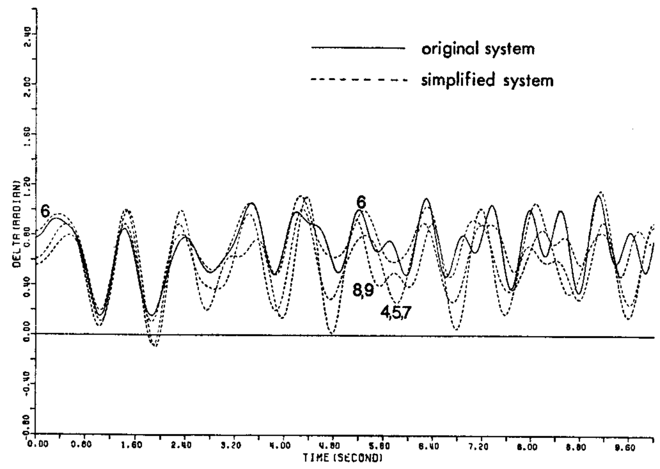

Fig. 11. Swing curves of coherent groups (Method II).

The variations of the mechanical inputs and the field voltages are shown in Figs. 12 and 13. The variation of the mechanical input to the equivalent generator is much closer to the sum of the variation for each generator than in Fig. 8. This is the reason for the improvement in the equivalence. Fig. 14 shows the swing curves of the retained generators in the case where the regulator parameters obtained by Method III were used. The results are similar to those of Fig. 10, as the

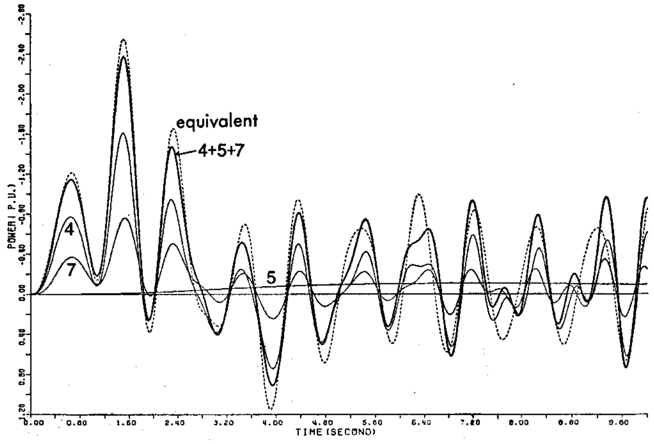

Fig. 12. Output of governor (Method II).

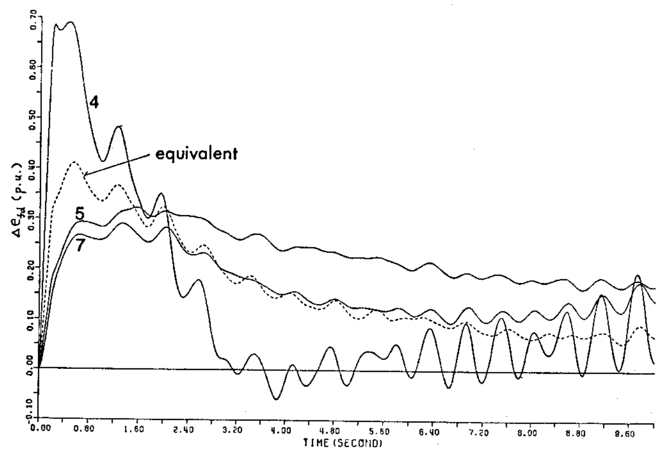

Fig. 13. Output of AVR (Method II).

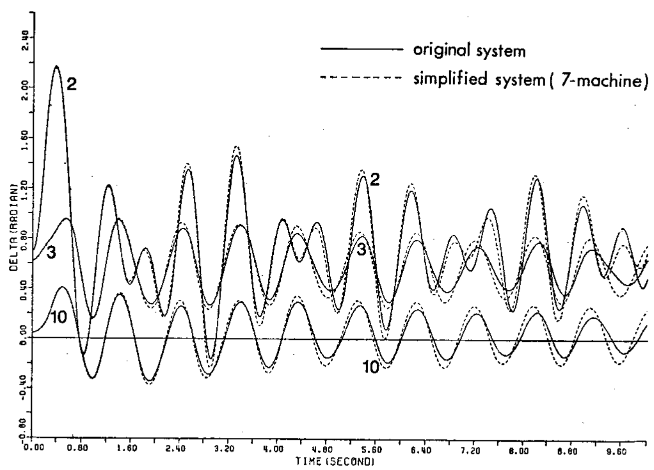

Fig. 14. Swing curves of retained generators (Method III).

parameter values of the equivalent regulators obtained by Method III are almost the same as those obtained by Method II.

In order to check the characteristics of the equivalent regulators themselves, the indicial responses and frequency responses of the regulators for the coherent group, Nos. 4, 5, 7 are calculated. They are shown in Figs. 15–20. It is seen

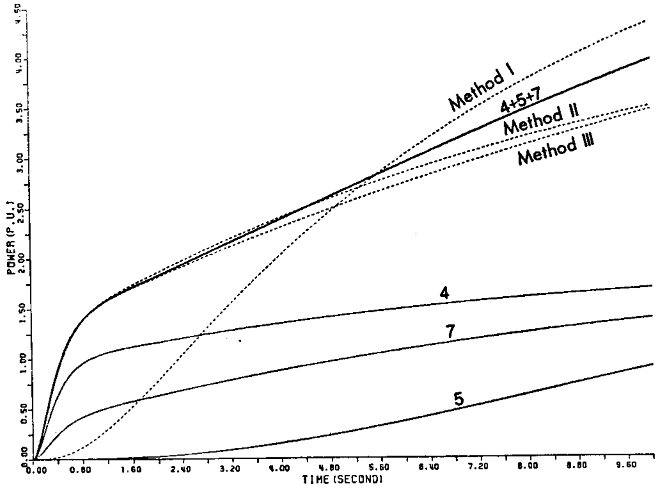

Fig. 15. Indicial responses of governors.

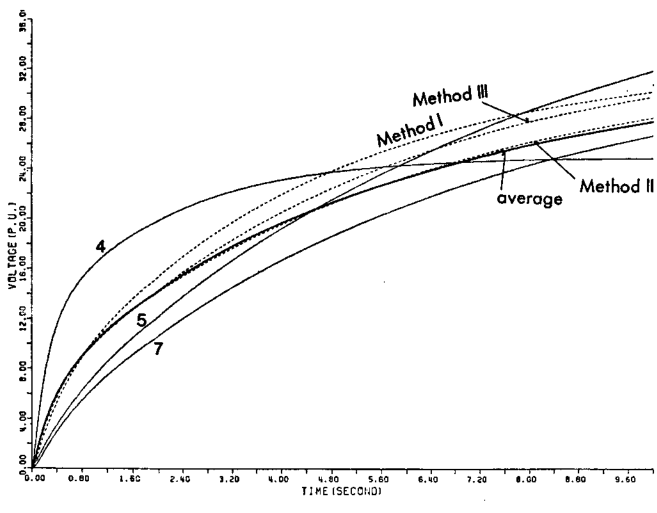

Fig. 16. Indicial responses of AVRs.

from Fig. 15 that the response of the equivalent governor obtained by Method I is very different from the ideal one. This is because of the slow-response of the No. 5 governor. The response of the equivalent AVRs does not show much

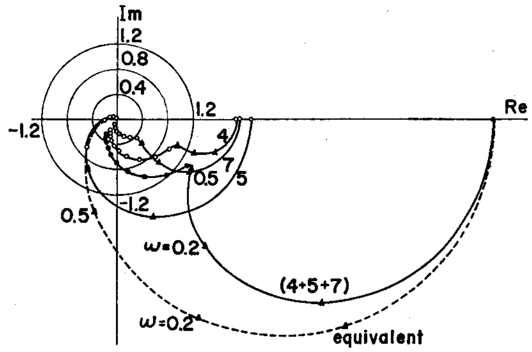

Fig. 17. Vector loci of governors (Method I).

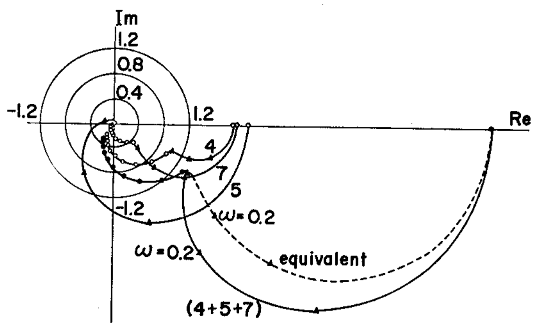

Fig. 18. Vector loci of governors (Method III).

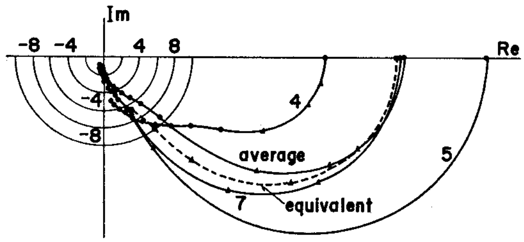

Fig. 19. Vector loci of AVRs (Method I).

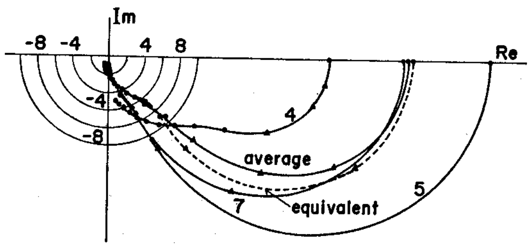

Fig. 20. Vector loci of AVRs (Method III).

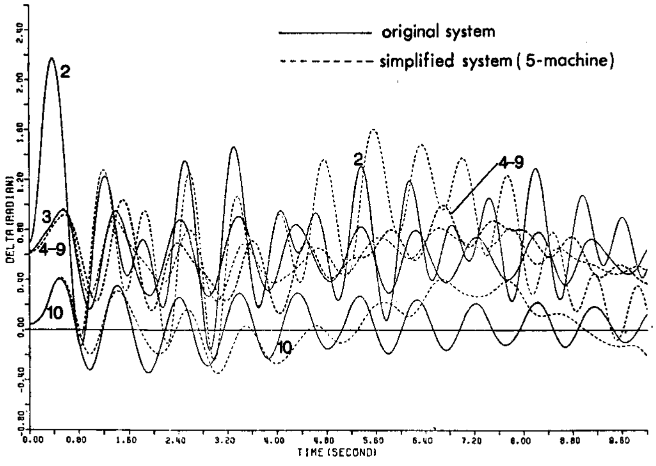

Fig. 21. Swing curves of retained generators (5-machine system, Method I).

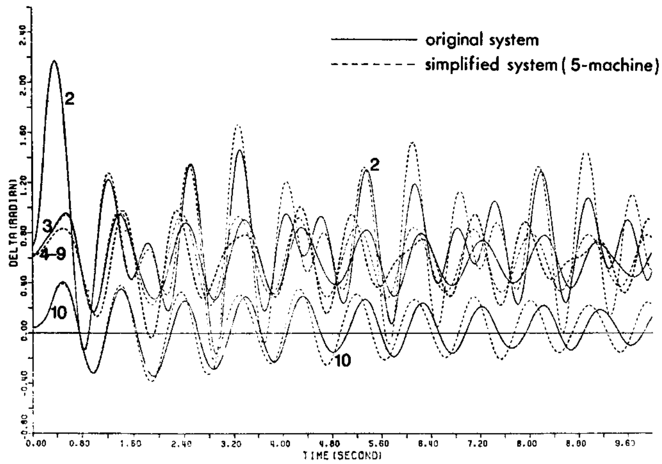

Fig. 22. Swing curves of retained generators (5-machine system, Method III).

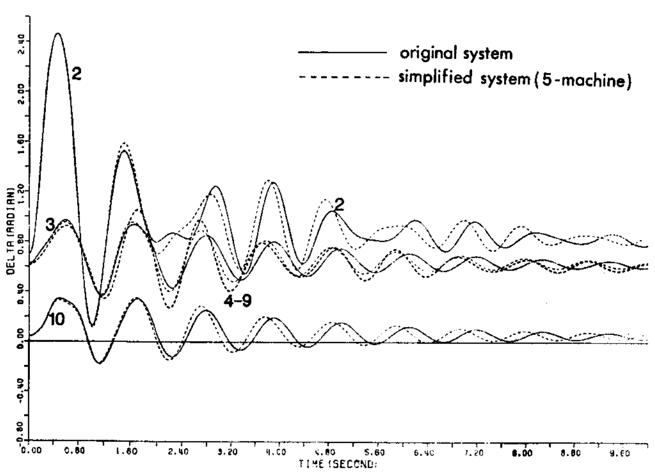

Fig. 23. Swing curves of retained generators (5-machine system, no regulators).

difference between the parameter determination methods. These are also shown in the vector loci of Figs. 17–20.

Lastly, the generators Nos. 4–9 are aggregated into one, and equivalent 5-machine systems are constructed. The swing curves of the retained generators for the equivalent systems are shown in Fig. 21 for Method I and in Fig. 22 for Method III. The equivalence is worse than the case of the equivalent 7-machine system. The influence of the aggregation is rather large even if Method III is used. As is seen in Fig. 23, which shows the results of the equivalent 5-machine

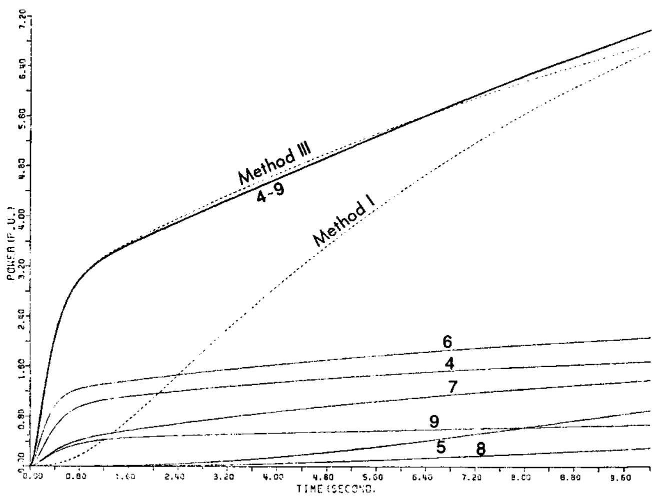

Fig. 24. Indicial responses of governors (5-machine system).

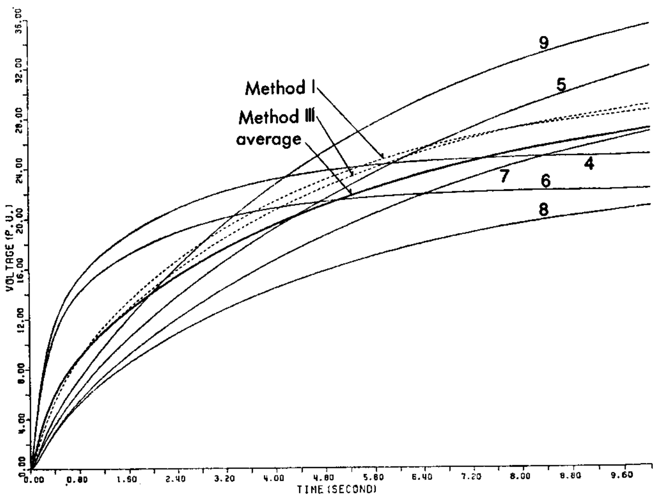

Fig. 25. Indicial responses of AVRs (5-machine system).

system without regulators, this is not only because of the regulators but mainly due to the aggregation of the generators and the transmission network. Figs. 24 and 25 show the indicial responses of the governors and AVRs, respectively.

6. Conclusions

In this paper, we proposed two methods for determining the regulator parameters in the construction of power system dynamic equivalents based on coherency. One is based on the indicial response of the regulators, and the other on the frequency response. The methods were applied to a sample ten-machine system, and the validity was examined. As for the results of the transient calculations, it was shown that the proposed method can derive equivalent parameters very close to the ideal equivalent parameters. This is true even if there are great differences between the parameter values of the coherent generator regulators. For this reason, we consider the proposed methods to be superior to the conventional method.

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