AN INQUIRY INTO ADJUSTABLE SPEED OPERATION OF A PUMPED HYDRO PLANT

PART II - SYSTEM ANALYSIS

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Abstract - Using the parameters of one of the motor/generators designed in Part I, the results of a system simulation which includes the exciter, prime mover, and converter are presented. The frequency content of the machine currents is determined during various converter operating conditions and used to evaluate the assumptions of Part I. The interaction of system components is examined and problem areas are identified.

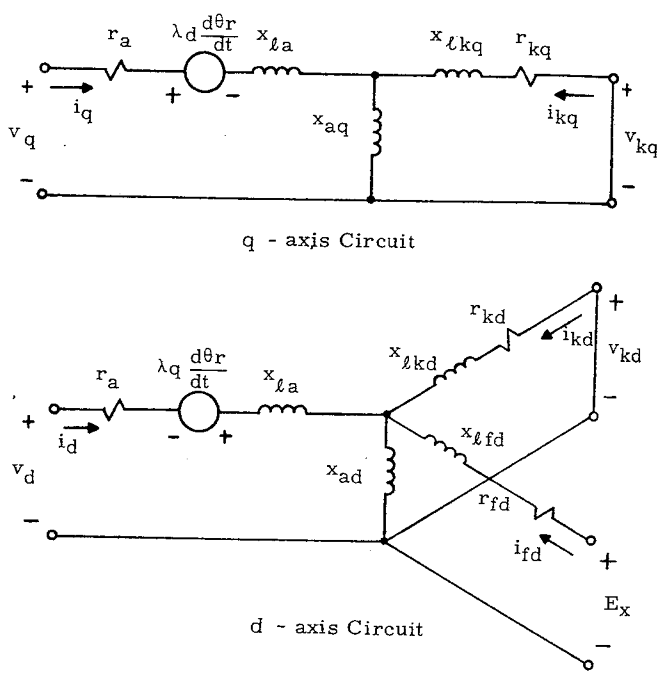

Fig. 1. d-q Equivalent circuits for a synchronous machine.

INTRODUCTION

In a companion paper [1], machine designs were presented that encompassed the spectrum of motor/generator ratings encountered in pumped hydro installations. Furthermore, it was pointed out that many of the mechanical and hydraulic problems that characterize hydro power can be successfully attacked by operating the plant on an adjustable speed basis. In this paper, the plant consisting of the motor/generator, prime mover, and converter link are simulated in detail. The simulated machine currents are analyzed in order to evaluate the assumptions used in the design of the machine. The interaction of the system components is investigated through the simulation of load fluctuation on the plant. This paper presents important characteristics of adjustable speed operation of pumped hydro plants and provides the impetus for further work on a novel operating scheme that results in increased system efficiency and reliability, and a means of optimal plant operation.

System Study

Many of the potential system problems which will arise from variable speed operation of a hydroelectric station can only be identified when considering the station as a system. In an effort to pinpoint these problems, a detailed simulation study was conducted on a hybrid computer. The system simulated consists of a hydraulic turbine with associated speed governor, a synchronous machine with associated voltage regulator, two 6-pulse converter units, each with a converter step-up transformer and a common intergroup reactor. In particular, the converter equipment was simulated in detail in order to determine the validity of the preliminary conclusions regarding commutating reactance, power factor, and harmonic heating.

The equivalent circuit used to model the synchronous machine is shown in Fig. 1. The machine was simulated in d-q components using Park's Equations. The machine parameters shown in Fig. 1 correspond to the 200,000 hp machine of Base Case 1 in Reference [1]. This machine was selected for the simulation study because it falls in the widely used medium size range for such equipment. Although not explicitly shown in Fig. 1, a modification of the d-axis circuit was included to incorporate magnetic saturation.

A block diagram representation of the excitation system is shown in Fig. 2. The system configuration corresponds to IEEE Type 1S modified for use in variable frequency application [2]. Note the addition of the limiter and multiplier to the converted excitation system. The multiplier automatically provides a constant volts/Hz command signal as speed changes. The limiter serves to prevent the command signal from exceeding its rated value above 60 Hz. It is important to mention that the multiplier introduces speed feedback coupling which changes the dynamic stability of the system. Values corresponding to the block diagram elements are contained in Table I. The power source for excitation system is assumed to be a 6-pulse bridge rectifier arrangement, commonly used for hydro applications [3]. It is assumed that excitation power is drawn from an isolated fixed voltage, and a fixed 60-Hz bus.

The prime mover system model was supplied by the Bureau of Reclamation. A block diagram of this model is shown in Fig. 3 [4,5]. The values of the time constants, droop, inertia, and water time constant are shown in Table I. These parameters correspond to 60-Hz operation. Although approximate, it was decided to use this linear representation of the water column and associated control over the full range of variable frequency operation. With the exception of the watering time constant T_w, all parameters were held fixed throughout this study.

The equivalent circuit and parameters of the transformer and intergroup reactor are also summarized in Table I. Following conventional design practices, the mutual reactance of one-half the intergroup reactor was

F 80 252-7 A paper recommended and approved by the IEEE Power Generation Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Winter Meeting, New York, NY, February 3-8, 1980. Manuscript submitted September 6, 1979; made available for printing November 8, 1979.

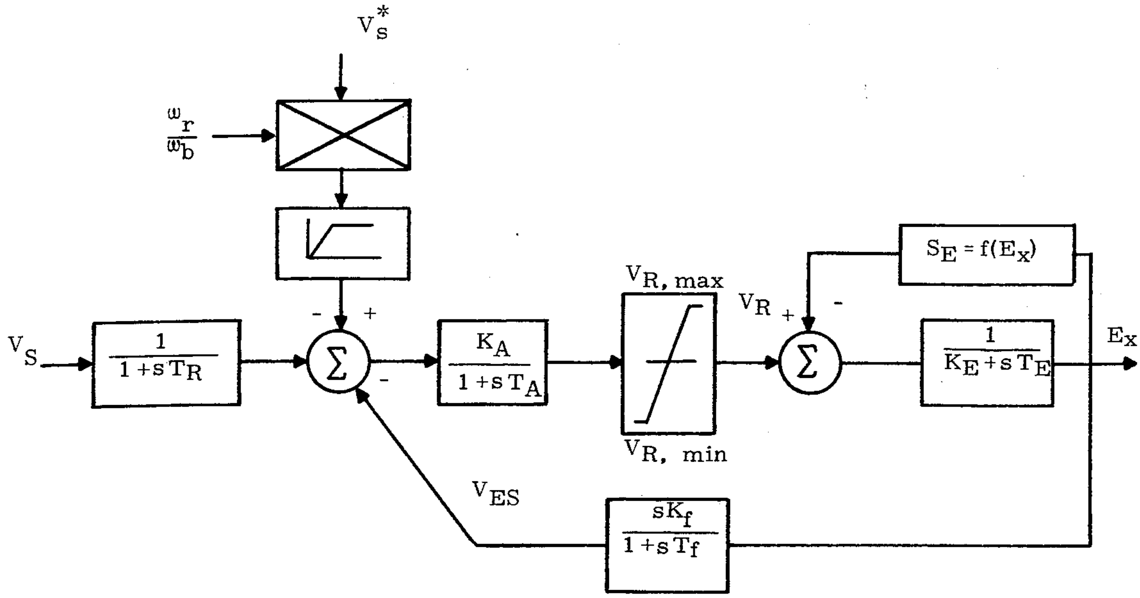

Fig. 2. IEEE Type 1 excitation system model.

TABLE I

System Parameters

Parameters for: Excitation System	Turbine and Governor	Per Unit Transformer and Intergroup Reactor Parameters: Transformers (Transformer Base)	Reactor (Machine Base)
KA = 90.8	δ = 0.05 s	$r_1 = r_2$ = .01	r_1 = 0.01
T_R = 0.0 s	T_1 = 8.0 s	$x_{\ell 1} = x_{\ell 2}$ = 0.125	x_ℓ = 0.05
T_A = 0.110 s	T_2 = 1.2 s	x_m = 2.5	x_m = 0.25
K_F = 0.0286	T_3 = 120.0 s		
S_E = 0.0	T_4 = 0.3 s		
T_F = 1.0 s	T_W = 4.25 at rated head and 100% gate		
K_E = 1.0			
$V_{Rmax.}$ = 3.85 p.u.	H = 3.6210		
$V_{Rmin.}$ = 3.26 p.u.			

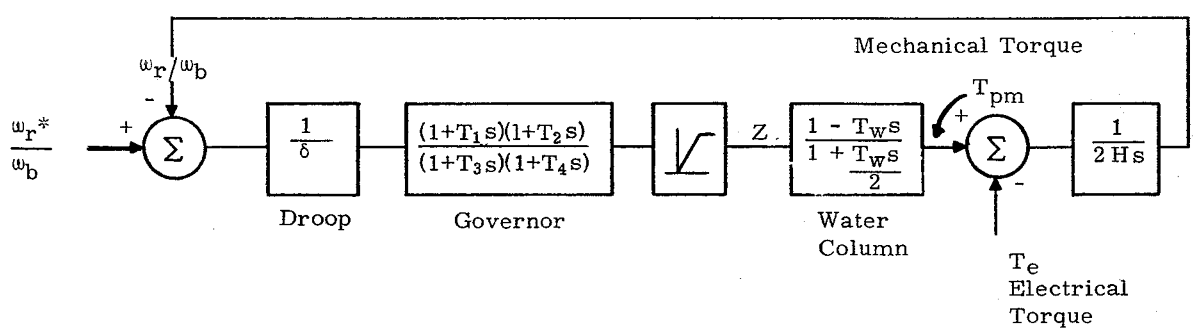

Fig. 3. Prime mover equipment circuit (generator operation).

selected to be equal to the machine subtransient reactance (0.25 per unit). Since the mutual reactances of the transformers are large their effect has been neglected to the simulation ($x_m \rightarrow \infty$).

Fig. 4 shows computer traces of the system using the system parameters summarized in Table II in Reference [1] and Table I. The operating point corresponds to rated power at rated speed, i.e., $P_e = T_e = 0.88$ and $f_e = 60$ Hz. The converter delay angle is set at 0^o so that the bridge is fully conducting (no delay). This condition corresponds to the point of maximum power factor for a given dc link current. In this computer run, the power source was assumed to be an ideal zero impedance infinite bus. The harmonic spectrum of the

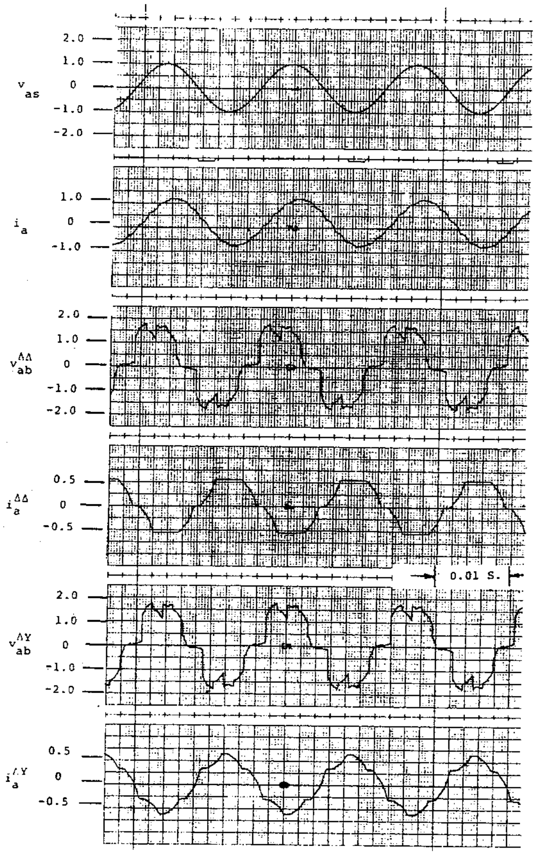

Fig. 4. System operation with a zero impedance voltage source, $\alpha = 0$, $T_e = 0.88$, $f_e = 60$ Hz.

infinite bus current together with displacement factor, distortion factor, and power factor was computed by real time sampling of the analog computer variables, then using Fast Fourier Transform analysis on the sampled points. The calculated results are tabulated in Table II. Note that the power factor is computed as 0.926. This value corresponds to a commutating reactance $x_k = 0.148$ on the power base of one converter (or one transformer) or 0.256 when expressed on the power base of the machine. This result checks well with a predicted value of 0.15 obtained by adding the transformer and intergroup reactor leakage on the transformer power base.

In Fig. 5 the infinite bus source has been replaced by the actual 200,000 hp synchronous machine of Base Case 1. Note the similarity in the waveforms. In Table III the harmonic spectrum and power factor of the machine current is again plotted. It can be noted that the harmonic spectrum is essentially the same as before. In particular, the power factor is again 0.924 for the same operating condition. This result is a clear indication that the machine reactances have negligible effect on commutating reactance when connected in the dual 6-pulse arrangement shown in Fig. 1 in Reference [1]. This conclusion is not predicted by conventional theory and suggests an avenue for further work.

In most cases a delay angle of approximately 8^o is introduced in each converter in order to provide a margin of voltage regulation. Fig. 6 shows system operation at the same point as before ($T_e = 0.88$, $f_e = 60$ Hz), when the delay angle $\alpha = 9^o$. Neglecting the machine substransient reactance, the power factor can be calculated from Eq. 10 of Reference [1] as

$$\cos u = \frac{1}{2}\left[(0.94 + 0.88)\right] = 0.91$$

TABLE II

Computer Analysis of Infinite Bus Current i_a Corresponding to Fig. 4

Fourier Results			
Harmonic	Magnitude	Phase	Percent
1	0.9536	-21.9862	100.0
2	0.0058	-0.3956	0.61
3	0.0078	-31.7893	0.82
4	0.0025	-8.5722	0.26
5	0.0021	54.4819	0.22
6	0.0034	-6.0003	0.35
7	0.0036	-30.0917	0.38
8	0.0034	-12.1413	0.36
9	0.0050	1.8991	0.53
10	0.0047	-5.4868	0.49
11	0.0260	155.4410	2.72
12	0.0023	28.6602	0.24
13	0.0213	-72.6694	2.24
RMS	Displ. F.	Distor. F.	Power F.
0.6749	0.9273	0.9992	0.9265

Number of Points = 417

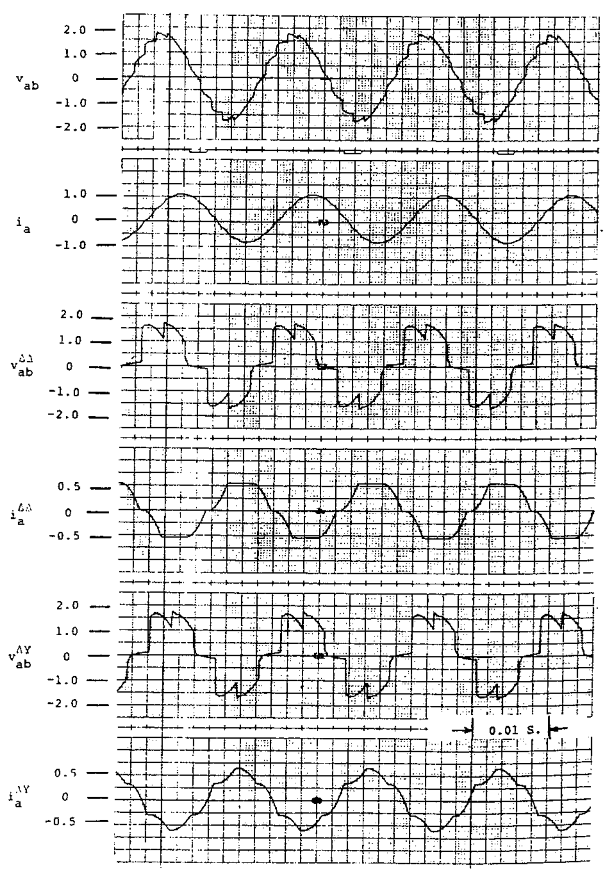

Fig. 5. System operation with synchronous machine as source, $\alpha = 0$, $T_e = 0.88$, $f_e = 60$ Hz.

Analysis of the current waveshape (Table IV) yields the same result, again suggesting that the machine reactances play a minor role in commutation for this configuration.

Because a power factor of 0.91 can now be practically achieved, the base case machines are capable of generating higher power output than the design value of 0.85 per unit. Alternatively, it would be desirable to

TABLE III

Computer Analysis of Machine Current i_a Corresponding to Fig. 5

Fourier Results			
Harmonic	Magnitude	Phase	Percent
1	0.9529	-22.4678	100.00
2	0.0021	-5.0554	0.22
3	0.0037	-10.9924	0.39
4	0.0011	44.8949	0.11
5	0.0017	33.6964	0.17
6	0.0005	22.0524	0.06
7	0.0008	62.5928	0.09
8	0.0007	46.0346	0.07
9	0.0016	74.3772	0.16
10	0.0005	63.5849	0.06
11	0.0187	273.5320	1.96
12	0.0004	-0.6785	0.04
13	0.0138	-26.5238	1.45
RMS	Displ. F.	Distor. F.	Power F.
0.6740	0.9241	0.9997	0.9238
Number of Points = 425			

TABLE IV

Computer Analysis of Machine Current i_a Corresponding to Fig. 6

Fourier Results			
Harmonic	Magnitude	Phase	Percent
1	0.9400	-24.5613	100.00
2	0.0060	-25.6214	0.64
3	0.0004	-4.4972	0.89
4	0.0032	3.3034	0.34
5	0.0040	8.2942	0.42
6	0.0027	7.7327	0.29
7	0.0027	21.6704	0.29
8	0.0026	16.1310	0.28
9	0.0035	33.1036	0.37
10	0.0029	31.6039	0.31
11	0.0158	256.6404	1.68
12	0.0012	17.5110	0.13
13	0.0177	-42.1221	1.88
RMS	Displ. F.	Distor. F.	Power F.
0.6650	0.9095	0.9995	0.9091
Number of Points = 423			

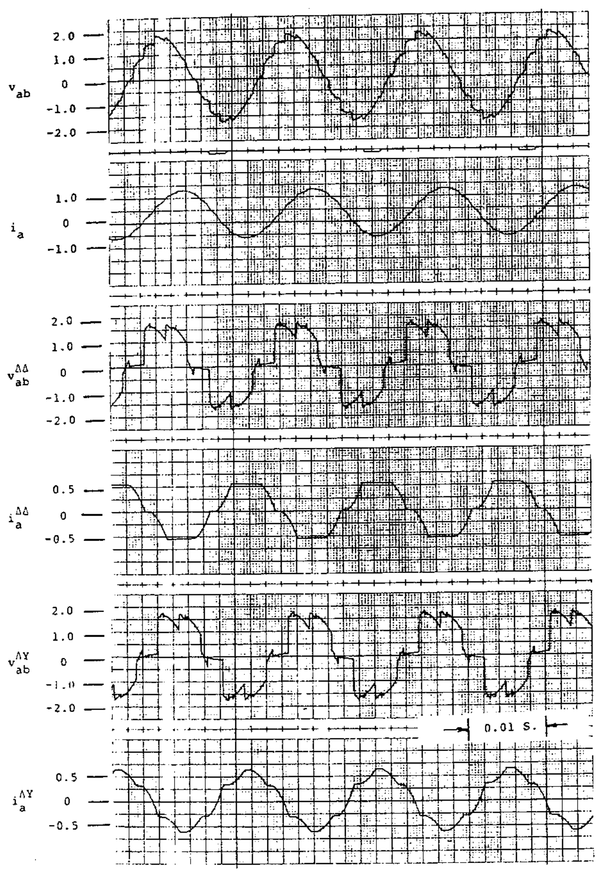

Fig. 6. System operation at nominal operating point with p.f. = 0.91, $\alpha = 9^o$, $T_e = 0.88$, f_e = 60 Hz.

redesign the machines for 0.91 power factor operation. This should be considered as the basis for the machine design for any future design studies. As a compromise for this study, the bridge delay angle was increased beyond the usual set point of 9^o to force the machine to operate at its rated power output with 0.85 power factor. Fig. 7 shows a computer trace for this operating condition. Again, $T_e = 0.88$, f_e = 60 Hz; however, in this case $\alpha = 28^o$ and the power factor is 0.85. This result is verified by the computer analysis of the current waveform, Table V.

During normal operation of the system, the synchronous machine may be generating (or motoring) at any stator line frequency between 30 and 81 Hz. As a result, pulsating torques of 12 times this frequency are impressed on the shaft of the machine (360-972 Hz). As a rule, these frequencies are too high to be of much concern. Conventional rectifier exciters are designed to operate from a fixed voltage bus. This bus often corresponds to the terminals of the machine itself. In this application, however, the terminal voltage is adjusted to maintain constant volts/Hz (not constant voltage) below 60 Hz. A conventional bridge rectifier excitation system cannot be used without modification of the rectifier firing circuits. In order to use conventional equipment and avoid these difficulties, it was assumed that an auxiliary 60-Hz bus will be available for excitation power. In this case ripple currents which flow in the field circuit have a frequency 6 times 60 or 360 Hz. These currents produce a corresponding 360-Hz ripple in the electromagnetic torque. Again, frequencies of this order are not of much concern.

One problem, however, which can arise that does not normally exist is beating effects between the variable frequency pulsating torques produced by the stator MMF harmonics and the fixed 360-Hz ripple produced by the field. This effect is suggested from the identity:

$$\sin A + \sin B = 2 \sin \frac{1}{2}(A+B) \sin \frac{1}{2}(A-B)$$

In particular, when the machine is running at 30 Hz:

$$\frac{1}{2}(A-B) = \frac{1}{2}(12x30 - 6x60) = 0$$

Hence, it is apparent that over the stator frequency range of 30-81 Hz, a mechanical frequency range is scanned from 0-1332 Hz. Any mechanical resonance which occurs over this wide range could be excited. These

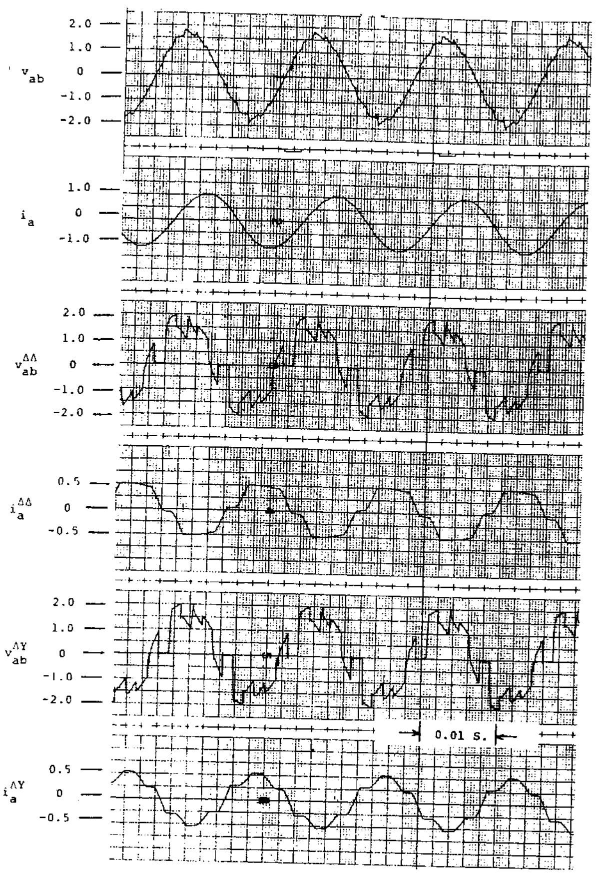

Fig. 7. System operation at nominal operating point with p.f. = .85, $\alpha = 28^0$, $T_e = 0.88$, $f_e = 60$ Hz.

TABLE V

Computer Analysis of Machine Current i_a Corresponding to Fig. 7

Fourier Results			
Harmonic	Magnitude	Phase	Percent
1	1.0601	-30.5599	100.00
2	0.0093	-44.1540	0.88
3	0.0026	15.9597	0.25
4	0.0063	30.4099	0.60
5	0.0013	47.1729	0.13
6	0.0023	18.3552	0.22
7	0.0010	40.9570	0.09
8	0.0038	5.0654	0.36
9	0.0020	9.9621	0.19
10	0.0034	43.4950	0.32
11	0.0070	227.7101	0.66
12	0.0023	14.1914	0.21
13	0.0077	186.6549	0.73
RMS	Displ. F.	Distor. F	Power F.
0.7497	0.8611	0.9998	0.8610
Number of Points = 417			

resonances could conceivably produce fatigue or even failure of the shaft and turbine assembly.

In order to investigate the severity of this problem, the excitation system was modeled in detail to include the effect of the 6-pulse bridge rectifier. Fig. 8 is a computer trace of system operation when generating a nominal turbine power for 31 Hz. At this point a harmonic torque with frequency

$$\frac{1}{2}\,(12.31 - 6.60) = 6 \text{ Hz}$$

is impressed on the shaft. Careful examination of the computer traces verify that these harmonics are extremely small because of the filtering action of the field inductance used in conventional hydro machines. It appears that the 360-Hz ripple currents resulting from the bridge rectifier will be negligible. As a result of this investigation, it was decided to reduce the complexity of the exciter representation. In all subsequent computer runs only the average value of the exciter output is considered. The 360-Hz ripple component has been neglected.

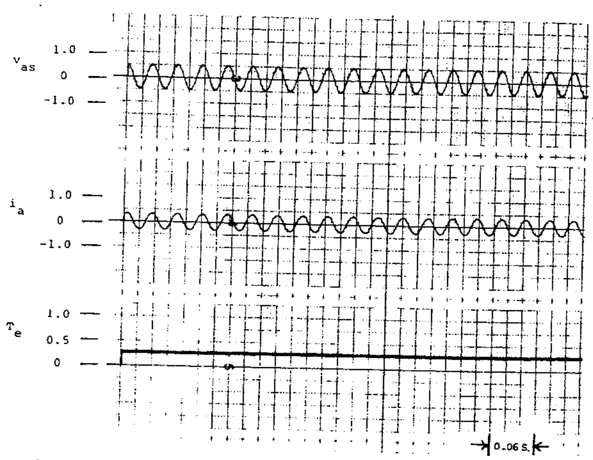

Fig. 8. Machine behavior with actual bridge rectifier field excitation. Operation at $f_e = 31$ Hz, $T_e = 0.27$ p.f. = 0.85.

Since conventional exciters are intended to operate only at one frequency, its behavior under variable speeds needs to be determined. In order to evaluate the dynamic and transient stability of the overall electrical system and answer this question, a detached study was performed on the hybrid computer. Operating points investigated include motoring and generating over the entire frequency range from 30-80 Hz. The delay angle of the bridge was adjusted to produce 0.85 power factor at the machine terminals. The governor was set up to produce a power-speed profile corresponding to Fig. 6. In each case a transient was initiated by introducing a 10% change in the link current. It is assumed that the converter control system is much faster than the exciter so that a step change in current essentially occurs. Because torque is proportional to armature current (assuming a fixed torque angle) the torque essentially drops 10% at the same instant. The results indicate that the system will be stable over the entire torque-speed profile for both motor and generator operation. It was observed that the stability deteriorated slightly as frequency increased. The speed feedback into the terminal voltage command signal appeared to have a slight beneficial effect on the stability of the electrical system when in service below 60 Hz. Stability for motor or generator operations at the same load and frequency was essentially identical.

The mechanical system incorporates the hydraulic turbine, speed governor, and synchronous machine torque versus speed characteristic. A series of computer runs were carried out to evaluate the behavior of the speed governor system under variable speed operation. In this study, the damping provided by the machine was assumed zero so that the machine equivalent circuit was considered as simply a torque "load" in series with a pure inertia. Fig. 3 shows the linearized model that was simulated. Since more accurate models were lacking, the time constants T_1 . . T_4 were held constant throughout the study. However, to be as realistic as possible the watering time constant was adjusted to account for changes in head as defined along the optimum head versus optimum torque characteristic.

In essence the torque input T_e was considered as the disturbance. The dc link current (and, therefore, torque T_e) was suddenly decreased by 5% and the prime mover allowed to establish a new operating condition. Figs. 9-14 summarize the results of this computer study. These figures show transient conditions for generation over the full range of frequencies. Corresponding traces for motor action were not included since they essentially upheld the same result.

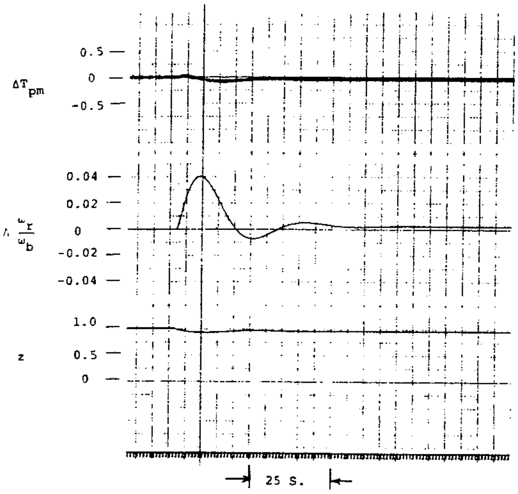

Fig. 9. Transient behavior of speed governor for 5% step decrease in generator load at 60 Hz. Initial operating point $T_{pm} = P_{pm} = 0.88$, pf = 0.85.

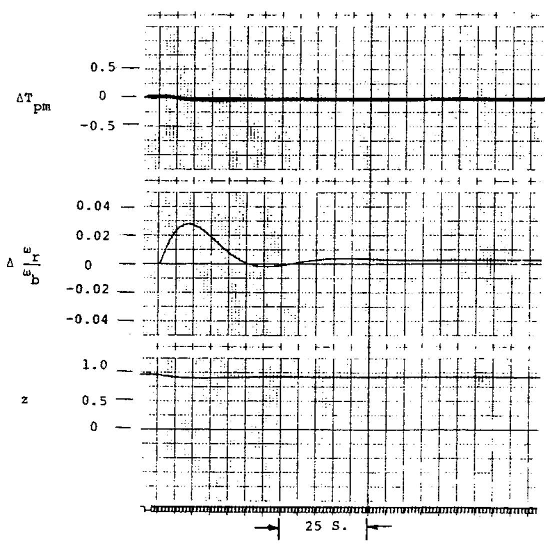

Fig. 10. Transient behavior of speed governor for 5% step decrease in generator load at 70 Hz. Initial operating point: T_{pm} = 0.754, P_{pm} 0.88, pf = 0.85.

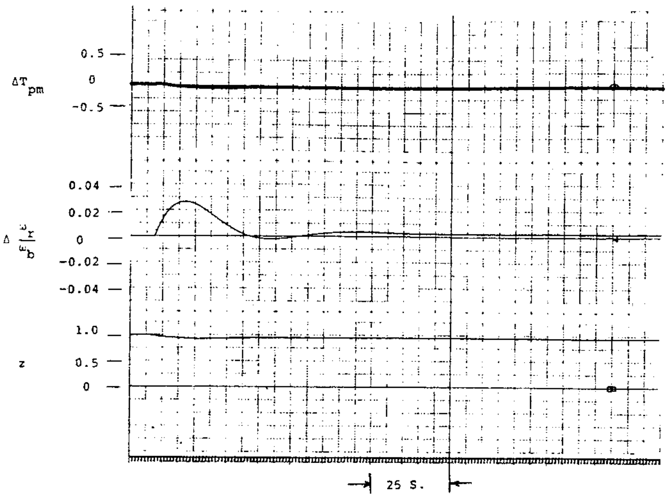

Fig. 11. Transient behavior of speed governor for 5% step decrease in generator load at 80 Hz. Initial operating point: T_{pm} = 0.66, P_{pm} = 0.88, pf = 0.85.

Fig. 9 shows the result for rated frequency of 60 Hz. The change in prime mover torque, change in per unit speed, and gate position are shown. Initially $\Delta T_{pm} = \Delta(\omega_r/\omega_b) = 0$ and z = 1 indicating best efficiency head with full gate position. When the machine torque T_e is suddenly decreased, ΔT_{pm} goes slightly positive and then ultimately becomes negative as is consistent with a nonminimum phase transfer function. It is important to note that the speed change does not become zero after the transient but takes on a slightly positive value. The speed error is not zeroed and, in essence, the machine operates after the change at a frequency slightly higher than 60 Hz. This result indicates that the changes in prime mover torque will not be proportional to the speed reference signal as is usually the case when a machine is tied synchronously to a system. Speed will ultimately assume a value which merely satisfies a new energy balance between prime mover and synchronous machine. Hence, difficulties will be encountered when attempting to drive the machine to specific torque-speed operation points.

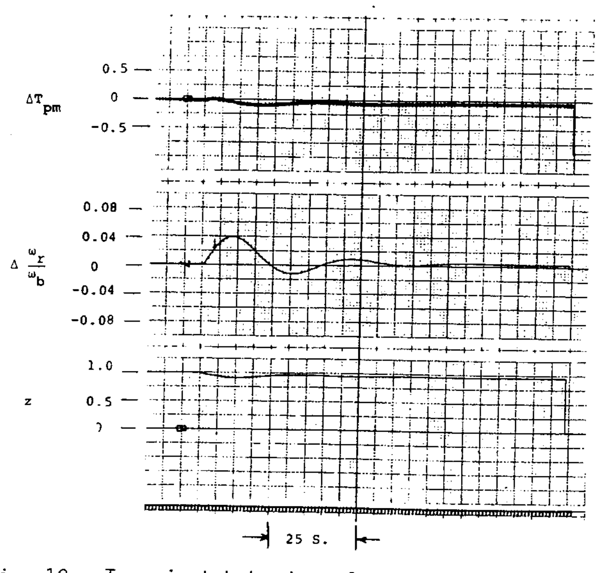

Fig. 12. Transient behavior of speed governor for 5% step decrease in generator load at 52 Hz. T_{pm} = 0.78, P_{pm} = 0.68, pf = 0.85.

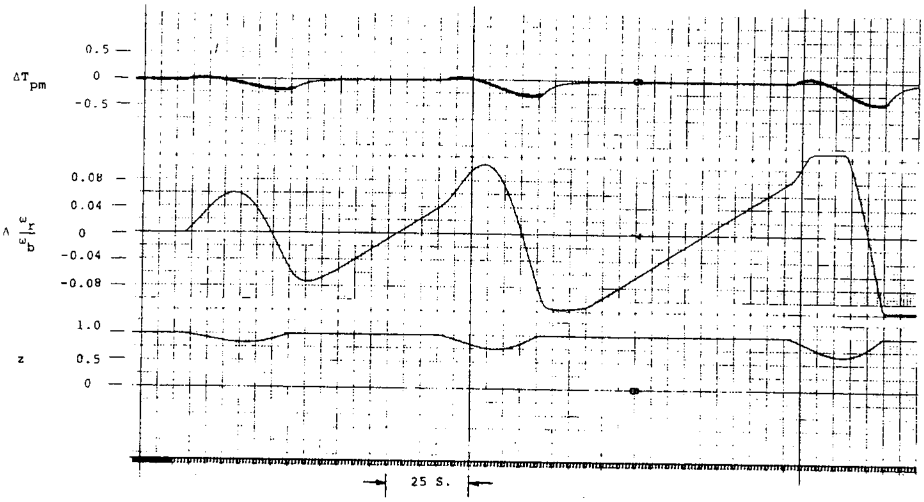

Fig. 13. Transient behavior of speed governor for 5% step decrease in generator load at 40 Hz. $T_{pm} = 0.46$, $P_{pm} = 0.31$, pf = 0.85.

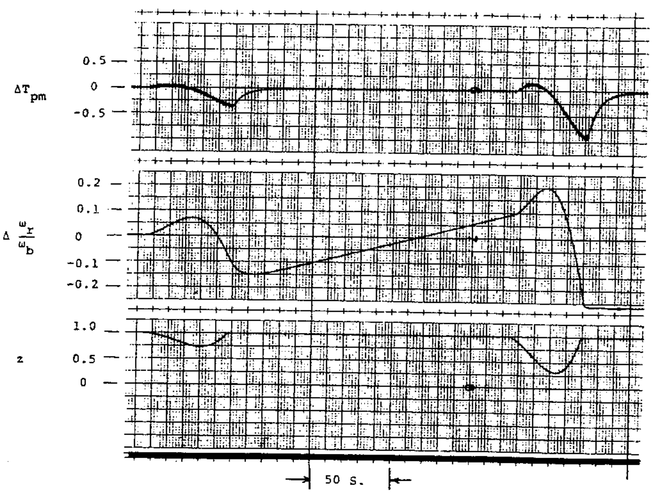

Fig. 14. Transient behavior of speed governor for 5% step decrease in generator load at 30 Hz. $T_{pm} = 0.26$, $P_{pm} = 0.13$, pf = 0.85.

When comparing the 6 traces corresponding to the 6 operating frequencies, it is immediately apparent that the changes in the watering time constant T_W introduce important changes in transient behavior. Damping becomes poorer as frequency is decreased and the computer results indicate that limit cycle operation can even occur over the 30-40 Hz range. Of course, these results should be treated with caution since the turbine model is approximate and the gate limit was assumed to be equal to optimum.

CONCLUSION

In this and a companion paper [1], the prospect of adjustable speed operation of a hydro power station has been investigated. Special consideration has been given to identifying problems associated with applying standard machine designs to variable speed operation. Specifically, problems which must be overcome involve the following:

- Improved insulation systems to extend the high-speed range of operation
- Improving ventilating systems to increase thermal capacity of the generator
- Redesigning of conventional speed governor systems to improve damping at low head (low speed).

Other problems which were investigated but were found to respond more satisfactorily to variable speed operation include fan losses, bearing losses, excitation system response, and torque pulsations.

At present, the operation of a hydraulic turbine over a variable speed may seem a remote possibility. However, the added benefits of dc transmission could make this alternative attractive in remote isolated locations. Since each point of improved efficiency can be related to tons of extra fossil fuel needed to supplement the hydro, such a system should be given serious consideration in future site development.

ACKNOWLEDGMENTS

This work was completed under U.S. Bureau of Reclamation Contract No. 6-07-DR-50090. The support and counsel of R.J. Pohl in the area of HVDC converter technology, and of V. Aare in hydro generator design is gratefully acknowledged.

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