IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 5 Sept/Oct 1980

AN INQUIRY INTO ADJUSTABLE SPEED OPERATION OF A PUMPED HYDRO PLANT
PART 1 - MACHINE DESIGN AND PERFORMANCE

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Abstract - The possibility of variable speed operation of a pumped hydro plant is proposed by providing an asynchronous tie between the hydro site and main ac grid. Variable speed operation results in a substantial improvement in system efficiency and improved system performance, as well as new flexibility in hydro plant siting and machine design. The problems associated with applying conventional synchronous generator technology to adjustable speed are evaluated and problem areas are identified.

INTRODUCTION

The increasing concern over the world's energy supply has necessitated a rethinking of many long-sacred tenets in the field of power generation. In particular, hydro-electric power generation with its inexpensive power source has not changed substantially in more than 100 years. Because the power source of a hydro power station is not subject to inflationary pressures, little attention has been paid to more efficient means of operating hydro equipment. Nevertheless, the remote location of such plants, coupled with the high cost of transmitting the generated power to population centers, provides unique opportunities only recently made possible by HVDC technology [1].

Today's hydroelectric and pumped storage installations necessarily operate at a constant speed mandated by the synchronous speed of the generator. This speed is selected on the basis of the hydrology of the site, attainable efficiency, system requirements, and cost. The turbine is designed to run at the specified speed under rated head and wicket gate opening; the hydraulic efficiency is then maximized under the constraints of the station and power grid [2-6]. Hydro installations are often used for base loading and/or peak loading. A high hydraulic efficiency over the anticipated changes in load and head is very desirable. If the site is a pumped storage plant, its primary purpose may be in meeting peak demand. In this case the pump turbine is designed on the basis of the anticipated duty cycle. Hydraulic efficiency is reduced because the turbine and pumping modes are not similar. In either application, efficient operation of hydro units inevitably suffers because the generator and, hence, the hydraulic turbine must be tied synchronously to the ac network [2,7-10].

It is useful to consider, however, the benefits that might result if the hydro power is transmitted by means of a dc rather than an ac link. It is evident that it would be no longer necessary to tie the generator synchronously to the ac 60-Hz grid. The speed of the hydraulic turbine could be adjusted freely to satisfy the load demand at the maximum possible hydraulic efficiency. This improvement in efficiency will be demonstrated to be 3-10% over conventional operating modes. These savings can be directly related to the cost of more precious fuels necessary to supplement the hydro plant. The use of an HVDC link results in additional savings since transmission line costs can be reduced by dc rather than ac power transmission. The combined savings could well justify the installation of such a scheme in remote, isolated hydro plants.

The benefits of variable speed operation is illustrated in Fig. 1 which shows the performance characteristic curves of a typical Francis turbine having 24 stationary gates and 18 rotating vanes. The abscissa and ordinate of this curve are ϕ_1 and HP_1, respectively, where in general

$$\phi_h = nD/1840h^{1/2} \tag{1}$$

$$HP_h = Pu\ D^2 h^{3/2} \tag{2}$$

and where h, the head, is equal to 1 ft and D, the diameter of the turbine vanes, is equal to 12 in. Pu is the unit power parameter which is constant for similar turbines. The closed solid lines denote points of constant efficiency while the dashed lines represent the locus for a fixed gate opening. The parameter σ_c is the cavitation susceptibility or "critical sigma" and N_s the specific speed. The point of maximum efficiency can readily be located in the curve as 91% at a gate opening of 67%. Note that both ϕ_1 and HP_1 are functions of head so that the optimum efficiency point at a particular head can only be reached at one value of head and power output (rated speed and rated power). Other values of output power at rated head can only be achieved by changes in gate opening which follows the heavy vertical line A in Fig. 1. This line is constructed for an assumed ±10% variation in power level. As the reservoir is drawn down, it can be noted from Eq. 1 that the vertical line of operating conditions moves to the right (line B) resulting in reduced efficiency at all power levels. Line B shows such a condition corresponding to a 25% decrease in head. Conversely, during the spring runoff, head levels can exceed the rated value but again the operating efficiency is decreased. A heavy line C is drawn for a 10% increase in head with the same ±10% power variation.

It is apparent that operation at constant speed constrains operation along a vertical line which is, regrettably, nearly along the direction for a maximum (rather than minimum) change in efficiency. In contrast, the possibility of adjustable speed would permit operation to be maximized so that operation is along the "ridge" of the efficiency loci resulting in a minimum reduction in efficiency for a given power demand as shown by curve D. Indeed, if the turbine is in a base loaded plant and the power output of the plant is adjusted to meet the demands of the available head, the

F 80 251-9 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 December 10, 1979.

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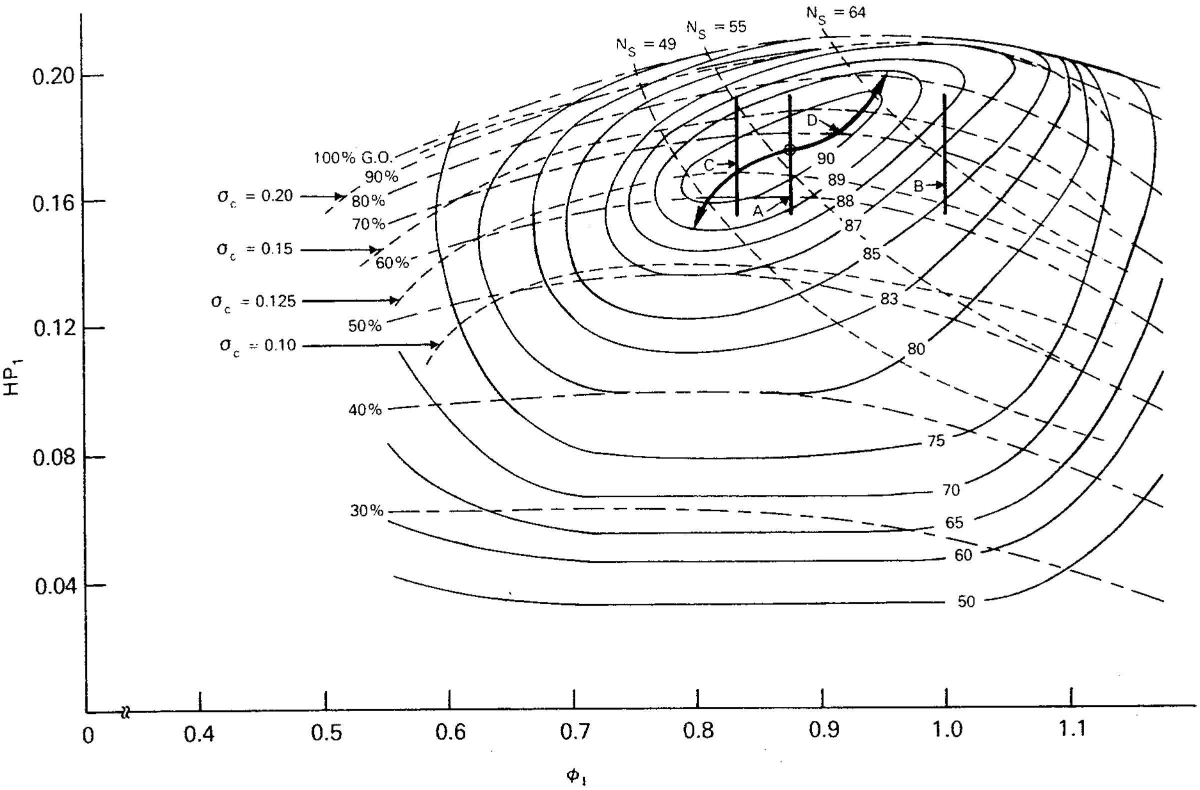

Fig. 1. Performance characteristics for hydraulic turbine model - 1 ft head.

plant would be able to operate year-round at a constant efficiency of 91%.

Pumped storage plants would realize an additional payoff in efficiency if variable speed operation were adopted. Because the reversible Francis pump turbine uses one runner for both types of operation, it is difficult to change the turbine and pump characteristics independent of each other. As a result the optimum speed for pumping is in the range of 1.1-1.2 that of turbining [7,11]. It is evident that constant speed operation at maximum efficiency cannot be achieved at any time for both modes with a single generator/motor. This problem would be overcome with variable speed operation since the optimum speed-horsepower profile for pumping and generating could be set independently.

In addition to the promise of significant energy savings, a number of other important benefits will be realized if the speed of the turbine can be adjusted. These are as follows:

(1) Reduced Noise, Vibration, and Cavitation Problems. Vibration and noise are unavoidable with present designs under constant speed operation. One such manifestation of this problem is turbine surging during overload which occurs when guide vane openings exceed the design point. Certain vane openings result in an unacceptable relationship between flow angle and runner vane entrance angle. Excessive vane openings can also result in severe cavitation problems. Another area of concern is turbine surging during partial load. At loads of 40-60% of rated, pressure surges are generated which often yield noise and vibration problems. Although these fluctuations can be reduced by providing compressed air, surging generally limits the range of automatic frequency control and partial load operation. Another undesirable characteristic occurs at low head during turbining. In this case the characteristic is a hysteresis phenomenon which tends to limit the operating head variation [7,12]. These difficulties can be avoided to a large extent if speed is allowed to fluctuate as demanded by the electrical load.

In the pumping mode two phenomena limit the range of operation. One is reverse flow at high head which causes cavitation growth, a decrease in efficiency, and an increase in both vibration and noise. The other results from operating at low head requiring increased discharge. Such operation again leads to lower efficiency and cavitation problems [7,11]. These problems can also be minimized if the power output is adjusted with an increase in speed rather than increased flow.

(2) New Flexibility in Site Selection and Sizing of Hydro Units. If the speed of the synchronous generator can be adjusted to accommodate the limitations of the hydraulic turbine, efficient operation will be possible over a much larger head variation than previously possible. This feature will in turn permit sizing of reservoirs and dams on a different basis since a wide range of operating head allows more flexibility in the design of the upper and lower pools for pump storage. A wider variation in head would allow use of deeper ponds with less surface area, opening up sites previously considered either marginal or requiring two distinct speeds [13-16]. In addition, variable speed operation would provide greater flexibility in the selection of the number and size of units to be installed in a station since each individual unit is capable of operation over a wide rather than narrow power range. These advantages translate into inherent cost savings in the overall hydro station design.

(3) Improved Implementation of Load Changes. In order to accommodate load changes which occur within the power system and to maintain constant speed, hydraulic and pumped storage plants rely on an assortment of devices. These control elements include movable gates and runners as well as a speed governor system which acts

to regulate the flow, power output, and speed to match the system demand. Such devices are cumbersome, difficult to maintain, and respond very sluggishly to the dispatcher's commands. These problems are compounded in pumped storage plants. An important characteristic of the single stage reversible Francis turbine is that they are not generally even capable of making load changes by means of wicket gate movement during pumping [17]. In addition, where reversible turbines are used under high head situations the pump turbine faces serious stress and vibration problems associated with the wicket gate operating assembly so that wicket gates are only infrequently adjusted [9,11]. These restrictions can be entirely removed if the turbining or pumping rate is adjusted by changing speed. Since synchronous motor torque can be developed at all rotor speeds, load changes can be made within a fraction of a cycle by simply changing the converter firing angle. The energy required to supply the momentary change in system load is taken out of the machine and turbine inertia as the machine and turbine rapidly slow down or speed up to satisfy the new load demand. Similar advantages could be gained during emergency braking of the unit since excess energy could be supplied to the electrical grid to brake the unit even if the wicket gates remain open.

(4) Relaxation of Parameter Requirements. By decoupling the synchronous tie through the use of a HVDC link, many restrictions on machine design imposed by system stability requirements may be relaxed. For example, minimum inertia requirements based on allowable frequency excursions may be eliminated [9.18]. This will allow the station units to be designed on the basis of the site's hydrology, cost, and best obtainable efficiency over head and load fluctuations. In addition, the need for bounds on machine parameters, such as the short circuit current capability, transient time constants, and damping, are now dependent only on the requirements of the site and not the electrical system.

(5) Inherent Starting Capability in the Pumping Mode. One characteristic of pumped storage plants is the need to stop and reverse rotation in order to commence pumping. To date, when transitioning from the turbining to the pumping mode, auxiliary pump motor starting or induction starting of the main synchronous machine is used to bring the system up to speed. Induction starting has been less often used because of the requirement of massive bars in the amortisseur windings and increased cost. In addition, this form of starting is often restricted by power system stability requirements [14,19,20]. Because of cost and size considerations pump motors must start the turbine in a dewatered state even though this is not necessarily desirable since much time is wasted bringing the unloaded machine up to speed [14,19,21]. Synchronous starting methods require the dedicated use of at least one unit in the generating mode per site. This reduces the number of reversible pump turbines by one and adds to the cost of the pumping mode by prolonging the pumping time [11,14,22]. If the synchronous machine is connected asynchronously to the ac grid by means of a dc link, the starting could be accomplished automatically without extra pump motors by proper control of the ac/dc converter station. Since the converter is rated at full power, adjustable speed operation would allow pumping to commence nearly upon starting with minimum loss of operating revenue.

The numerous benefits derived from variable speed operation justify a renewed look at pumped hydro station operation from the point of view of adjustable speed. The needed technology for such an application is only now emerging and much research is needed to approach an optimum design. However, the most important immediate concern is how conventional power station equipment will function under such operation. This paper reports the results of such a study aimed at evaluating how conventional station equipment will perform under variable speed conditions. Particular attention is paid to the design of the turbine generator, its excitation, and speed governor system. Three machine designs are considered, differing widely in rated speed and horsepower rating. Practical application considerations such as stator and rotor thermal limits, bearing losses, and excitation power requirements are evaluated. The results of a complete system stability are reported and a detailed representation of the entire turbine-generator-converter system is given. Probable difficulties are identified and suggestions are made for refinements in future system design.

ASSUMPTIONS AND CONSTRAINTS FOR BASE CASE MACHINE DESIGNS

Fig. 2 shows a schematic of the 12-pulse HVDC converter station which has been selected for this study. This system consists of two 6-pulse bridges connected in

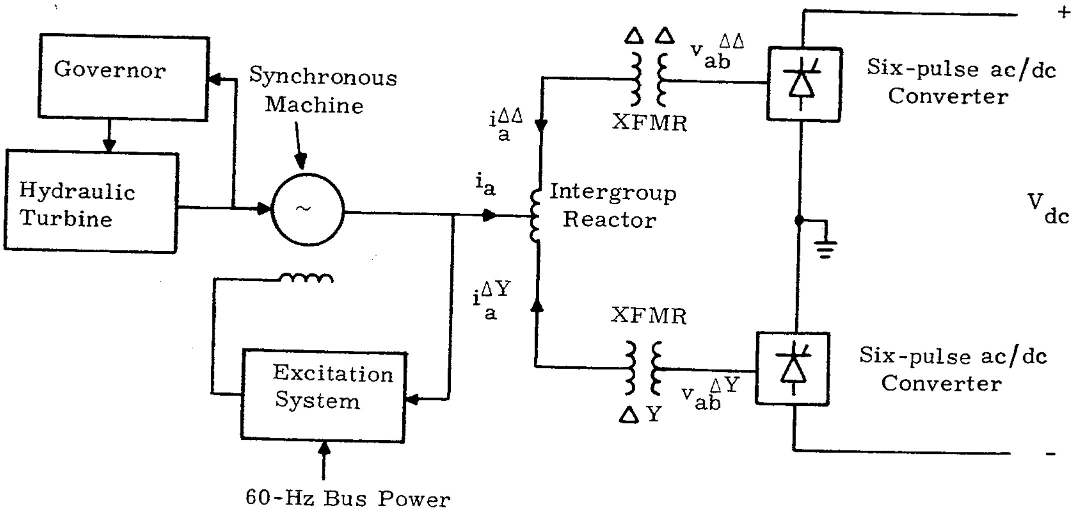

Fig. 2. One-line diagram of system studied.

series. The stepup transformers are ΔΔ and ΔY units in order to shift the currents 30° between converters and, thereby, reduce harmonic currents in the machine windings. The converters are interconnected by an intergroup reactor which serves to aid commutation and reduces cross talk between converters. Worthy of note is the absence of tuned ac line harmonic filters which are not included due to variable frequency operation of the bridge. Also, power factor correcting capacitors have been omitted in favor of a larger machine design.

In order to develop the base case machine design and proceed with the system study, a number of assumptions were required concerning: (1) heating due to converter harmonics; (2) machine nameplate power factor; and (3) operating power versus speed characteristic.

Because ac filters have been omitted, harmonic currents will be present in the ac line. The harmonic spectrum expected from the converter configuration is given by h = 12k$\pm$ 1 for k = 1, 2, 3... Because of the commutating reactances, the line currents are not ideal step waves but are rounded. As a consequence of this rounding, the relative magnitudes of the harmonics present is fixed by the overlap angle u, defined as the time of commutation between any two phases in electrical degrees.

In general, the overlap angle for a 6-pulse bridge is defined by

$$\cos u = 1 - \frac{I_{s1} x_k}{V_{s1}} \tag{3}$$

where Is1 and V_{s1} are the RMS fundamental current and voltage per bridge. The commutating reactance is comprised of three parts

$$x_k = x_{kt} + x_{ki} + x_{km} \tag{4}$$

where x_{kt} is that portion of the commutating reactance contributed by the transformer (transformer leakage reactance), x_{ki} is the leakage reactance of one-half the intergroup reactor, and x_{km} is that portion contributed by the machine (negative sequence reactance). If the machine current fundamental is I_s, then the converter current I_{s1} is one-half the machine current I_s. The per unit negative sequence reactance must be expressed on a different base, the base of the transformer (one bridge).

Hence,

$$x_{km} = \frac{I_{s1}}{I_s} x_2 = \frac{1}{2} x_2 \tag{5}$$

Taking representative values for the reactances x_{kt} = 0.125, x_{ki} = 0.05, x_{km} = 0.25 the commutating reactance for each bridge is approximately

$$x_k = 0.125 + 0.05 + (1/2)0.25 = 0.30 \tag{6}$$

Hence,

$$\cos u = 1 - 0.3 = 0.7 \tag{7}$$

and

$$u = 45.57^{\circ} \tag{8}$$

Using this value of overlap, approximate values for the harmonics as a percentage of the fundamental for the 12-pulse converter may be obtained [23]. The resulting RMS current is found to be

$$I_{rms}/I_s = \sqrt{1.00071} = 1.00035 \tag{9}$$

Thus, even without a line filter the expected heating due to harmonic currents is small and can be safely neglected for the machine designs.

The commutating reactance also has an important effect on power factor. The power factor angle ϕ is related to the overlap angle u and delay (firing) angle α by

$$\cos \phi = \frac{1}{2} \left[\cos \alpha + \cos(\alpha + u)\right] \tag{10}$$

It is assumed that at rated conditions, $\alpha = 0$ so that the power factor becomes

$$\cos \phi = \frac{1}{2} \left[1 + \cos u\right] = \frac{1}{2}(1 + 0.7) = 0.85 \tag{11}$$

This value of power factor was used in the design of the synchronous machines.

As discussed previously, it is assumed that the machines are conventional and designed for rated operation at 60 Hz. However, practical considerations such as thermal limits and voltage stress limits must be carefully considered above and below rated speed. Below rated speed it is well known that in order to prevent saturation of the machine, terminal voltage must be decreased proportional to frequency below 60 Hz (constant volts/Hz). Therefore, the power output capability of the machine also becomes proportional to frequency.

At above-rated speed the same constant volts/Hz operation would result in an intolerable rise in terminal voltage if the power were permitted to increase. Since it is assumed that conventional insulation is used, voltage cannot rise more than 10% over the rated value without risking insulation failure. For practical purposes, it is assumed that machine voltage is limited to rated voltage at speeds above-rated and therefore, power is assumed constant. It can be shown [24,25] that the optimum operating profile of a turbine follows a cubic function of speed. Since the machine power output varies linearly with speed below 60 Hz and constant above, the net output power is then fixed by the turbine below 60 Hz and by the machine above 60 Hz. The resulting net permissible operating region is shown in Fig. 3. The top frequency of 81 Hz was chosen on the

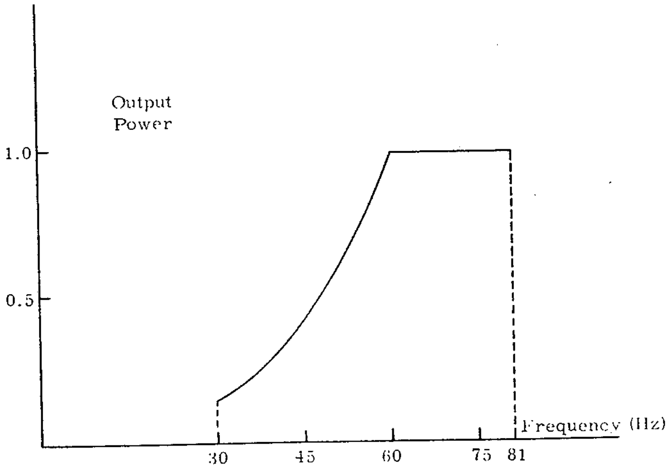

Fig. 3. Net permissible operating region during generation (machine heating neglected).

basis of the overspeed limit generally built-in to existing machine designs.

BASE CASE MACHINES DESIGNED AT 60 Hz

Three machines, with motor/generator ratings which represent the broad spectrum found in hydro installations, were designed for the purpose of evaluating adjustable speed operation. Design criteria which were based on conventional practice are included in Table I. The design frequency for each machine was 60 Hz, and the voltage level was selected on the basis of acceptable design practice. Even though converter operation would lessen any minimum inertia requirements, only representative values were considered when establishing the target inertiae of Table I. Thus, the WR^2 for each case is a handbook value and differs slightly from the standards. The minimum stator bore was set by the largest turbine component to be removed.

TABLE I

Generator-Motor Design Data

Data		Case 1	Case 2	Case 3	Notes
Rated Frequency, Hz		60	60	60	
Rates Speed, rpm		200	200	72	
No Poles		36	36	100	
No Phases		3	3	3	
Rated Voltage, kV		13.8	13.8	17	
Generator					
Rated	MW	150.0	50.0	600.0	
	PF	.85	.85	.85	(1)
	MVA	176.5	58.8	706.0	
Motor					
Rated	MW	149.2	50.4	671.4	(2)
	PF	.85	.85	.85	(1)
Input (Approx.)	MVA	179.0	60.5	802.4	(2)
Stator and Rotor Temp. Rise					
Rated	$^{\circ}$C	60	60	60	(2)
115% Load	$^{\circ}$C	80	80	80	
Cold Air, max.	$^{\circ}$C	40	40	40	
Pull-Out-Torque, min. %		150	150	150	(3)
Subtrans. React., X''_d		.18-.24	.18-.24	.18-.24	(4)
Type of Amortisseur		Cont., Low Resist.	Cont., Low Resist.	Cont., Low Resist.	(5)
Starting Method		Synchr.	Synchr.	Synchr.	(6)
Mechanical					
WR^2, min Kg-m^2		2.63×10^6	0.67×10^6	114.98×10^6	
Runaway Speed, rpm		336	370	140	
Turbine Mass, Kg		90,720	45,360	907,209	
Hydr. Thrust, Kg		272,162	90,720	4,536,047	
Total Mass and Thrust, Kg		362,882	136,080	5,443,256	
Min. Stator Bore m		5.59	4.37	12.7	
Ventilation		Self-Vent	Self-Vent	Self-Vent	(7)
Excitation System		Static	Static	Static	

Notes: (1) Required for converter-inverter operation.
(2) Motor rating is the limiting rating for rated temperature rise. 115% load provision with 80 $^{\circ}$C max. temp. rise.
(3) This pull-out-torque requirement will result in SCR = 1.0 to 1.3 for generator rating.
(4) Design target range for X''_d considering converter-inverter operation.
(5) Continuous amortisseur required for rectifier loading.
(6) Low frequency synchronous start using converter-inverter equipment.
(7) Air circulation will be provided by the fan action of the rotor. No external fans.

Although the goal was to investigate the applicability of conventional machine design to adjustable speed applications, a number of parameters must be targeted on a basis of converter operation. For example, the 0.85 power factor was established as a reasonable first guess as to the achievable power factor. In addition, the subtransient reactance X''_d of Table I is a target range based on converter requirements.

Other factors to be considered are the operating limits established by the motor as determined by the temperature rise. Since the machines are selfventilated, the temperature rise will be a key factor in determining the operating limits under variable speed.

Table II gives the calculated machine characteristics at the design frequency of 60 Hz. As this table indicates, the machines were designed to meet the criteria established in Table I. In particular, the SCR of 1.0, 1.15, and 1.2 fall within the 1.0 to 1.3 requirement of Table I. Also, the minimum pull-out torque of 150% is exceeded in each case.

TABLE II

Calculated Machine Characteristics for 60-Hz Base Design

Data		Case 1	Case 2	Case 3
Generator Rating, MVA		176.5	58.8	706.
Motor Rating, MW		149.2	50.4	671.4
Motor Input (Approx. MVA)		(179)	(60.5)	(802.4)
Power Factor		.85	.85	.85
Speed, rpm		200	200	72
Frequency, Hz		60	60	60
Efficiency (Excluding Excitation Losses)	Motor	98.38	97.95	98.58
	Generator	98.39	97.97	98.56
Short-Circuit Ratio		1.0	1.15	1.2
Pull-Out-Torque, %		214	232	232
Stator and Rotor Temperature Rise, Rated $^{\circ}$C		60	60	60
Reactances (Generator Base)				
Synchronous Reactance		1.063	.987	.925
Transient Reactance		.248	.229	.287
Subtransient Reactance		.206	.207	.198
Negative Sequence Reactance		.195	.172	.203
Zero Sequence Reactance		.076	.077	.122
Time Constants (Generator Base)				
Transient Open-Circuit		6.173	4.544	9.01
Transient Short-Circuit		1.42	1.056	2.794
Subtransient Short-Circuit		.019	.019	.024
Total Mass and Thrust of Turbine for Bearing Design, Kg		362,882	136,080	5,443,256

Table III shows the effect of the 0.85 power factor imposed by the converter on machine efficiency. Although the comparison is for the same machine but at different power factors, it does provide a detailed breakdown of the losses and of the total loss reduction to be expected if the machine were to run at unit power factor. It is clear that if a second machine were designed for unity power factor and a comparison made with the 0.85 power factor machine, the loss reduction would be greater.

TABLE III

Effect of Power Factor for 60-Hz Base Design

Data	Case 1		Case 2		Case 3	
Generator Output, MW	150.0	150.0	50.0	50.0	600.0	600.0
MVA Rating	176.5	150.0	58.8	50.0	706.0	600.0
Power Factor	.85	1.0	.85	1.0	.85	1.0
Summary of Losses, kW						
(1) Friction and Windage	800	800	215	215	2950	2950
(2) Core Loss	553	553	301	301	2087	2087
(3) Stray Load	235	170	75	54	1050	759
(4) I^2R Arm	497	359	260	188	1384	1000
(5) I^2R Field	366	195	181	97	1262	655
Total Loss, kW	2451	2077	1032	855	8733	7451
Loss Reduction	0	374	0	177	0	1282
Efficiency, %	98.39	98.63	97.97	98.32	98.56	98.77

VARIABLE FREQUENCY STUDIES OF THE BASE CASE MACHINE

In order to establish the variable speed capability of traditional 60-Hz designed machines an analysis was performed over the frequency range 30-81 Hz. The purpose was to evaluate the performance of the machines in terms of efficiency, adverse operating conditions, and identify areas that would require a redefining of design criteria.

The first area of concern was to determine the operating profile. The profile of Fig. 3 was established without regard to heating effects. Fig. 4 shows the results of computer analysis programs that calculated the maximum power capability of the

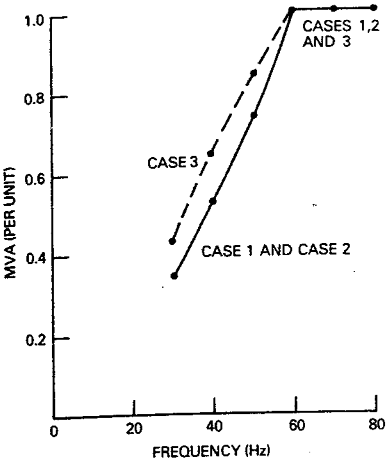

Fig. 4. Volt-amp capability of machine at the thermal limit versus frequency.

motor/generator, based on the allowable temperature rise.

Fig. 4, together with the optimum head versus optimum speed curve of Fig. 5, yields the net operating profile in Fig. 6. The base volt-amp, the frequencies f_B at which the optimum pump turbine profile intersects the machine thermal limits profile, together with optimum torque values, are given in Table IV. Figure 6 shows that for Cases 1 and 2 the frequency at which the optimum turbine profile intersects the machine thermal limit curve is slightly less than 60 Hz (52 and 54 Hz, respectively). This is reasonable considering the difference in power capability of the hydraulic system when pumping and turbining. This power differential is also reflected in the motoring and generating MVA values (179.0 MVA versus 176.5 MVA and 60.5 MVA versus 58.8 MVA, respectively). Case 3, however, indicates a substantial difference in the motoring and generating capability of the machine (802.4 MVA and 706.0 MVA). Thus, the optimum turbine profile intersects the machine thermal limit curve at a frequency above 60 Hz and allows operation along the optimum profile from 30 Hz to 78 Hz.

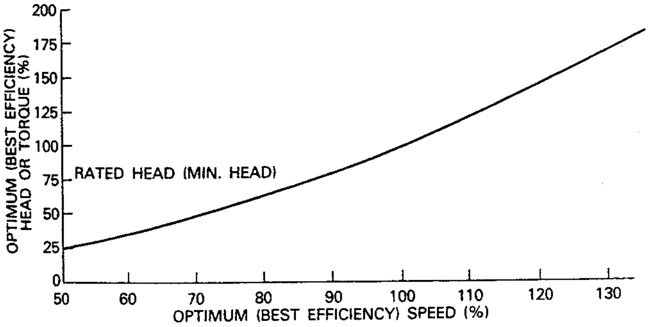

Fig. 5. Optimum head versus optimum speed (pumping and turbining).

Of the multitude of variables affected by frequency, a number of them are not volt-amp dependent. These variables include ventilation, windage, thrust bearing temperature, losses, and open circuit saturation curves. Because the windage loss is a function of ventilation, the first quantity investigated was the variation of the air flow with frequency. The result of this investigation is not shown. However, the air flow linearly increases with the speed as would be expected since all other quantities affecting air flow, e.g. duct size, remain constant. As a result of the air flow variation, the windage loss changes considerably over the frequency range of interest. This is shown in Fig. 7 from which we see that the windage varies approximately as the cube of the per unit speed. Even though the windage loss increases dramatically above 60 Hz, it remains less than 1% of the machine rating.

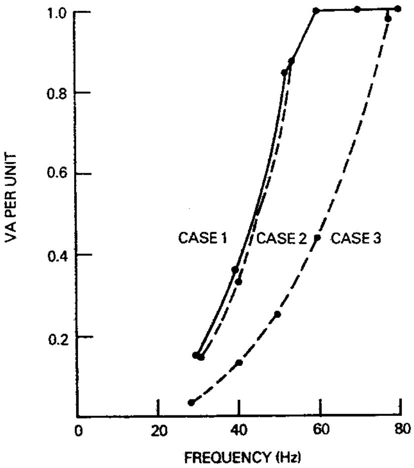

Fig. 6. Net operating profile.

TABLE IV

Optimum Turbining, Torque and Speed Values

Case	100% Torque (ft lbs)	100% Speed (Hz)	MVA	Power Factor	f_B (Hz)
1	6,530,000	60	179.0	0.85	52.0
2	2,075,000	60	60.5	0.85	54.0
3	29,385,000	60	802.4	0.85	78.0

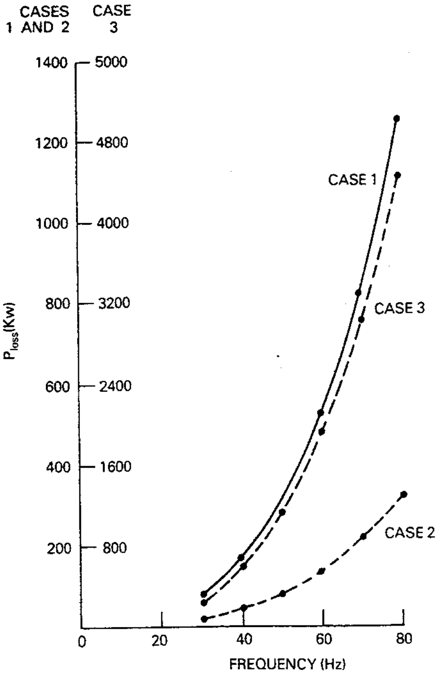

Fig. 7. Windage loss versus frequency.

Another parameter of interest is the variation of the thrust bearing temperature with frequency plotted in Fig. 8. The results shown were obtained under the most severe load as determined by the axial thrust versus speed curves with wearing rings worn to twice design clearance. It should be pointed out that from 30-60 Hz,

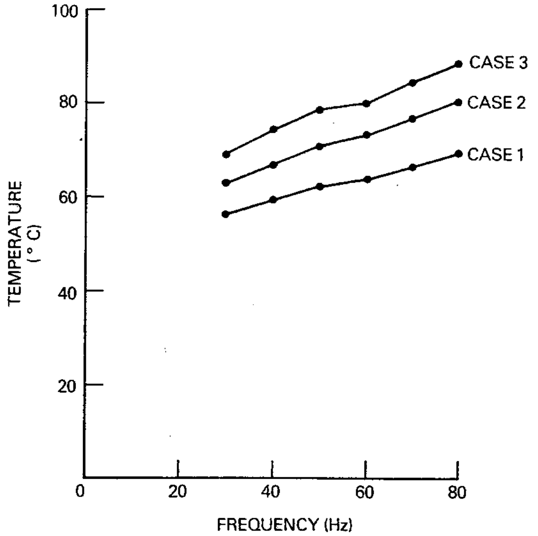

Fig. 8. Thrust bearing temperature versus frequency under most severe load.

the axial thrust during pumping yields the most severe load while above 60 Hz, the turbining mode is most severe. The increase in the bearing temperature above 60 Hz operation is not excessive; however, careful monitoring of the temperature is advisable in order to avoid exceeding the design tolerances. The thrust bearing losses are shown in Fig. 9. Note the dramatic rise in the losses for frequencies above 60 Hz, emphasizing the need for concern when operating existing installations above rated speed.

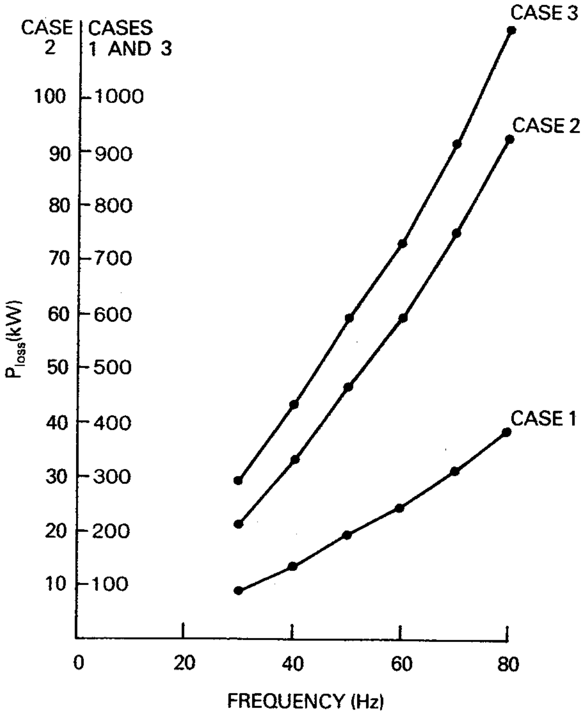

Fig. 9. Bearing loss versus frequency under most severe load.

The effect of variable speed operation on the open circuit saturation curves for Case 1 is presented in Fig. 10. Due to the voltage constraint imposed by adjustable frequency operation, the vertical axis uses base-rated design voltage above 60 Hz and a base voltage that decreases at a constant volts/ Hz rate below 60 Hz. The current base for all frequencies is the field current necessary for rated, open circuit terminal voltage at 60 Hz.

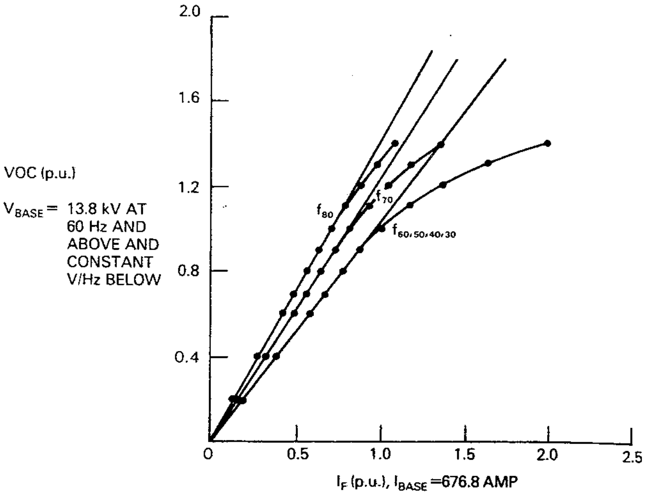

Fig. 10. Open circuit saturation curves.

For frequencies below 60 Hz, the field current needed to maintain the constant volts/Hz curve remains constant, whereas for frequencies above 60 Hz, the required field current decreases.

Using the volt-amp versus frequency profile of Fig. 6 for both the turbine and pumping modes, a number of volt-amp dependent quantities may be examined. Figs. 11-13 show the variation in stator and field temperature and excitation power requirements for the turbining mode. The reduced stator and field temperature at low frequencies is because the machine is limited below base speed by the turbine output. Thus, the machine is operating below its thermal limits resulting in less armature reaction and reduced armature losses. The field current required to maintain the constant volts/Hz voltage profile is thereby reduced resulting in lower field power requirements while operating below f_B, the point where thermal limits overtake optimum turbine operation. Conversely, above f_B the field power loss again decreases due to terminal voltage limitations above 60 Hz.

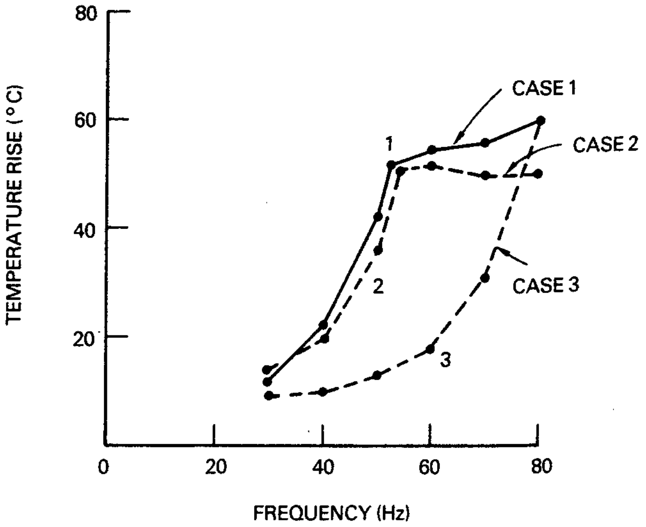

Fig. 11. Stator temperature rise versus frequency.

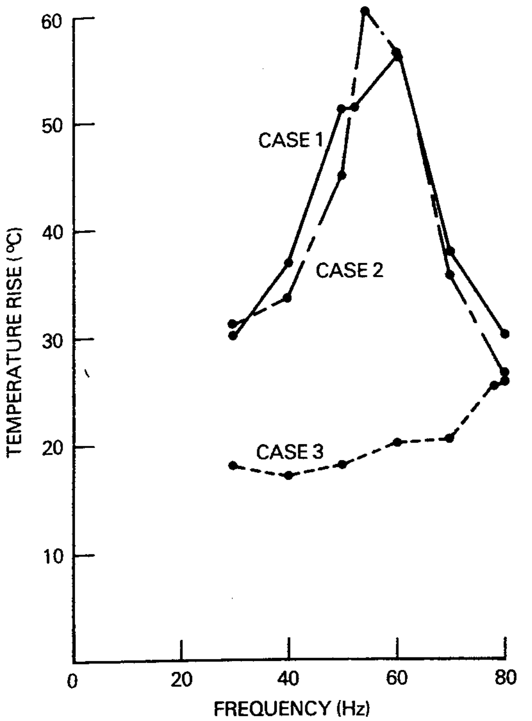

Fig. 12. Field temperature rise versus frequency.

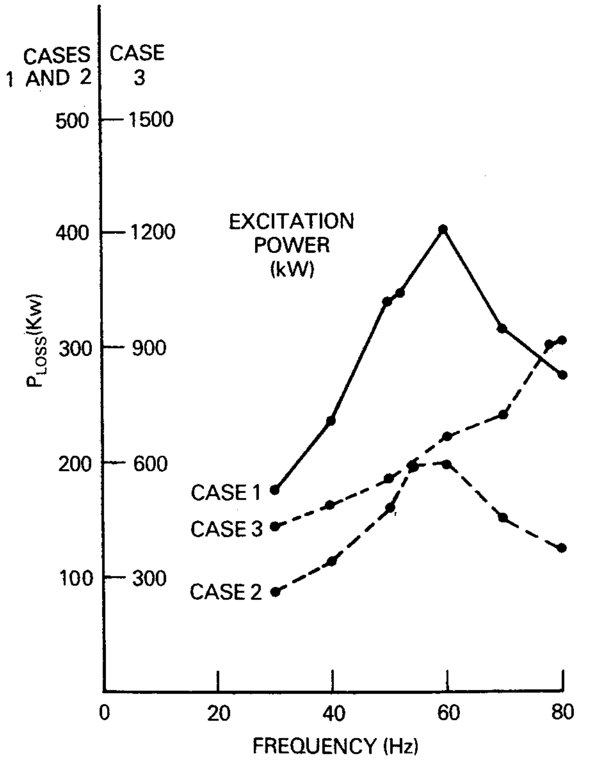

Fig. 13. Excitation power.

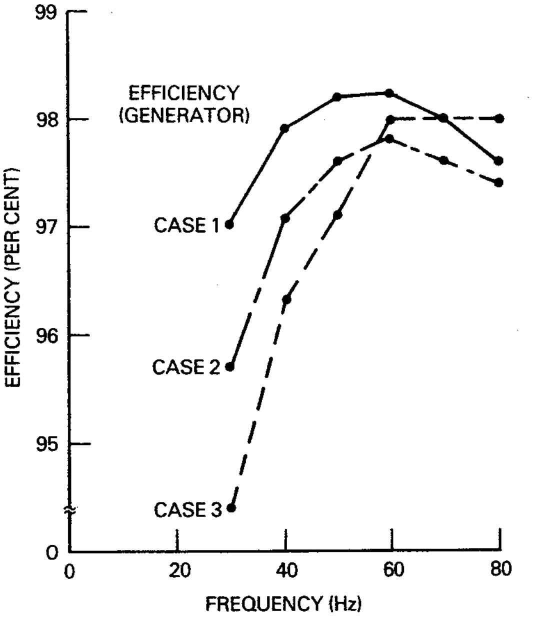

Fig. 14. Generator efficiency versus frequency (at 0.85 power factor turbine characteristics).

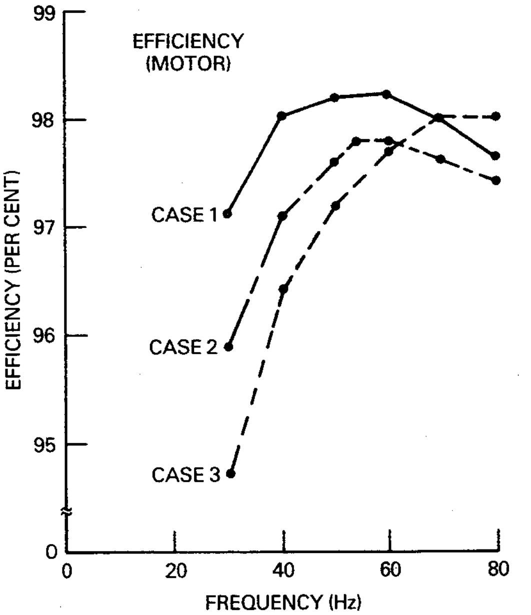

Fig. 15. Motor efficiency versus frequency (at 0.85 power factor optimum pump characteristic).

MACHINE EFFICIENCIES

Figs. 14 and 15 show the overall machine efficiencies over the frequency range 30-81 Hz for the loading of Fig. 6; Fig. 14 is the generating or turbining mode and Fig. 15 the motoring or pumping mode of operation. The reduction in efficiency for low frequency operation in spite of the reduction in short circuit core losses is primarily the result of operating below the thermal limits in combination with the frequency dependent open circuit core loss. The more gradual reduction with frequency above base speed is due to changes in core loss.

In order to establish a basis for comparing the efficiencies obtained above, the machine efficiencies for the same loading profile, but a fixed speed of 60 Hz, were calculated. Some of the results are shown in Figs. 16 and 17. Here, the efficiency for both the motoring and generating modes of Case 1 are exhibited. From these results it is clear that even for machines

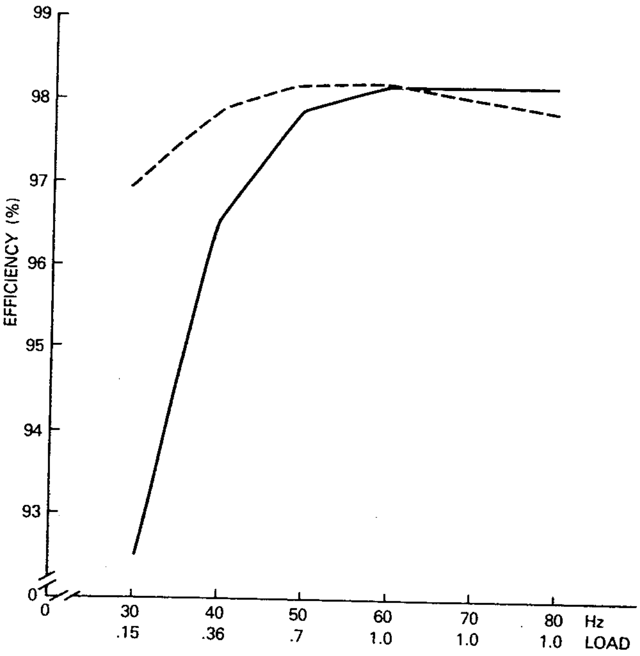

Fig. 16. Comparison between 60-Hz operation and variable frequency operation at specific load points for Case 1 operating as a motor.

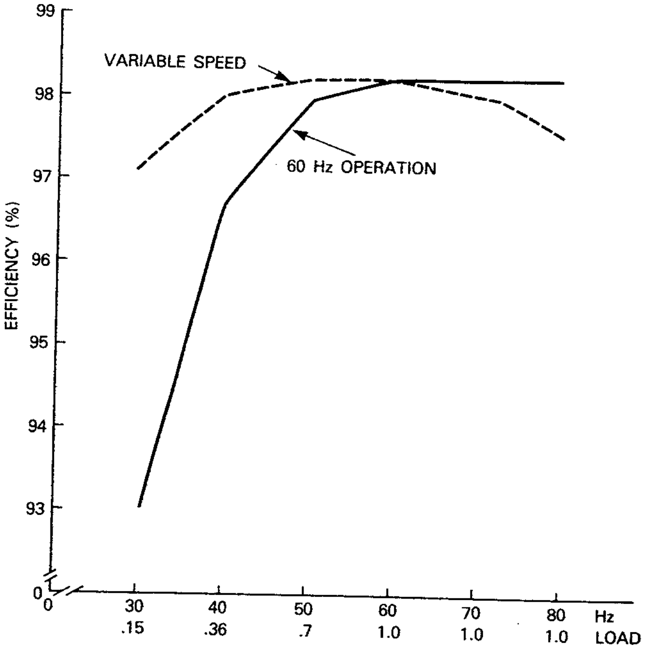

Fig. 17. Comparison between 60-Hz operation and variable frequency operation at specific load points for Case 1 operating as a generator.

designed on a 60-Hz basis, the overall machine efficiency is improved for low head (light load) conditions. Operation above 60 Hz (high head) would not be advantageous for machines with small overload capability.

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