J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

HYDRAULIC TURBINES

Hydro-Plants

Large hydroelectric installations run at almost constant hydraulic head and grid synchronous speed. Optimizing the power output under these conditions is relatively easy. Small installations, such as “run of river systems,” on the other hand are subject to much more variable hydraulic conditions, and optimum power (or efficiency) from such an installation is much more difficult to achieve.

In most large installations, flow of water through the turbine is varied using a governor system to maintain constant generator speed. This is achieved by (1) varying the guide vane angle in Francis and other reaction turbines, (2) adjustment of blade angle and possibly entry vane angle to Kaplan and propeller turbines, and (3) adjustment of capacity in the cross-flow turbine. In impulse turbines such as the Pelton wheel a variable inlet nozzle is used. With this control method at constant head, the delivered torque to the generator is proportional to the flow, and the turbine speed is that required for synchronous generation at the particular grid frequency. This type of installation is a constant speed, constant frequency (*CSCF*) system; and ideally, optimum power (measured in real time) corresponds to constant speed operation.

In smaller installations in which the hydraulic head is relatively low and variable over a wide range, normally it is not possible to obtain optimum power at constant speed; and, for coupling to a grid, the variable speed but constant generated frequency (*VSCF*) requirement has, in the past, made such small sites nonviable for mains electricity generation. Power produced in these sites has been suitable only for local heating which has a much lower commercial value than grid frequency electricity.

Today, however, small hydroelectric systems will become more financially attractive by virtue of modern developments in low-cost power converters (from 100 W upwards), special VSCF generators, and cheap computing units for on-line power measurement and optimizing control. All these will lead to different approaches to system design, and this article discusses some of the relevant techniques.

Turbine and Generator Coupling

Turbine Characteristics (23,24). As an example, power–speed, efficiency–speed, and torque–speed characteristics of a Francis turbine with head as a parameter are shown in Fig. 1, Fig. 2, and Fig. 3, respectively. It can clearly be seen that optimal power is available from the turbine at different speeds corresponding to different heads.

If optimal efficiency is required rather than optimal power, then Fig. 2 shows the turbine should run again at variable speed depending on the head. These speeds are slightly higher than in an optimal power operation and correspond to smooth flow to the inlet of the turbine (1,2,17,18). In both cases, the optimal load line for the operation is the locus of the peak power or peak efficiencies shown in Fig. 1 and Fig. 2. The torque–speed

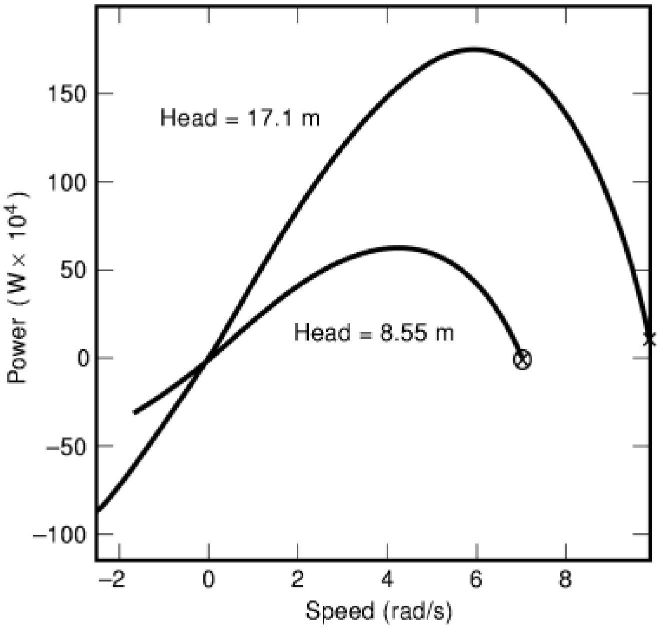

Fig. 1. Power–speed theoretical characteristic of a Francis turbine. Head as a parameter. This figure is useful for determining the optimal speed for maximum power production from the turbine.

characteristic, Fig. 3, which is derived from Fig. 1, is important for stability analysis of the system, discussed in the following section.

System Equations. The torque produced by a turbine, T_t, depends on hydraulic head, H, flow rate, Q, blade setting, θ, and speed, w, while the generator torque, T_g, is a function of voltage, E, current, I, and speed. The generator torque–speed characteristics are discussed in detail in the section entitled “Electrical System,” but at this point the system equations can be written as

$$J\dot{w} + Kw = T_t(Q, H, w, \theta) - T_g(E, I, w) \tag{1}$$

where J is the moment of inertia the rotating assembly and K is a frictional torque coefficient.

The current supplied by the generator depends on the load impendance, Z, the supply frequency, f, and a control variable, u_e, as well as on voltage and speed:

$$I \equiv I(E, Z, f, w, u_e) \tag{2}$$

while the turbine flow depends on load, speed, vane setting, and a control variable, u_m (which has in the past been supplied by a mechanical governor):

$$Q = Q(H, w, \theta, u_m) \tag{3}$$

Assuming no control action, the solution of Eq. (1) may or may not be stable depending on the relative slopes of the turbine and generator torque characteristics at the operating condition, and this can be shown by either of the following:

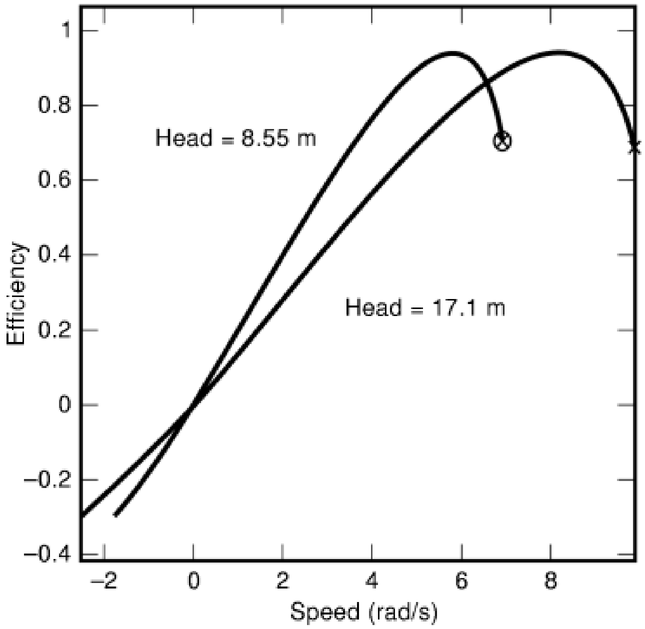

Fig. 2. Efficiency–speed theoretical characteristic of Francis turbine. Head as a parameter. This figure is useful for determining the optimal speed for maximum efficiency of the turbine.

(1) Linearizing Eq. (1) for small disturbances, δw, around the mean operating speed assuming all other parameters are constant, that is (20),

$$J\delta\dot{w} + K\cdot\delta w = \left[\frac{\partial T_t}{\partial w}(Q,H,w,\theta)|_{w=w_0} - \frac{\partial T_g}{\partial w}(E,I,w)|_{w=w_0}\right]\cdot\delta w \quad (4)$$

Ignoring friction, δw is stable if the term on the right-hand side is negative.

(2) Graphical static stability analysis—that is, superposition of the steady-state turbine and generator characteristics. The operating speed will be stable if the generator slope is greater than the turbine slope at the intersection (operating point).

Notice that in each case the mean or steady-state operating speed, w_0, is given by

$$T_t(Q,H,w_0,\theta) = T_g(E,I,w_0) + Kw_0 \quad (5)$$

which corresponds to the point of intersection of the curves T_t and T_g (for the case $K = 0$).

Under closed-loop control conditions where control actions u_m and or u_e are applied, system stability is much more difficult to determine, particularly when several generating systems are supplying a common grid since Eq. (1) becomes a multivariable equation.

Optimal Operation. The optimal operating speed, w_{opt}, for maximum power (or maximum efficiency if so desired) will vary with hydraulic conditions (e.g., head), and the control system on the turbine or generator (or both) should be designed to maintain this optimal operation. Such a closed-loop control system must

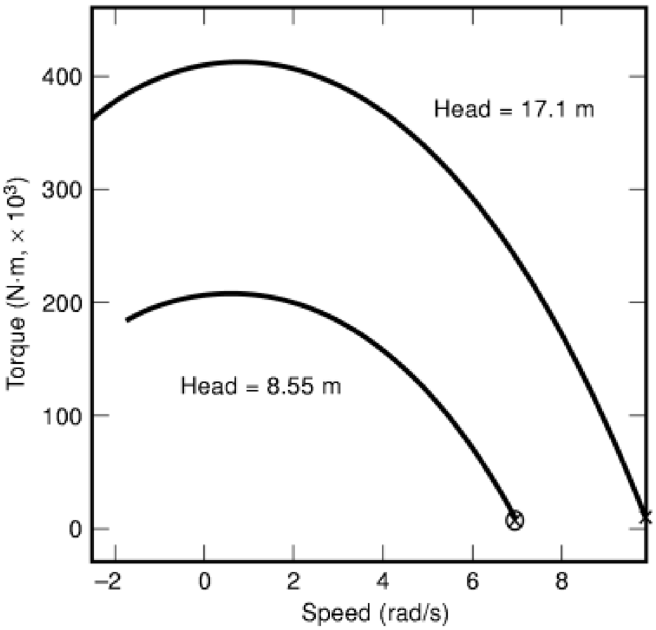

Fig. 3. Torque–speed theoretical characteristic of a Francis turbine. Head as a parameter. This figure is important for determining the stability of turbine-generator coupling.

continuously monitor the generator output power (or system efficiency) and use the control variables u_e and/or u_m to adjust the speed so that maximum power (or efficiency) under the prevailing conditions is obtained.

In older installations a mechanical governor was used to provide control action, u_m, so that constant (synchronous) speed was maintained. This governor could be replaced by a variable-speed (or range-speed) governor so that the speed set point corresponded to the optimal speed as determined by the optimizing computer. However, it is more satisfactory in modern installations to minimize the mechanical adjustments and to use the computer to provide control action u_e on the generator or electrical side, although care should be taken to ensure that overspeed protection is still provided on the mechanical side.

Electrical System

Synchronous Alternator and Induction Generator. Hydraulic power is not constant but varies seasonally or, for a "run of river" system, almost continually, depending on rainfall, but when connected to a power grid of capacity much larger than that of the individual hydro-station, fluctuations in supply can be easily accommodated.

In conventional systems, the generator is usually a dc excited alternator in which the generated frequency is proportional to the speed of rotation. As such, this may not match grid frequency (if the turbine tends to run at nonsynchronous speed), but fortunately the electrical constraints provided by the grid, such as voltage, frequency, impedance, and so on, force the turbine to run at a constant speed w_s (called synchronous speed), producing therefore the same grid frequency. The torque–speed characteristic of this synchronous alternator is shown in Fig. 4, its vertical line indicating that the torque can vary up to the maximum value, T_{max}, at synchronous speed. The unit may also run as a synchronous motor. If the turbine torque increases above T_{max},

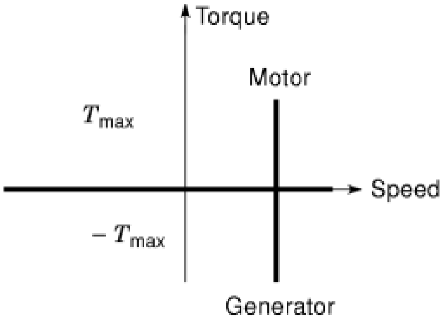

Fig. 4. Torque–speed characteristic of synchronous machine. This figure is important for determining the operating point of the system and stability (turbine-gear box-generator coupling).

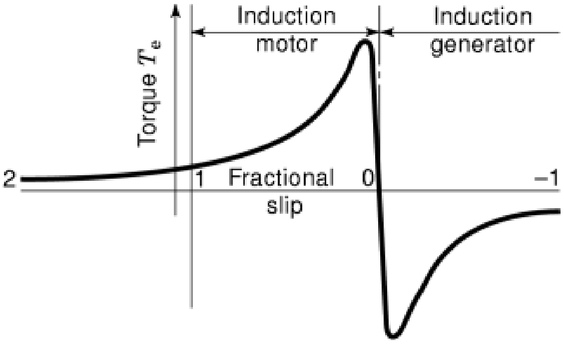

Fig. 5. Torque–speed characteristic of asynchronous (induction) machine.

then the alternator will not be able to absorb all the turbine power, speed runaway will occur, and the system will be said to be out of synchronism.

Induction machines with small slips can also be considered as constant-speed systems. (*Note:* Percent slip is the difference between synchronous and actual speed. For a four-pole 50 Hz induction machine, synchronous speed is 1500 rev/min. Used as a motor at 1485 rev/min, the "positive slip" = $(1500 - 1485)/1500 \times 100 = 1\%$). Used as a generator and run at 1515 rev/min, the "negative slip" is 1%). An induction generator can operate on an infinite bus at slip speeds 1% to 5% above synchronous speed, a small variation compared with typical shifts in turbine speed. Hence, induction systems, which maintain constant speed due to electrical constraints imposed by a grid irrespective of turbine speed, are sometimes also classified as CSCF systems even though they are in fact VSCF in a narrow range above synchronous speed. Slip higher than 5% is not practical, since the electrical losses increase substantially and the efficiency deteriorates. In particular, this is true for large generators. The torque–speed characteristic of an induction generator is shown in Fig. 5. Similar to the synchronous machine, if the turbine torque increases above the peak, Eq. (3) will no longer be satisfied and the system becomes unstable, speed runaway occurs, and the machine generates no power. In induction machines, this maximum torque is also called "runaway" or "pull-out" torque. The induction generator can also be classified as a variable-torque, constant-frequency machine since at synchronous speed its torque is equal to zero and increases with speed.

Since the characteristic in Fig. 5 is constant and cannot be varied for a squirrel cage generator, the control variable u_e is constant. An important characteristic of an induction generator is that it uses reactive power usually drawn from the grid in order to enable it to generate real power. This means that grid failure would prevent generation unless the reactive power was supplied by a capacitor station system. Since capacitors always exist on the machine (from grid lines, for example), self-excitation is still possible and there is a danger of power being supplied from the induction machine in small hydro-stations. Fatalities have occurred among power-line workers due to lines being supplied from unknown sources, and protection at the generator must be provided to prevent this. Therefore, even in the induction generator case, there is no automatic protection, contrary to what many people may think. In the case of power loss, overspeed protection of the turbine must be provided.

If used on a wind station rather than a hydro-station, runaway would be more acute and although a speed controller is not necessary, some mechanism to dump excess wind power would be needed. However, in the wind station, a useful characteristic of the induction generator is that the same machine runs as a motor, drawing power from the grid, when below synchronous speed. This may be used to advantage on wind turbines which may not be self-starting and need to be motored up to self-sustaining speeds. If the rotor of the induction generator is a wire-wound type, then its torque–speed characteristic can be controlled with variable resistances in series with the rotor windings. The result will be a variable-torque, variable-speed (narrow-range) characteristic similar to the isosynchronous generator (see the section entitled "The Double-Stator (Cascade or Isosynchronous) Induction Machine").

Although the technical merits of synchronous and induction generators have been extensively argued in the literature, they deserve at least a brief summary here. A synchronous generator runs at constant speed and hence requires costly speed controls if not run in conjunction with a grid. However, it can supply negative reactive power to the grid system, and, if necessary, it operates as a synchronous condenser, whereas an induction generator lacks this capability and also needs additional power factor improvement equipment. On the other hand, stability problems can arise where the synchronous generator of the hydro-system is "thinly" connected to other synchronous machines because of its location in the power network (a large amount of reactance exists between the main fossil-fuel generator and the hydro-power generator). Any additional series electrical impedance with the output of the machine will alter T_e and reduce the stability range of the operating point. Induction machines have a distinct advantage in this matter.

It is worth mentioning that the instability may not be in speed (or frequency) but in power supplied to the grid, if long power lines with large series impedance are used.

Variable-Speed, Constant-Frequency (VSCF) Systems. In most cases, variable-frequency power must be converted to constant-frequency power. The conversion can be made with the aid of rotary electromechanical machinery or with solid-state converters using transistors and thyristors. In some cases, nonconventional generators produce constant frequency from a variable speed source. As a result, generation schemes involving variable-speed rotors are normally more complicated than constant-speed systems.

Variable-speed, constant-frequency systems can be summarized as follows:

Ac Generator (Alternator). As shown in Fig. 6, the alternator is a variable-output-frequency generator when coupled to a varying-speed prime mover. Its field is derived from a permanent magnet or dc excited coil. The output of this machine is a variable-frequency, variable-voltage waveform. If this voltage is not used for heating or lighting, it may be processed in oder to be converted to a constant frequency output. Therefore, the generator output of varying frequency is rectified to give direct current, which is converted to ac by an inverter. The ac–dc–ac conversion is an established technology in high-voltage dc transmission, and the operation of inverter technology on the ac power grid is well understood within certain parameters, including system short-circuited and voltage stability at the point of interconnection. Application of this scheme to hydropower is limited only by the cost of power-processing equipment.

For this system, the control variable u_e can be taken as equal to the field current and may be used to reduce the field losses at low output power. In small permanent magnet machines, the field is constant and therefore u_e does not exist.

Field Modulation Techniques, Frequency Down Conversion. The machine shown in Fig. 7 is basically a three-phase wire-wound rotor slip rings machine excited by a single-phase grid frequency (10). The output

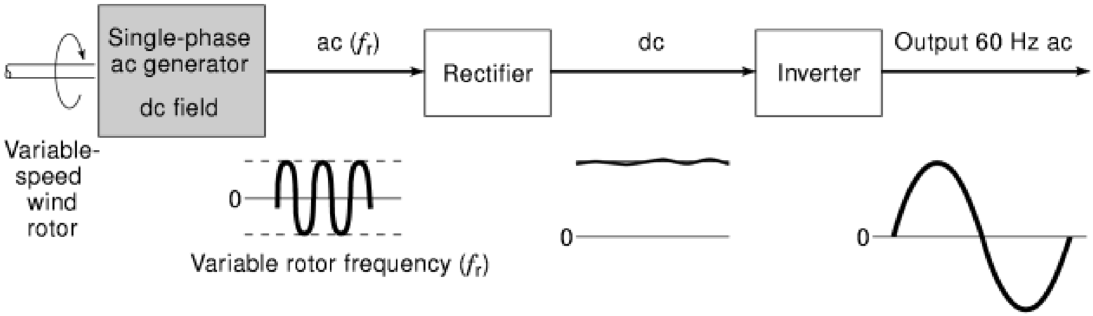

Fig. 6. Alternator and frequency conversion system for producing constant output frequency from a variable speed prime mover.

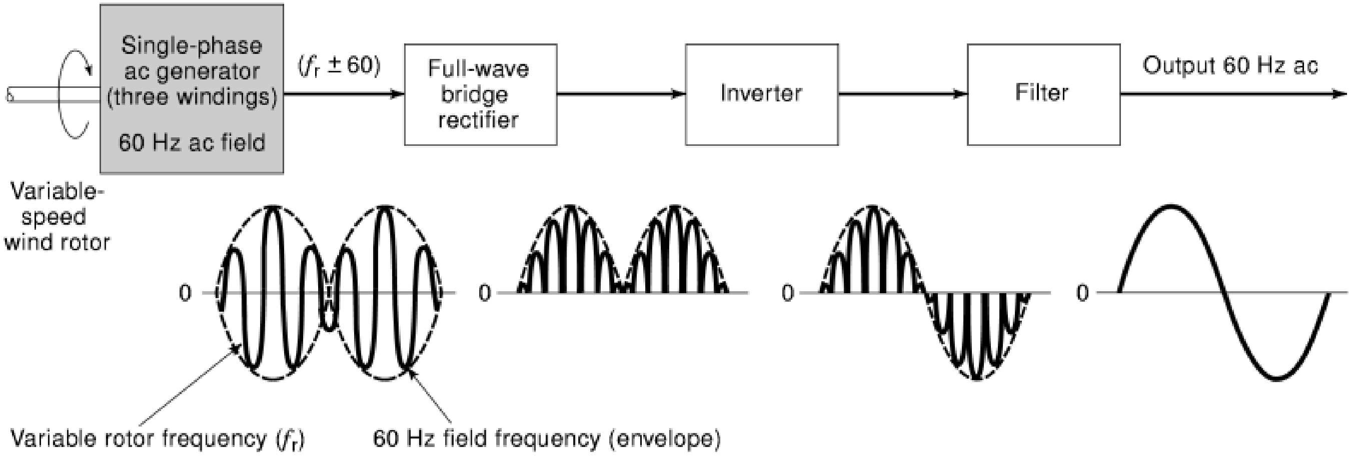

Fig. 7. Field modulation system for producing constant output frequency from a variable speed prime mover.

from the slip rings is at grid frequency, amplitude-modulated by the speed frequency of the machine which consists of double-sideband frequency components without carrier. The output is then demodulated in a bridge rectifier, inverted by a SCR inverter and filtered to get grid frequency output.

The unique feature of this scheme is that it uses three separate phase windings for the alternator to produce single-phase output. The output phase voltages are rectified and added together. This causes the ripple component to be dramatically reduced, an effect similar to increasing the pulse number (sampling rate) in converter circuits. To produce a three-phase output, three sets of such a scheme have to be used while maintaining the proper phase difference between corresponding single-phase outputs. To keep dc and lower sidebands content down, the rotational frequency of the machine must be much higher than its synchronous speed (or at least 10 times the grid frequency divided by the number of pole pairs).

The control variable u_e in this system is the single-phase field. This can be adjusted by a variable transformer, for example.

Ac Commutator Generator (ACCG). Using an ACCG for hydro-energy is perhaps the simplest means of deriving constant-frequency output from a variable-speed machine (see Fig. 8), and the suggestion was first made by M. P. Kostenko in 1984 (21). Employed in a hydro-generating station interconnected with a power grid, ACCG field excitation can be derived from the grid (11,12). The machine output frequency is equal to the excitation frequency and can be connected back directly to the grid. The ACCG provides line frequency output

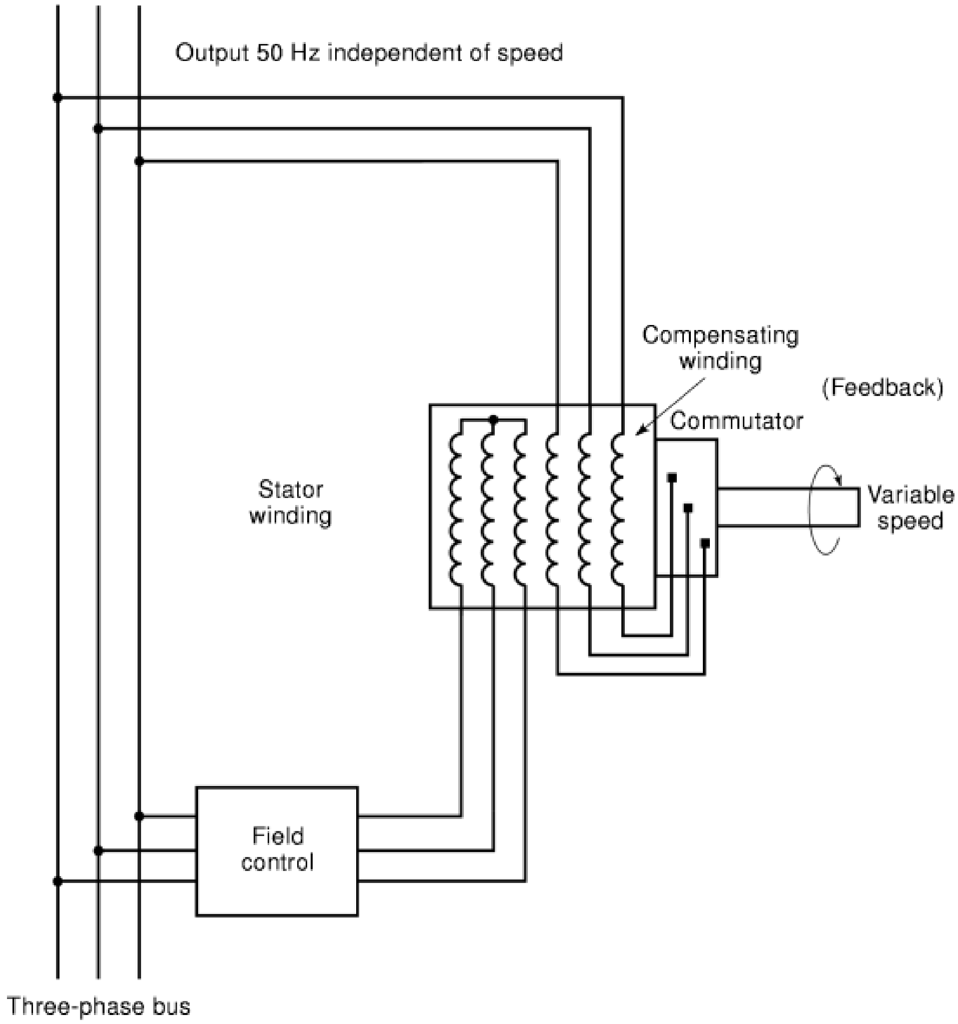

Fig. 8. Ac commutator generator (ACCG) system for producing constant output frequency from a variable speed prime mover.

due to its commutator and rotational voltage only, at any speed (without transformer voltage), since feedback compensation for its armature voltage is used. Therefore, the characteristics of this machine (mechanical and electrical) are linear and very similar to dc machines. The output current of the machine is not affected by the rotor inductance due to compensation which is practically equal to the difference between grid voltage and the generated voltage divided by the total resistance in the circuit. In ACCG there is another parameter which can modify the characteristic of the machine other than the excitation voltage, and this is the phase between the stator and grid voltages. If this phase is adjusted (for example, by adjusting the position of the commutator relative to the stator), then the torque magnitude and direction can be controlled. The machine can work both as a generator and a motor.

For this machine, the control variable u_e can be regarded as a vector—that is, field voltage and field phase.

The disadvantage is of course the commutator. The problem of reliable commutation in ac machines is serious. Several proven techniques are available to improve commutation, including high-resistance brushes or

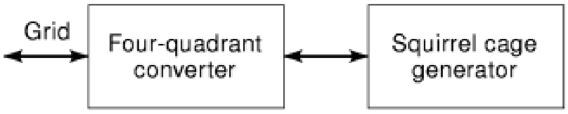

Fig. 9. Squirrel cage induction machine with a four-quadrant power converter used for producing constant output frequency from a variable-speed prime mover.

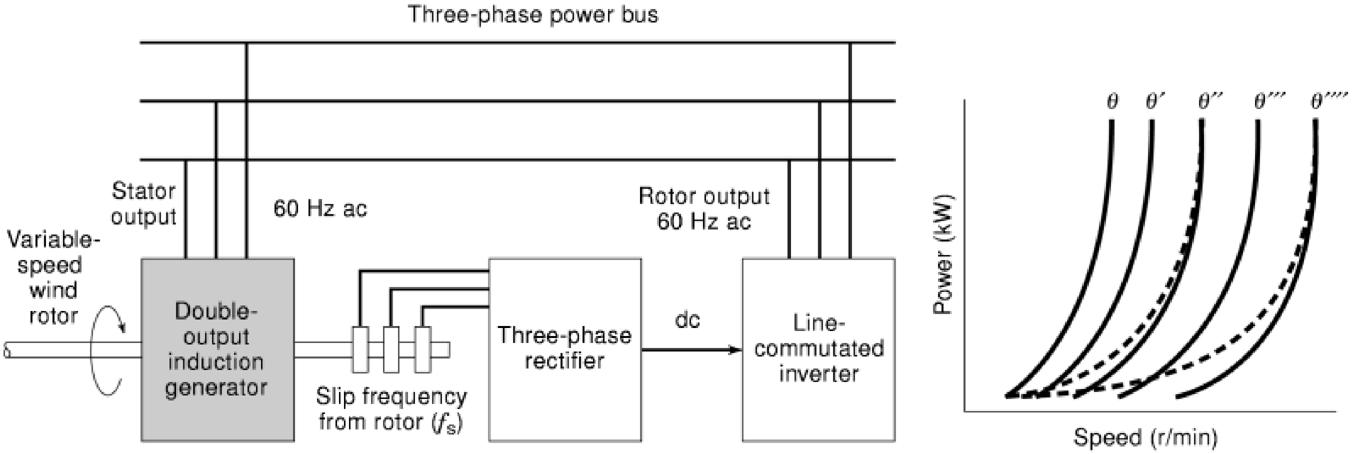

Fig. 10. Double-output machine with slip power recovery with the aid of a frequency converter. The figure shows a two-quadrant converter used for negative slip (supersynchronous) power generation. $u_e = \Theta =$ constant is the triggering angle.

commutators with many segments. The latter techniques have already been used to build large ac commutation motors successfully. These additional features make the machine costly and according to the best of this author's knowledge, no commutator generators are available for sale today on the market.

Squirrel Cage Induction Machine with a Converter. A VSCF system can be designed from a squirrel cage induction machine and a converter acting as a frequency changer. In Fig. 9 here the induction generator works as a CSCF generator in small slip; however, its self-synchronous speed is dictated and can be adjusted by the converter.

Although a reliable squirrel cage machine is used, the disadvantage of the system is that the converter is a four-quadrant type (i.e., able to drive the machine as a motor as well as a generator—in other words, able to absorb and feed power in both directions). Also, the converter should accept variable frequency at its input and produce constant frequency (grid frequency) at its output. All solid-state converters produce undesirable frequencies, which may be unacceptable if they cannot be filtered properly before the output is fed to the grid system (16).

The reactive power in this case is dictated by the converter characteristic but not by the machine itself. The control variables in this case are the converter output voltage and frequency. Therefore u_e can be regarded as a two-variable vector which modifies the characteristic in Fig. 5. This type of converter is relatively expensive today and is produced by few companies. An alternative solution is the double-output induction generator system.

The Double-Output Induction Generator (DOIG) System (4,5,6,7,8,9). Figure 10 illustrates the machine used as a generator is a wire-wound-rotor slip-rings induction machine (or a cascade induction machine if a contactless machine is desired without slip rings).

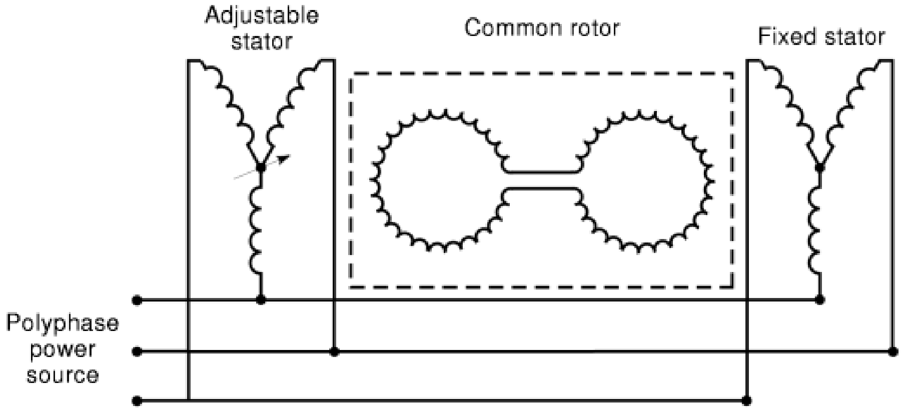

Fig. 11. Double-stator (cascade, isosynchronous) induction machine. The torque–speed characteristic can be varied by adjustment of the electrical angle $u_e = a(0 \leq a \leq 180^\circ)$ between the two stators.

As a generator, the output is connected to two different frequency supplies. One of them is the grid system, where power is fed from the machine, and the other is supplying slip power to the machine. Therefore, one port of the machine is used to deliver power, while the other is used to absorb power at positive slip (subsynchronous speed). The vector sum is obviously equal to the mechanical power supplied by the prime mover plus the losses.

At negative slip (supersychronous speed operation), both supplies absorb power from the machine (Fig. 10). If the machine is used as VSCF generator at subsynchronous and supersynchronous speeds, then a four-quadrant power converter should be used in order to supply and absorb power in both directions. Since two different frequencies are involved, the machine is operating in the synchronous mode at speeds which consist of the sum or difference of these input frequencies. Therefore, similar to any synchronous machine, a governor (mechanical or electrical) is needed to control the turbine speed in order to be connected to the grid. It is worth mentioning that the connection to the grid is more complex in this case, since the converter frequency, voltage, and phase should be measured and adapted (equalized) to the rotor frequency, voltage, and phase for minimum current at the appropriate synchronized speed before connection. The advantage of this installation is that the converter will be responsible for the slip power (around 50%) only, in contrast to the squirrel cage induction machine with converter (Fig. 9) where the converter was responsible for all of the power. The disadvantage is stability problems (since two frequencies are involved). The reactive power is not better than an ordinary induction machine.

In this case $u_e = \theta$, which is the triggering angle of the inverter. Figure 10 shows a family of curves for different values of θ.

In asynchronous mode, variable resistors are connected to the rotor port in order to control its variable-torque, variable-frequency characteristic in narrow range similar to the isosynchronous machine.

The Double-Stator (Cascade or Isosynchronous) Induction Machine. The turbine mechanical power is equal to the torque multiplied by speed (see Fig. 11). Variable-speed, constant-frequency generators are therefore matching the turbine power to the load power on the generator. In the same way, matching turbine power to the load can be carried out with variable-torque, constant-speed generators. The cascade induction machine characteristic is similar to the wire-wound-rotor induction machine characteristic which is controlled by variable resistors in its rotor's ports.

Therefore, this machine is also an induction type with controllable characteristics in motoring and generating region (13,14). It can be used as a variable-speed motor as well as a variable-speed generator in narrow range at negative slip. Therefore, it can be also classified in the variable-torque, constant-frequency family. The machine consists of two polyphase (or single-phase) wire-wound rotors machines with their rotors windings connected in cascade. One stator winding is fixed and the other can be manually or automatically adjusted to match the mechanical power to the electrical power when used as a generator or as a motor. The machine itself is self-protecting, and no current limiting device is needed. It can be coupled directly to the power grid and to the prime mover without an interface network or a governor.

In application as a generator, the machine is connected directly to the grid and to the prime mover through an appropriate gear ratio, which is designed according to the optimal output of electrical power to the grid, which corresponds to an almost constant speed (variable speed in narrow range). This speed is equivalent to the ordinary squirrel cage machine optimal speed in the generator mode (for negative slip) and is independent of the angles between the two stators. However, the torque is a function of the angle between the stators, and it is zero for zero and maximum for an electrical angle of 180 degrees. Therefore, in this case $u_e = \alpha$, the angle between the two stators.

This machine is equivalent to an ordinary induction machine with an ideal variable transformer turn ratio (Variac) introduced between the machine and grid ($u_e =$ turns ratio). Simulation of the machine can be made easily in the laboratory using a Variac and an ordinary induction machine. In practice, this arrangement is not practical. As stated before, it is also equivalent to a wire-wound-rotor induction machine controlled by variable resistors at its rotor ports.

As the turbine power changes due to changes in the flow rate, the generator angle needs to be varied in such a way that the power fed to the grid is maximum. This will correspond to optimal power output from the turbine. The adjustable stator is normally geared to a single-phase ac servomotor which permits manual adjustment as well as automatic closed-loop adjustment with the aid of a computer. The two machine systems can also be designed as a single-unit machine with a special-shaped squirrel cage rotor, but with two, or a single winding of two, different poles pairs in order to avoid the coupling between the two ports (4). In an asynchronous mode, one stator is connected to the grid while the other is connected to variable resistances which control its characteristic, as in the case with a wire-wound-rotor induction machine.

An example is the 15 kVA hydro-plant which incorporates a double-stator induction generator (Fig. 12). This plant was commissioned in 1985 by the author in an abandoned water mill site (Liffey Mills), Nenagh, County Tipperary, Ireland, as a demonstration small-scale hydro-plant. Found on the site was an old nonadjustable gate, “horizontal Francis turbine” in relatively good condition, and therefore it was used for this project without any civil work investment. All the required safety devices were installed and approved by the power authority. The feature of the installation is as follows: As the turbine power changes due to changes in the flow rate, the generator angle (angle between the two stators—a control variable) is varied by a microprocessor in such a way that the power fed to the grid is maximum. This will correspond to optimal output power operation of the Francis turbine used to drive the generator. The adjustable stator is geared to a single-phase ac servomotor which permits manual adjustment as well as automatic adjustment with the aid of a microprocessor control circuit. The microprocessor measures the output power from time to time and adjusts the servomotor for maximum output power. For the rest of the time, the microprocessor is used for monitoring purposes such as in the case of electrical or mechanical power failure, and it will adjust the angle between the stators to zero for protection. This cannot be done immediately due to power failure, but it is done after the power is again restored and before the machines are connected back to the grid. In this manner, minimum grid current is assured which is equal to the magnetization current of the iron only before the rotation is again restored. When this happens, the microprocessor adjusts smoothly the angle between the stators and increases its speed as it works as a motor to drive the turbine up to the synchronous speed where the latter in turn takes over for the negative slip. The torque–speed characteristic of the generator is shown in Fig. 13, the mechanical power is shown in Fig. 14, and the electrical power is fed to the grid in Fig. 15.

The effect of adjustment of the angles between the two stators is clearly indicated in Fig. 15. This effect is similar to the adjustment of variable resistances in the rotor ports of a wire-wound-rotor induction machine.

It is worth mentioning that this site cannot justify hydro-installations other than the present one, due to uncontrollable turbine, water level fluctuation, and relatively low output power.

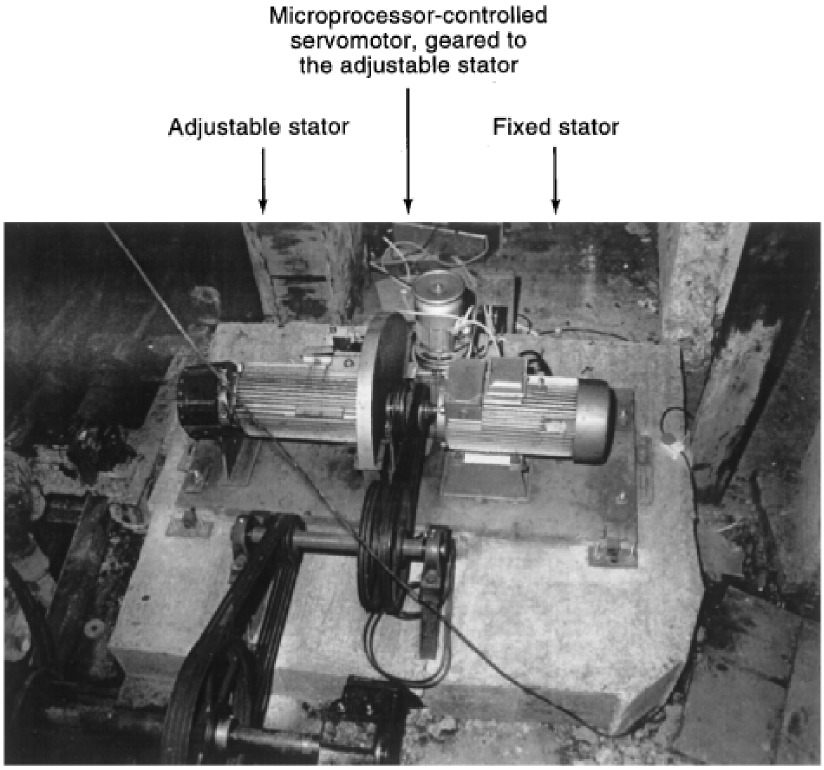

Fig. 12. A 15 kVA double-stator induction machine in Liffey Mills, Nenagh, County Tipperary, Ireland. The system provides optimal output turbine power at constant frequency from a variable torque.

The Programmed Pole Machine (Roesel Generator). The machine in Fig. 16 is basically a synchronous machine with a continuous variation of the number of poles to match the rotor speed, and therefore it is a "synchronous machine" at wide range of speeds. This machine is very flexible and has the advantages of the standard synchronous machine as well as the induction machine. The salient advantage of the machine becomes obvious when it is used as a self-excited alternator or as a VSCF generator to feed power to the grid from any prime mover such as in hydro-, wind, or sea wave turbines without any interface, synchronization network, or governor (15,19). The machine can be constructed as a single-phase or polyphase unit. The rotor is made from a layer of hard magnetic material with a rectangular hysteretic loop (typically barium ferrite or ceramic) with no windings and therefore has no slip rings or commutators.

The basic operation of the machine can be summarized as follows: The output frequency of any synchronous machine is given by the angular speed divided by the number of pole pairs. (All conventional synchronous electrical machines have an even number of poles determined by physical windings.) This means that the output frequency varies with rotational speed. The Roesel generator is different in that the number of poles can be varied continuously; and when varied in inverse proportion to the speed, the output frequency is maintained at a constant value.

The variation of the number of poles is achieved with the aid of an excitation coil wrapped around an exciter head inside the stator, in addition to the usual output windings. Therefore, the shape of the stator is different from that of an ordinary machine, and it is noncylindrical. The mutual inductance between the

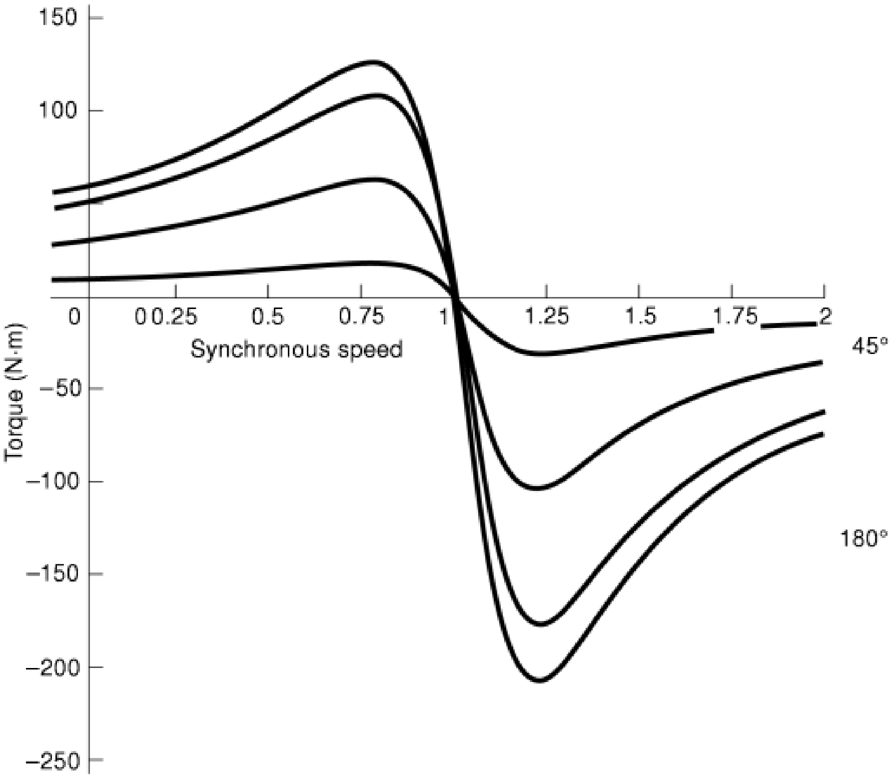

Fig. 13. Torque–speed characteristic of the cascade machine. The figure is important for determining the operating point and stability of the system.

excitation coil and the output winding is practically equal to zero in order to prevent direct power feeding from the exciter to the output windings. In this way, the two coils are practically decoupled from each other.

A reference frequency (or line frequency) is applied to the excitation coil and magnetizes a pole on the rotor as it turns. This is called “writing” a pole. The pole then induces a voltage in the stator windings at the same frequency. The output frequency then has the same value as the input frequency, independent of shaft speed at steady state (zero acceleration). As rotor speed decreases, the length of the poles shorten, so more of them are written around the circumference of the rotor. As rotor speed increases, the circumferential length of the poles increases and fewer of them are written around the circumference of the rotor. On one extreme, there will be an even-pole synchronous speed where an even number of equal-length poles are spaced uniformly around the rotor. At the other extreme, there will be an odd-pole synchronous speed, where an odd number of equal-length poles are equally spaced around the rotor. Between these extremes there will be fractional poles in the vicinity of the exciter head as poles are being partially rewritten. At the even-pole synchronous speed, the poles remain in the same position from one revolution to the next, so no rewriting of poles actually takes place. There will be no rotor hysteresis loss in this case, since the rotor iron magnetization does not change with time. At the odd-pole synchronous speed, however, every positive pole is being exactly replaced with a negative pole during each revolution, so rotor hysteresis losses will be maximum at this speed. This loss can be minimized with the proper exciter shape design. For stand-alone power generation, the output voltage can be controlled by regulating the exciter head current. For this case $u_\varepsilon =$ exciter current. Figure 17 shows the open circuit output voltage as a function of speed at constant exciter current. The stator in this case was compensated at lower

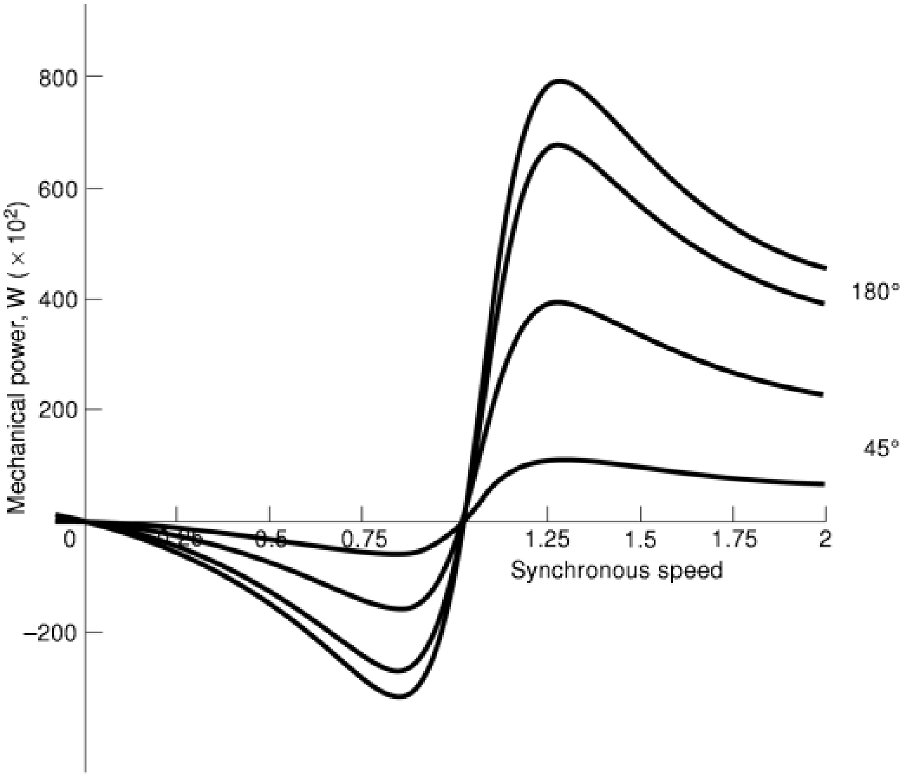

Fig. 14. Mechanical power–speed characteristic of the cascade machine. The figure is useful for determining the mechanical output power from the turbine.

speed. For application of parallel to the grid power production, an additional control facility of the machine characteristic is available. By controlling the electrical phase angle between the exciter head current and the output winding voltage, the machine characteristic can be controlled over a wide range.

The study of the machine characteristics for application in wind energy power generation was sponsored by the European Union “Joule” Programme during 1989–1992. A prototype of the machine was developed by the author for that purpose.

Speed Against Size

For any generator, irrespective of whether it is CSCF or VSCF, the output power per unit volume of the machine is proportional to the square of the flux density and the machine speed. This flux density is constant for a given lamination material. Therefore, in order to reduce the machine size, the operating speed should be as high as possible or even above synchronous speed. For that reason, a gear ratio is always needed for low-speed turbines even if in principle a machine can produce power at low speed. The nominal operating speed of the generator should therefore be a compromise between the turbine speed and generator size. A gear ratio of 1:7 is normally acceptable in small installations and can be used as a guideline. For example, when coupling a 150 rev/min Francis turbine to a three-pole-pair induction generator at 5% slip, the generator will run at 1050 rev/min.

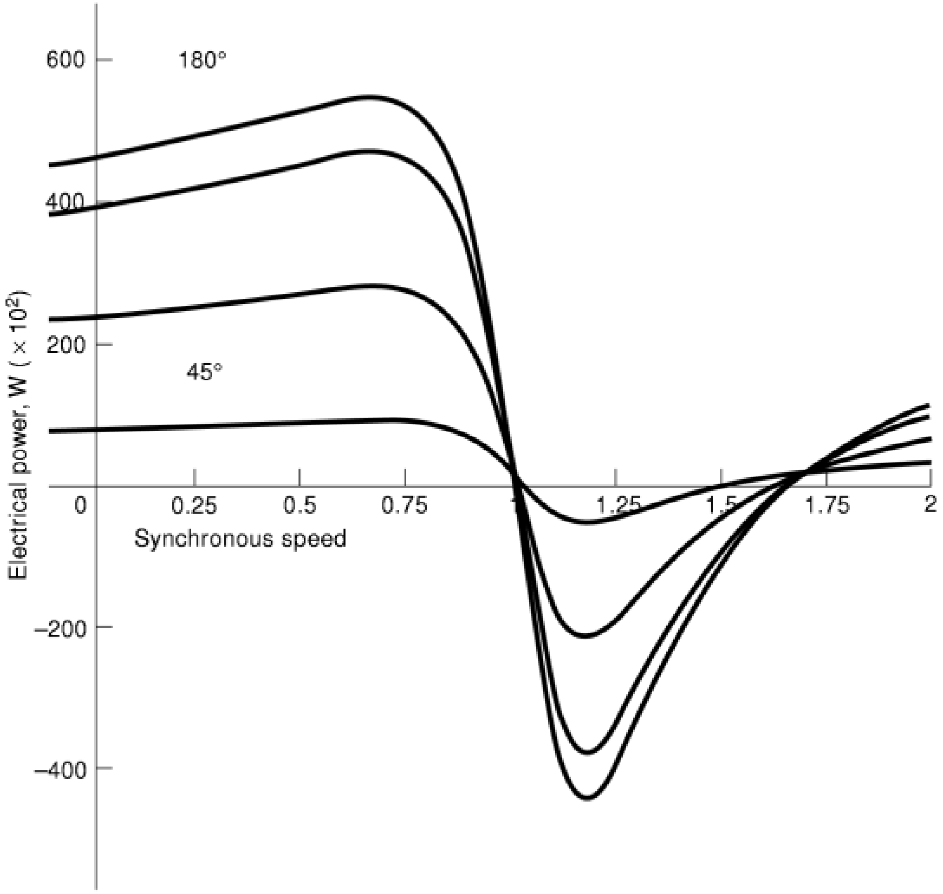

Fig. 15. Electrical power–speed characteristic of the cascade machine. The figure is useful for determining the optimal electrical power output from the generator.

In very large hydro-power stations such as on the Niagara River in Ontario and James Bay in Quebec, a 1:1 gear ratio is used in order to reduce maintenance and increase system reliability on account of size. A typical 76,475 kW, 13,800 V, 95% power factor synchronous generator on the Niagara River with a head of 292 ft, running at 150 rev/min, is designed with 24 pole pairs in order to produce 60 Hz output frequency.

The size of this generator would be much smaller with a better power factor if it was designed with many fewer pole pairs.

It is worth mentioning that the power of a VSCF generator can never be constant but proportional to its speed. For the CSCF generator, its power also can never be constant but proportional to its torque or square of the flux density. Therefore for both cases, the optimal generator size is dictated by its maximum operating power.

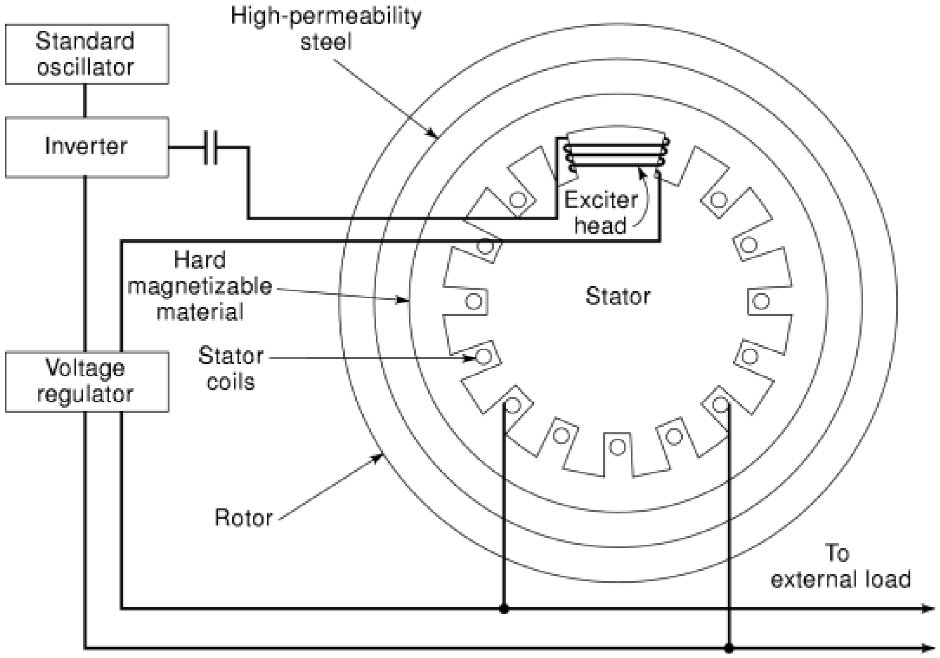

Fig. 16. Programmed pole (Roesel) machine. The torque–speed characteristic can be varied by adjustment of the electrical angle $u_e = \mu_0$ between the writing head (exciter) current and the grid (output) voltage in parallel grid connection. At stand-alone operation, the machine produces constant output frequency from a variable speed prime mover.

Stand-Alone Generators (25)

Ideal stand-alone generators are almost-constant power machines with a decreasing torque–speed characteristic for a given output voltage and load. This is true for all types of generators (dc or ac), including induction generators. Prime movers which are not regulated are generally unstable with stand-alone operation. However, any practical generator can offer an increased torque–speed characteristic due to its losses. This characteristic is stable for electric power generation from most prime movers. A stand-alone system using a squirrel cage induction generator was developed by the University of Toronto (22) where excess power generated due to load or speed variation was dampened using variable resistance heating elements. In this way, constant output voltage at constant frequency was achieved by variable-speed operation.

Protection

A hydro-plant, independent of size, must have minimal protection devices by law. This is of particular importance if the plant is operating parallel with the power authority system. Before a license is granted, the following protection devices should be installed and approved by the power authority:

(1) Over and under voltage relay
(2) Over and under frequency relay
(3) Over current relay
(4) Single (or more)-phase failure and ground fault relay

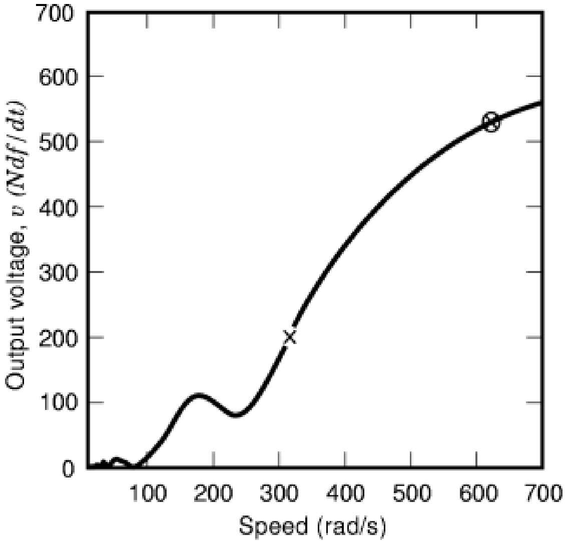

Fig. 17. Open circuit output voltage of the programmed pole generator compensated at lower speed. The frequency of this voltage is constant and equal to the exciter head frequency. The voltage shown is for constant exciter current, which can be regulated by variation of the exciter head current.

(5) Over and under speed protection (trip for faults on hydro-feeder)
(6) Fuses
(7) Reverse power relay

Extra optional protection devices are

(1) Phase balance relay
(2) Phase sequence relay

All installations should prevent islanding. For synchronous generators, additional safety devices are required as follows:

(1) Devices which provide a dedicated synchronizing and fault interrupting circuit breaker for each unit
(2) A synchro-check relay or autosynchronizing on each synchronous unit

A power factor correction, normally below 90% to 95%, is required. However, the connection of capacitors in parallel with the generator need special approval from the power authority, and in any case it should be switched off together with the generator when the latter is disconnected for any reason.

Voltage flicker or other voltage problems on the grid should be avoided. This can happen in synchronous generators, and therefore it should include special control of the excitation system and loading/unloading ramps rate.

For connection to the grid system at voltages above 50 kV, special isolating arrangements should be made with the power authority. If a frequency converter is used, then a facility should be designed to prevent objectional harmonics or voltage distortion on the grid system or on other customers' electrical or communication equipment.

For induction machines operating in parallel with the grid, voltage and frequency protection are still necessary since in case of grid failure the induction generator may resonate (become self excited) with the grid impedance and produce different voltages at different frequencies (possibly also harmonics).

Cost

It is evident that the cost of computers and electronic systems is progressively declining in terms of real and constant dollars. However, the cost of mechanical systems is rising. Therefore, it is clear that the most economical system will be the less mechanically complicated one, disregarding its electronic complexity, such as the cost of closed-loop real-time optimization. The cost of power electronics processing systems such as solid-state converters and inverters is also declining, which leaves the market highly competitive. Therefore, for the present and near future, the induction generator driven by a four-quadrant converter as a VSCF optimal system looks to be the most reliable and economically sound relative to other options.

In the intermediate future, it is possible that the Roesel generator will also be competitive in the market when more research and development has taken place.

The synchronous machine will continue to dominate the large power stations. However, many of these machines will be replaced with induction machines.

Conclusion

Many run-of-river sites which were considered nonrelevant in the past can be considered relevant today due to availability of new types of generators and solid-state power processing systems. These allow the plant to operate from a low-variable head at variable speed in order to produce constant frequency output at optimal power efficiency. Constant speed and constant frequency optimization are used by large hydro-plants which are able to maintain a constant head by switching turbines or by adjusting of the flow entrance to the turbine. In the latter, the load on the turbine is varied according to the flow in order to keep the speed constant.

In plants using closed-loop installation, a sensor may be used to measure the output power and adjust an independent control variable in the electrical system in such a way that this power is always maximum.

There are minimum safety procedures required by law on the operation of a hydro-plant—in particular, when it is connected to the grid.

List of Symbols

E	Voltage (V)
f	Grid frequency (Hz)
H	Head (m)
$I, I(E, Z, f, w, u_e)$	Current (A)
J	Inertia of the rotating parts ($\mathrm{kg} \cdot \mathrm{m}^2$)
K	Friction constant ($\mathrm{Nm} \cdot \mathrm{s}$)
Q	Flow rate (m^3/s)
$T_g, T_g(E, I, w)$	Electromechanical torque of the generator ($\mathrm{N} \cdot \mathrm{m}$)
$T_t, T_t(Q, H, w, \Theta)$	Torque of a turbine ($\mathrm{N} \cdot \mathrm{m}$)

u_{e}	An independent electrical control variable. A vector in general.
u_{m}	An independent mechanical control variable. A vector in general.
Z	Grid and machine impedance (Ω)
α	Electrical angle between two stators (rad)
δ	Small variation
μ_0	Electrical angle (rad)
Θ	Blade sitting angle (rad)
θ	Electrical angle of triggering (rad)
w	Speed (rad/s)
w_{s}	Synchronous speed (rad/s)
w_0	Equilibrium speed (rad/s)

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