ASYNCHRONIZED MACHINES FOR THE ELECTRIC POWER INDUSTRY

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Synchronous generators are traditionally used in the electric power industry. Asynchronized machines are a new class of electrical machine valve systems that have a series of advantages over conventional synchronous machines. Asynchronized machines have been widely used in thermal and hydro power stations, wind power plants, and networks as reactive power compensation units.

Keywords: asynchronized machine; doubly fed machine; turbine generator; hydrogenerator; synchronous condenser; energy storage.

Asynchronized turbine generator T3FAU-160-2U3 with 160 MW capacity at unit 11 of CHP-21 by Mosenergo

GENERAL PROVISIONS. DESIGN, EXCITATION, CONTROL

In the 1950s, on the initiative of and under academic supervision of M.M. BOTVINNIK, D.Eng.Sc., development and practical application of asynchronized machines (ASMs) in the power industry became a focus of special efforts in the USSR. Headed by VNIIE (presently JSC R&D Center at FGC UES), the activities were conducted at a number of scientific and design institutes and factories [1,2].

Later, approximately in the early 1980s, design, development and operation of ASMs were carried out by the world's leading companies: Mitsubishi, Toshiba, Hitachi, ABB, Alstom, Siemens, and others. In western literature, these machines are known as double fed asynchronous machines.

An ASM, in contrast with a synchronous machine, contains not one but two or three excitation windings on the solid rotor that are arranged at an arbitrary angle to each other and whose magnetizing force may be different. The excitation windings are fed from reversible rectifiers, i.e., frequency converters built from power electronic hardware components. The structural diagram of an ASM is shown in Fig.1.

With a rotor speed of 3000 rpm and 1500 rpm, the ASM is built with an unlaminated rotor, while a laminated rotor is used for a speed of 1000 rpm or lower.

An ASM with an unlaminated rotor is operated in a steady-state condition with synchronous speed (slip s=0), since with nonsynchronous speed the rotor's solid block losses would increase substantially.

ASM STRUCTURAL DIAGRAM

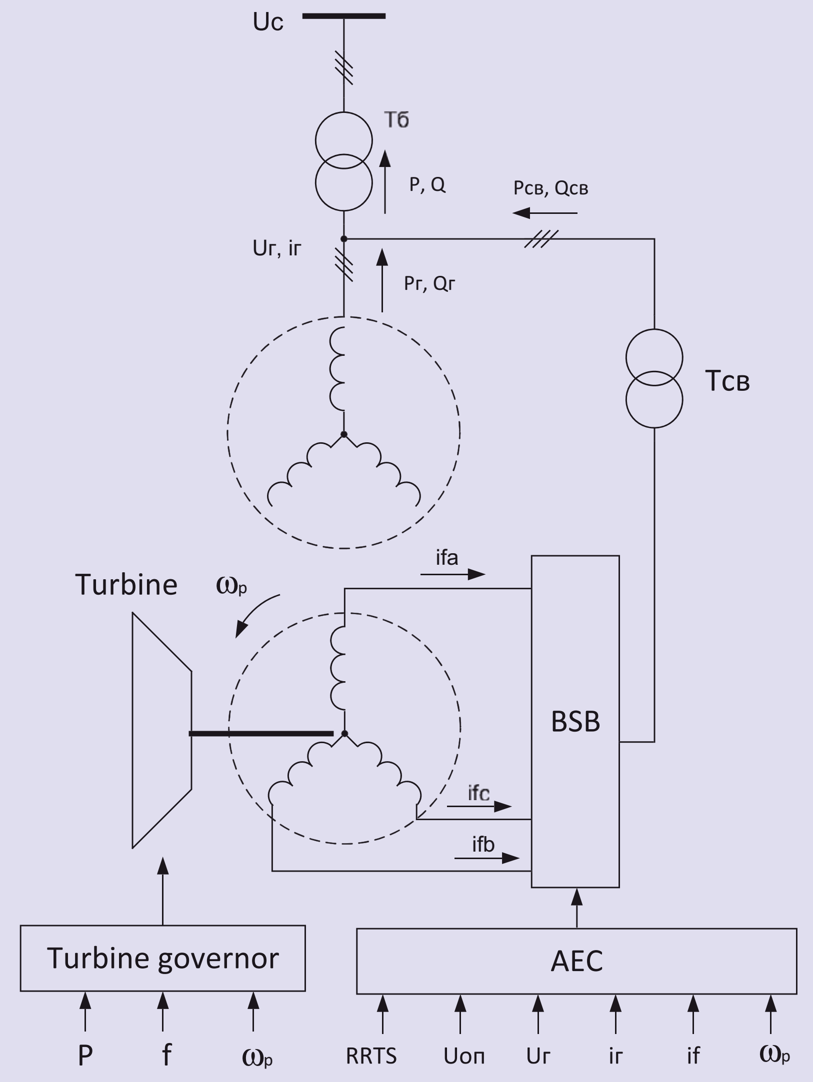

Fig. 1

An ASM with a laminated rotor can operate in a wide range of rotor speed settings. Fig. 2 shows a possible classification of ASMs.

ASMs utilize the so-called vector excitation control principle[1] where the following duty parameters are controlled separately and independently of each other: active power or electromagnetic torque and reactive power or machine voltage. The excitation voltage output frequency of an ASM (ω_f) is formed as the difference between the mains frequency (ω_c) and the rotor speed (ω):

$$\omega_f = \omega_c - \omega = s\omega_c,$$

where $s=(\omega_c-\omega)/\omega_c$ is slip of machine.

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[1] In some publications this control principle is called an asynchronized control principle [3]

If the rotor speed and the mains frequency are identical, the output frequency of the excitation system converters is zero, and the rotor rotates with synchronous speed. At $\omega_c \neq \omega$ the machine's rotor rotates with non-synchronous speed, while the frequency of stator currents and voltages remains unchanged and equal to the mains frequency. This means that in an ASM the rotor speed and the mains voltage frequency are "unlinked" from one another, which determines a series of advantages of ASMs over synchronous and asynchronous machines.

Fig. 3 shows a vector diagram of ASM operation through reactance (x) to infinite buses (U).

Active power (electromagnetic torque) and reactive power of an ASM that has two excitation windings correspond to:

$$P = M \cdot \omega_c = \frac{UE_q}{x}\sin\delta - \frac{UE_d}{x}\mathrm{cc}$$

$$Q = -\frac{U^2}{x} + \frac{UE_q}{x}\cos\delta - \frac{UE_d}{x}\sin\delta \qquad (1)$$

Emfs $E_q = x_a \cdot i_{fd}$ and $E_d = x_a \cdot i_{fq}$ are induced in the ASM stator by excitation currents i_{fd} and i_{fq}.

Currents i_{fd} and i_{fq}:

$I_{fd} = \alpha \sin\delta + \beta \cos\delta;$

$I_{fq} = \beta \sin\delta - \alpha \cos\delta.$ (2)

Substituting (2) in (1), after rather simple transformations, the following is derived:

$$M \cdot \omega_c = P = \frac{U \cdot x_a}{x}\alpha$$

$$Q = -\frac{U^2}{x} + \frac{U \cdot x_a}{x}\beta \qquad (3)$$

By changing α and β as necessary, independent and separate control of active and reactive power of the ASM is achieved. The vector diagram in Fig. 3 implies that $x_a \cdot \alpha = E_y$, $x_a \cdot \beta = E_x$, where E_y and E_x are projections of vector E onto the coordinate axes that rotate synchronously with the power bus vector (U).

If the value of is

$\alpha = \alpha_0 - \alpha_1 \cdot \Delta s,$ (4)

where Δs is deviation from the steady-state slip value s_0, then from the equation of motion we get

$$T_j \frac{d\Delta s}{dt} + \alpha_1 \frac{U \cdot x_a}{x}\Delta s = 0 \qquad (5)$$

The static stability condition according to the result obtained is written as:

$\alpha_1 > 0$ (6)

Hence, it can be seen that the static stability of an ASM is independent of the machine's duty parameters and is ensured at any possible values of active and reactive power of the machine. This means that it is possible to ensure stable operation of an ASM at any values of reactive power, from output to consumption. The operating areas of an ASM are limited only by the nominal stator and excitation currents (Fig. 4).

CLASSIFICATION OF ASYNCHRONIZED MACHINES (ASMS)

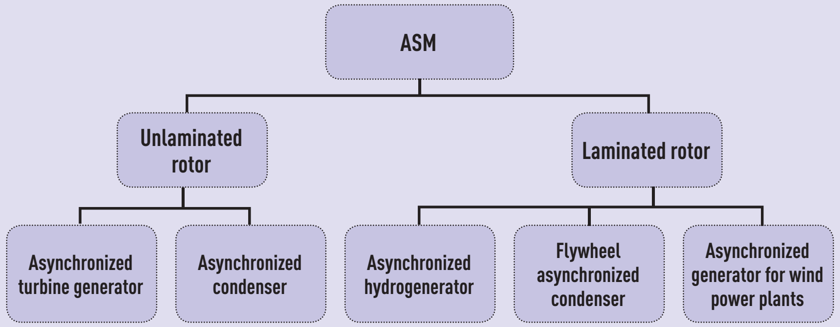
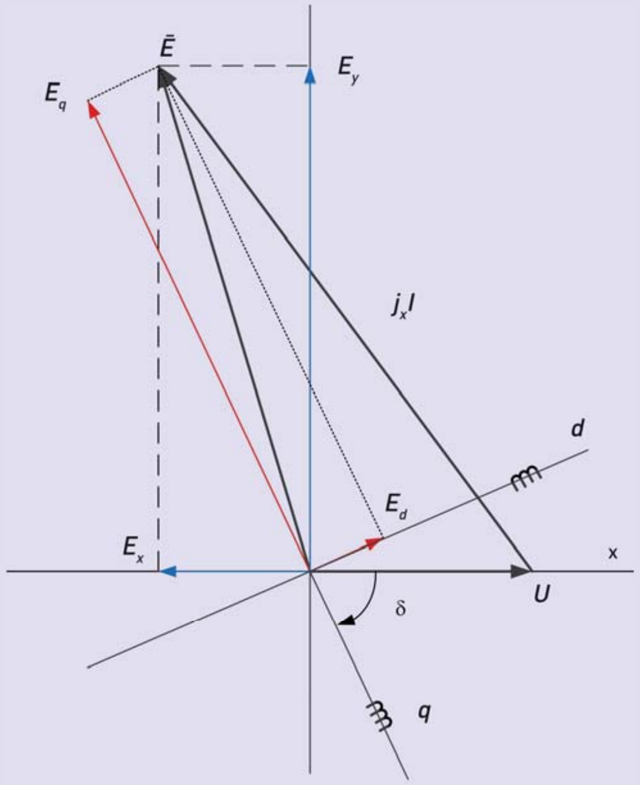


Fig. 2

ASM VECTOR DIAGRAM



E is ASM emf vector;
E_y, *E_x* are projections of vector E to "synchronous" axes *xy*;
U is power system voltage vector (reference vector);
E_q, *E_d* are projections of vector *E* to rotor winding axes.

Fig. 3

PERMISSIBLE DUTY AREAS OF ASYNCHRONIZED TURBINE GENERATORS (ASTG) AND HYDROGENERATORS (ASHG) COMPARED WITH SYNCHRONOUS TURBINE GENERATORS (STG) AND HYDROGENERATORS (SHG)

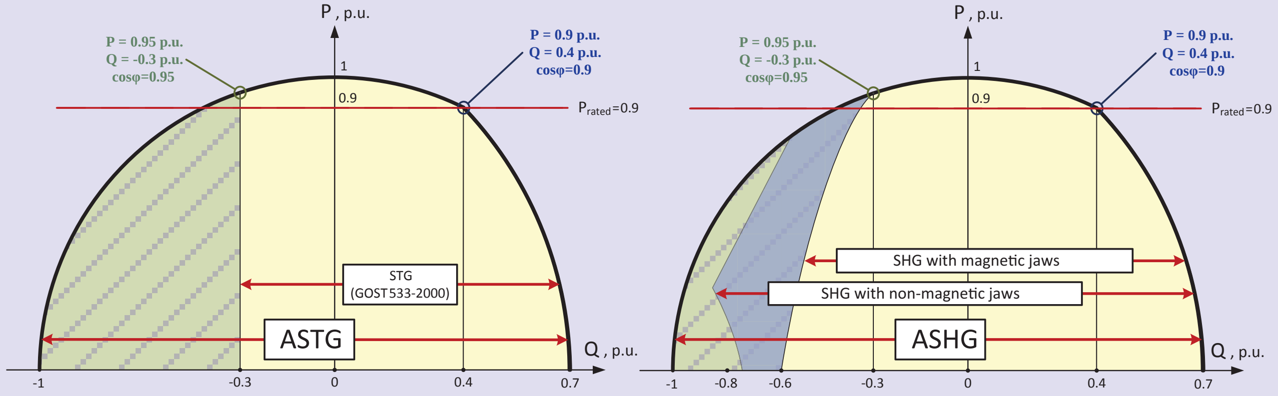


Fig. 4

BLOCK DIAGRAM OF ASM CONTROL

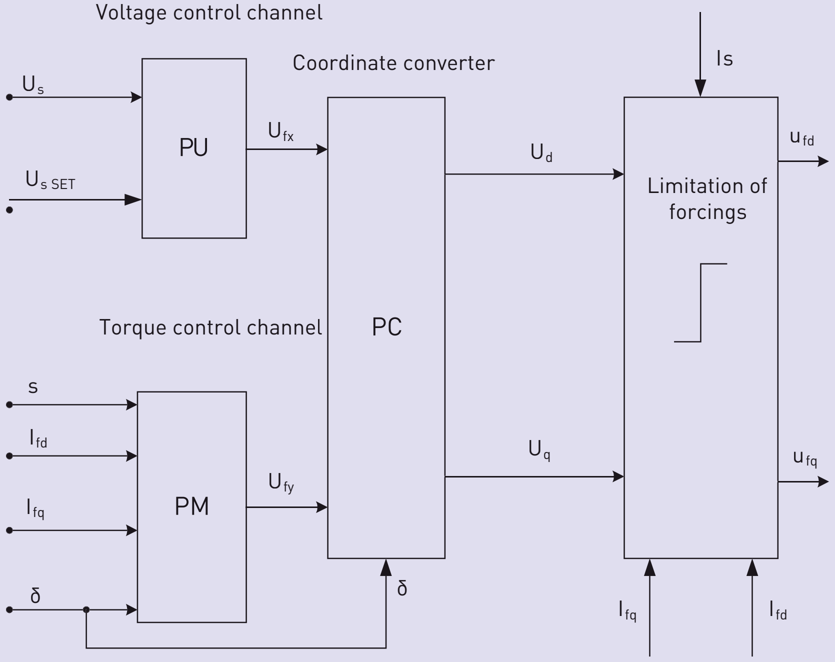


Fig. 5

DEFINITIONS

Energy system stability area — the range of energy system operating parameters for which stability is guaranteed under disturbances.

Static stability of a power system is the power system's ability to return to the set mode after minor disturbances. Note: a minor disturbance is understood as a condition in which parameter fluctuations are incommensurately small compared to the values of these parameters.

Energy system static stability reserve — an indicator characterizing static stability of the energy system operating mode compared to extreme stability threshold.

Dynamic stability of a power system is the power system's ability to return to the set mode after major disturbances without going into asynchronous mode. Note: a major disturbance is understood as a condition in which parameter fluctuations are commensurate with the value of these parameters.

Asynchronous mode is a transitional operation mode of a power system, which is characterized by stable deep periodic fluctuations of the voltage, current and power, periodic changes in the EMF angle of power station generators, and a difference between frequencies in parts of synchronous zone while preserving electrical connection between them.

Disturbances in a power system are unintended changes in the operating conditions of an electric power system caused by short circuit, failure or disconnection of individual elements, etc., resulting in transition processes at power stations, in electrical grids and at consumer equipment.

A common structural diagram of ASM vector control is shown in Fig. 5.

Vector control has a positive effect on the limits of dynamic stability. For example, in case of a short circuit in the network, it is possible, in principle, by acting on the angular position of emf E or E', to turn the emf to the side opposite to the rotation of the rotor. This action depends, inter alia, on the degree of voltage forcing by ASM excitation, initial duty cycle, etc.

ASYNCHRONIZED MACHINES WITH UNLAMINATED ROTOR

TURBINE GENERATORS

As stated before, since turbine generators have an unlaminated rotor, operation in steady-state conditions with a slip would be disadvantageous because high rotor losses would occur. Therefore, in steady-state conditions, ASTGs are operated with synchronous speed. In addition, the electromagnetic moment and voltage are independently controlled in accordance with the control system described above.

It is a known fact that with synchronous turbine generators (STG) in under-excitation modes a lowest excitation limit (LEL) is introduced due to intense heating of the stator ends and a considerable reduction in static and dynamic stability margins.

For asynchronized turbine generators, the diagram of permissible duties in its left-hand section is limited only by the rated stator current. As can be seen from Fig. 3, asynchronized turbine generators have by far greater controlling capabilities in terms of reactive power consumption in comparison with synchronous turbine generators.

The technical and economic effects of utilization of asynchronized turbine generators are as follows:

1. No need for additional reactive power compensation devices (reactors) on station buses installed to prevent synchronous turbine generators from operating in reactive power consumption modes.
2. Improved reactive power duty cycles of synchronous turbine generators in a power station that operate in parallel with the ASTG by avoiding the modes that are unfavorable for the STG with reactive power consumption (or close to that).
3. More reliable operation of generating equipment in general.

As for the functional reliability of an ASTG itself, from the formal standpoint, its reliability should be lower due to a greater number of components that could fail (two excitation windings, two reversible thyristor converters, etc.). However, considering the ability to remain operable with limited functionality, an ASTG will offer unquestionable advantages.

First, in the event of failures in one of the thyristor converters it is possible to work with one excitation winding. In this case, the generator becomes a conventional synchronous generator. However, an ASTG is not disconnected from the network but remains in operation. Once the fault is rectified, on command from an operator the generator will again be switched to asynchronized mode with excitation by two windings.

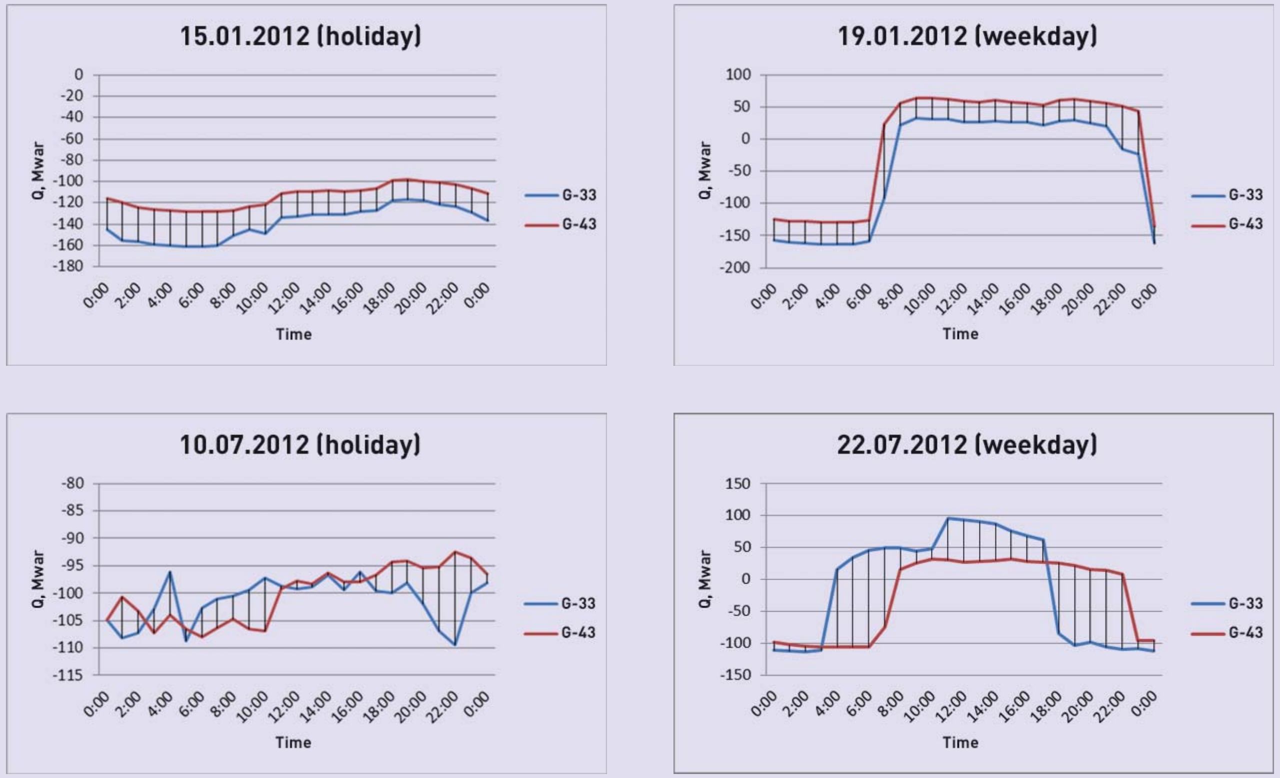
Second, an ASTG can operate for an indefinitely long time without excitation. Operation of synchronous generators in case of excitation loss is limited by the time (max 30 minutes) and active power (max 60% of the nominal value), after which the generator will be disconnected from the network. In most practical cases, the wide area protection is designed in such a manner as to disconnect the generator from the network immediately. Due to electromagnetic asymmetry of a synchronous generator's rotor in asynchronous mode, considerable variations of voltage, current, and electromagnetic torque would occur. In an asynchronous turbine generator, the rotor is electromagnetically symmetrical; the generator's cycle parameters are stable during operation without excitation. An ASTG in these modes can run continuously with active power up to 75–80% of the rated one.

The advantages listed above have been much needed in the Mosenergo system. In 2002, to improve the controllability of modes in terms of maintaining the required voltage levels and controlling the reactive power flows, as well as to enhance the power system stability and reliability, JSC Mosenergo installed ASTGs in a number of power stations.

The first stage in the introduction of such machines consisted in the installation of Russia's first industrially operated ASTG at CHP-22 by JSC Mosenergo. In December of 2003, a prototype ASTG of the T3FA-110 2U3 type was put into trial operation at CHP-22, station unit No. 8, manufactured by JSC Power Machines — the Elektrosila plant.

The ASTG is operated both in reactive power output and consumption modes. In consumption modes, the generator is normally operated during night hours and round-the-clock on weekends. The average level of reactive power consumed is 30÷–40 MV·A under a lowered active load. Two challenges were addressed simultaneously: to maintain the required voltage on the station buses and to prevent unit 7 running in parallel with the synchronous turbine

THE DAILY SCHEDULES ON THE REACTIVE POWER OF ASYNCHRONIZED TURBOGENERATORS NO. 33 AND NO. 43 OF TPP-27 MOSENERGO FOR WINTER AND SUMMER DAYS


15.01.2012 (holiday)

19.01.2012 (weekday)

10.07.2012 (holiday)

22.07.2012 (weekday)

Fig. 6

AVERAGE REACTIVE POWER VALUES AND AVERAGE SERVICE HOURS OF OPERATION IN REACTIVE POWER OUTPUT AND CONSUMPTION MODES

Month	Station number	Q sign	$Q_{average}$, Mwar	Hours
January	33	+	14	161
		–	–128	580
	43	+	28	248
		–	–116	333
July	33	+	49	303
		–	–97	348
	43	+	–96	439
		–	36	336

Table 1

TECHNICAL CHARACTERISTICS ASC-100-4

Name of parameter	Value
Rated power, MV·A	100
Reactive power, Mvar	±100
Stator voltage, kV	20
Stator current, A	2,900
Rotor winding current:	
on axis d, A	2,200
on axis q, A	740
Speed, rpm	1,500
Total compensator losses, kW	1,500
Cooling	All-air

Table 2

generator from operating in reactive power consumption modes that are damaging.

The second stage of ASTG implementation consisted in the commissioning of additional three turbine generators in 2007 and 2008. Turbine generators T3FAU-160-2U3 with 160 MW capacity were installed in steam and gas units (CCGT) with a total unit capacity of 450 MW at CHP-27 (units 3 and 4) and CHP 21 (unit 11) (Fig. on p. 60) [4].

Table 1 lists average values of reactive power and average service hours for operation in reactive power output and consumption modes of asynchronized turbine generators T3FAU-160-2U3 at CHP-27 by Mosenergo (station No. 33 and 43). Fig. 6 shows daily reactive power trends for winter and summer periods.

In December of 2009, 320 MW asynchronized turbine generator T3FSU-320-2U3 was put into operation at unit 3 of the Kashira power plant. All generators were designed and manufactured by JSC Power Machines — the Elektrosila plant.

ASYNCHRONIZED REACTIVE POWER COMPENSATORS

One of the vital elements of modern electrical grids is reactive power compensators. They help not only maintain the voltage levels in network nodes but also reduce network losses by selecting the best operation mode.

Electric machine reactive power compensators, in contrast to static devices, can withstand short twofold overloads, which can only be achieved for static devices by doubling the installed capacity. Another important feature is stability to possible pulse overvoltages in the lines (e.g. due to lightnings). Electric machine compensators don't generate higher harmonics to the network.

JSC R&D Center at FGC UES jointly with JSC Power Machines — the Elektrosila plant designed, manufactured and commissioned asynchronized reactive power compensators of the ASK-100-4 type with 100 MVA capacity [5]. The experience with asynchronized turbine generators was taken into account during their design and manufacture.

With two excitation windings with an excitation system and vector control, such compensators have new features and advantages in comparison with conventional synchronous compensators with one excitation winding:

1. Wider reactive power control range between +100 Mwar and –100 Mwar (for conventional synchronous compensators it is between +100 Mwar and –40 Mwar).
2. Prompt reactive power/voltage control actions owing to the possibility of reversing currents in the excitation windings.
3. Improved damping of the duty parameter fluctuations in case of disturbances in the network.
4. Enhanced survivability owing to the possibility of standby operation in case of failures in the excitation system.

Two ASK-100-4 compensators were installed at the Beskudnikovo substation in Moscow. Basic technical data are given in Table 2.

ASYNCHRONIZED MACHINES WITH LAMINATED ROTOR

ASYNCHRONIZED HYDROGENERATORS

Given today's operating conditions of electrical grids, it is critical to maintain the high quality of power as well as the reliability and controllability of a power system. Basic power quality indicators are frequency, levels and harmonic contents of voltages in power system nodes.

The most flexible and, consequently, most suitable power plants for frequency and capacity control in a power system are hydro (HPP) and pumped storage (PSP) plants. The rate of active power control in this type of power stations is determined by the speed of opening/closing of the guide vanes, being up to 500 MW/min, and is limited by the water hammer triggering conditions, control apparatus parameters, and other hydrodynamic characteristics.

These advantages of HPP and SPS have led to their wide application in the power industry. However, there are a number of challenges associated with both the electrical and hydraulic part of a hydraulic unit with a synchronous generator:

- decrease in hydraulic turbine efficiency at variable heads (loss of generation);
- presence of forbidden zones (unsteady flow) in the operation of hydraulic turbines;
- limited active power control rate;
- limited voltage and reactive power control in wide ranges;
- insufficient margins of dynamic stability.

Let us consider the efficiency of ASHGs with some examples.

INCREASED POWER GENERATION

Operational characteristics of constant speed hydraulic units are expressly dependent on the duty parameters (head and power of the turbine), with a small optimal performance zone where the efficiency is the greatest.

In an example of the PL 20/661 turbine, with the unit's synchronous rotation speed n_c = 62.5 rpm, the optimal efficiency zone lies within the limits between 20 to 32 MW at a head of 11.5 m and 30 to 38 MW at a head of 15.5 m (Fig. 7).

ASHGs with variable rotation speed, owing to the control of the unit's rotation speed by the highest efficiency criterion, allow expanding the optimal performance zone substantially. In the case above, if a synchronous generator is replaced with an asynchronized one with a variable speed of the unit ($59 \leq n \leq 77.5$ rpm), the optimal zone will be between 18 to 30 MW at a head of 11.5 m and 42 to 66 MW at a head of 20 m (Fig. 8). Therefore, operation with maximum efficiency becomes possible across the whole operational range of heads.

FROM HISTORY

Specific features of conventional synchronous turbine generators, conditioned by their operating principle, do not allow to solve a number of problems in the function of electrical power systems — for example, to ensure the necessary degree of stability, reliability and economy of systems operated in normal (steady-state) and transient (dynamic) conditions. The idea of creating better and improved generators as an alternative to synchronous turbine generators first emerged as far back as in the early 20th century in connection with development of collector cascades. But it was only in 1956 that the All-Union Electric Power Research Institute of the USSR, on an initiative of professor M.M. Botvinnik, began researching a new type of alternating current electric machines — asynchronized machines.

AVOIDANCE OF FORBIDDEN ZONES (UNSTEADY FLOWS)

A specific feature of propeller-type and mixed flow turbines, especially high-pressure turbines, is that at low loads such turbines have a range of cycles where operation is forbidden due to higher hydrodynamic stresses and vibrations caused by unstable flows (a forbidden zone). In Fig. 9 the forbidden zone is marked red. The respective limitation for a turbine running with partial capacities is specified by the equipment manufacturer on performance characteristic H_T–N_T.

By using variable speed units, it is possible to avoid the forbidden zone by transferring to a mode with the same turbine power lying outside the forbidden zone. Fig. 9 shows an example of avoidance of forbidden zones for the PR 20/811 propeller tur-

OPERATIONAL CHARACTERISTIC OF THE PL 20/661 TURBINE AT THE UNIT'S SYNCHRONOUS SPEED OF N_C = 62.5 RPM

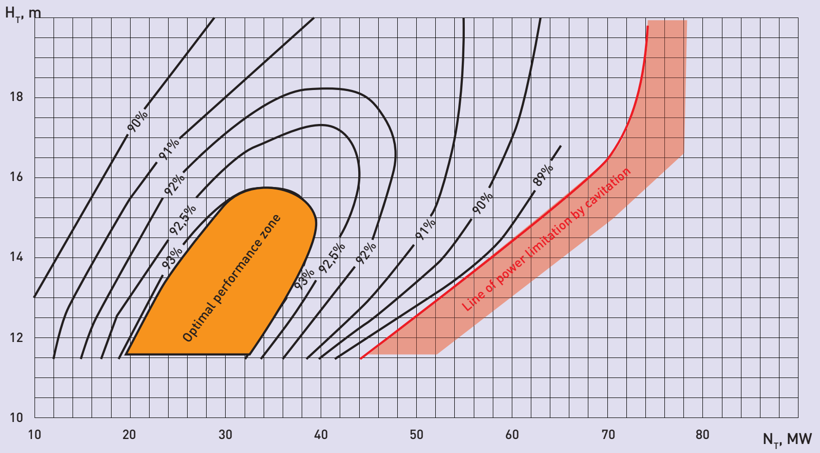


Fig. 7

bine with nominal speed $n = 37\ \text{min}^{-1}$. In order to avoid the forbidden zone at initial speed $n = 37\ \text{min}^{-1}$, it is necessary to increase the rotor speed by $\Delta n = 5\ \text{min}^{-1}$ at power NT = 11 MW and to decrease the rotor speed by $\Delta n = 5\ \text{min}^{-1}$ at power NT = 12 MW. The new mode points will lie outside the forbidden zone.

MOBILE ACTIVE POWER CONTROL

In a synchronous generator, the active power fed into the network can be changed only by controlling the turbine output. The rate of change of the electric active power is determined by the speed of control of the turbine's guide vanes.

In an ASHG, it is possible to control the active electric power independently of the mechanical power while varying the rotation speed within certain limits.

This allows virtually instantaneous control of the active power delivered/consumed in the network. With such control, the variation of active power of the machine's stator will substantially outstrip the variation of the mechanical power output of the turbine. The resulting imbalance between the electromagnetic and mechanical torques on the unit shaft will lead to braking/acceleration of the unit, and the power needed to accelerate the ASHG active electrical power control will be covered by changing the kinetic energy of the spinning masses of the rotor.

ENSURING DYNAMIC STABILITY

In order to compare the dynamic stability of synchronous and asynchronized hydrogenerators, benchmark calculations were made for generators of equal power in a generator — transformer — transmission line — infinite buses setup. Fig. 10 shows the trends of critical time of a 3-phase short-circuit on the station buses vs. reactive power.

It can be seen from the figure that the maximum short-circuit time for an SHG is about 0.2 sec, while for an ASHG it is 1 sec, since in a synchronous generator the rotor displacement angle increases as the short-circuit duration gets longer. The stability limit is reached when the ultimate angle is achieved at which the rotor cannot be slowed down. The displacement angle margin is decreased as the transfer to under-excitation modes progresses because the initial load angle is increased.

OPERATIONAL CHARACTERISTICS OF THE PL 20/661 TURBINE AT THE UNIT'S VARIABLE SPEED ($59 \leqslant N \leqslant 77.5$ RPM)

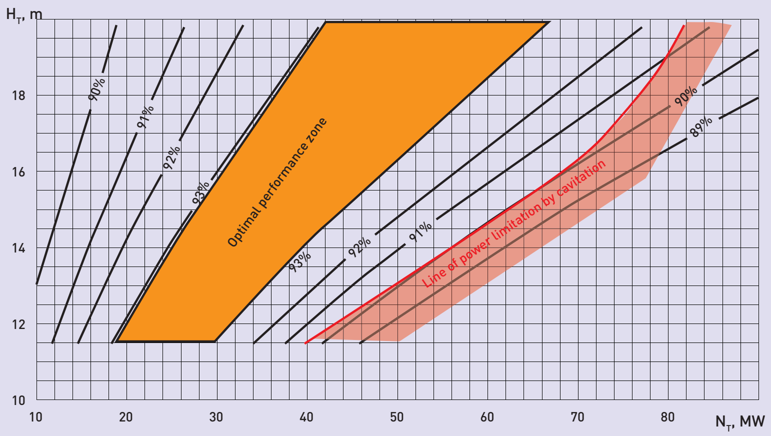


Fig. 8

AVOIDANCE OF THE FORBIDDEN ZONE FOR PROPELLER TURBINE PR-20/811 AT VARIABLE SPEED AND CONSTANT HEAD H = 6 M

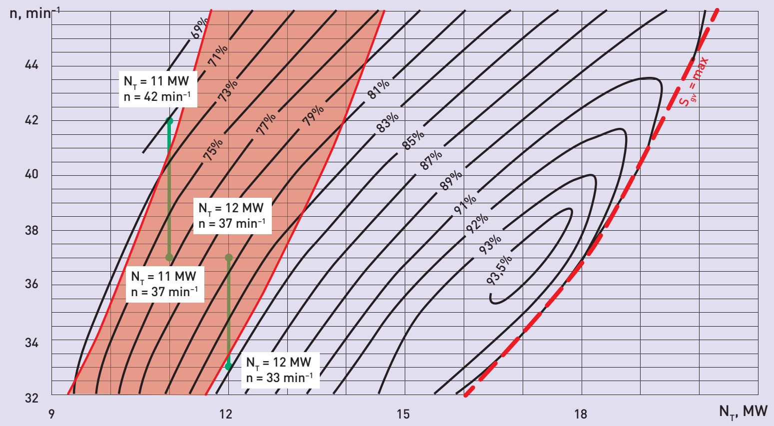


Fig. 9

CRITICAL SHORT-CIRCUIT TIMES FOR SHG AND ASHG

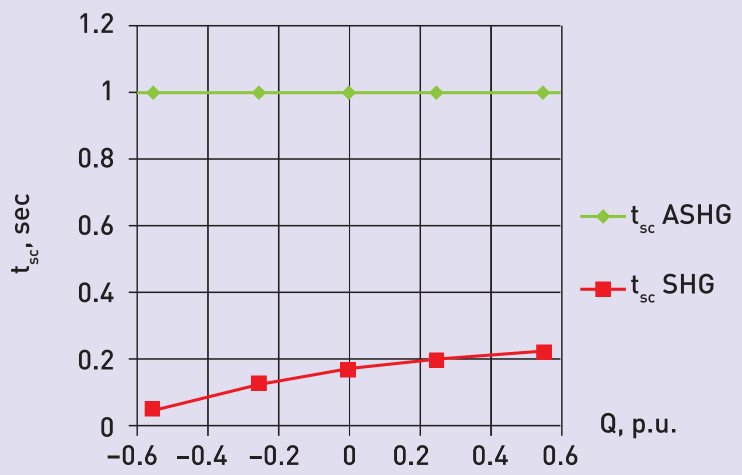


Fig. 10

In an ASHG, thanks to the possibility of prompt and independent active power control and variable rotor speed operation, the dynamic stability is maintained in the case of rated disturbances in the power system. Speed variation within the operating range during transients for an ASHG is not associated with loss of 'synchronism.' This explains the considerable margin of dynamic stability of an ASHG as compared with an SHG.

It must be noted that the world's first ASHGs with 40 MW capacity were designed and manufactured in the 1960s in the USSR at the Elektrosila plant. Presently, a 3 MW ASHG model with an excitation and control system has been manufactured and tested at JSC Power Machines — the Elektrosila plant, and a basic design has been drafted for a 200 MW ASHG.

In the past 20 years, a number of foreign companies manufactured and introduced over 20 ASHGs with unit sizes ranging from 80 MW to 420 MW.

FLYWHEEL ASYNCHRONIZED CONDENSERS

Asynchronized machines with a laminated rotor with a flywheel on the shaft can be used in the power industry as an electromechanical energy storage compensator.

Such a device is able, by varying the rotation speed and kinetic energy of spinning masses, to ensure the accumulation or generation of considerable energy. In addition, an FASC possesses all of ASC properties in respect of reactive power control.

Structurally, an FASC is designed as an electric machine with a symmetrical multiphase winding on a laminated rotor. The FASC rotor is connected to the network. Similarly to an ASHG, the installed capacity of the converter in the rotor winding circuit is proportional to the machine's full power (at the rated reactive and maximum permissible active power) and the rotation speed control range. A reasonable ratio of power of the machine and exciter is achieved with the slip range within ±10%.

> *Asynchronized generator is a term introduced into scientific practice by Mikhail BOTVINNIK, a Soviet scientist and chess player, in 1955*

For an FASC, a vertical structural design appears more preferable. In the conditions of ensuring the laminated rotor's strength, the synchronous speed of the rotor should be limited to 1500 rpm or lower.

An FASC can share active power with the network only briefly, within the change of kinetic energy of rotating parts with the speed varying in permissible limits. The peak active power can also be limited by the maximum current of the semiconductor exciter. As a first approximation, the maximum active power may be assumed equal to the rated reactive power.

An FASC, like any electric machine compensator, ensures balancing of reactive power and control of voltage. In addition, an FASC has a wider control range because it has no limitations in terms of stability in the reactive power consumption zone.

Additionally, an FASC improves the power system's stability and increases the capacity of transmission lines, stabilizing voltage not only by its magnitude but also by the phase, creating a 'rigid bus' effect. To enable this function, an FASC should have a power substantial for the power system (in Russian conditions, at a level of 100 to 160 MVA).

Besides the general functions of voltage control and stability improvement, FASCs can have specific applications, which are conditioned by prompt active power control and power sharing with the network in a given volume.

For instance, when installed at consumer substations with abrupt variations of active loads, FASCs are able not only to stabilize the voltage level but also to fully or partially absorb active load fluctuations.

When installed in a large power system hub, a FASC will considerably improve the quality of post-fault transients by creating the 'rigid bus' effect, as it maintains not only the magnitude but also the phase of voltage in the point of coupling, absorbs (inasmuch as possible) fault interruptions, and reduces the probability of escalation. In view of the above, it is also recommended to install FASCs at intermediate substations of long bulk power transmission lines. FASCs deployed in this manner will ensure islanding of transmission, containment and damping of fault interruptions, and higher reliability and capacity of the TL.

In off-grid power systems, an FASC may also be utilized for frequency control.

CONCLUSION

1. Asynchronized machines are a new class of electrical machine valve systems that have a series of advantages over conventional synchronous machines.
2. Asynchronized machines are widely used in the power industry. In Russia, these are asynchronized turbine generators and reactive power condensers. In other countries, those are asynchronized hydrogenerators and wind power plant generators.
3. There are a number of areas where asynchronized machines may also be found usable: electromechanical energy storages, electromechanical AC back-to-back stations between power systems, and an electrical drive based on asynchronized motors.

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