SELECTED PROBLEMS OF TURBOGENERATORS PROTECTION

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The report brings solutions for selected failure conditions of turbogenerators in power plants. From the point of view of the stability of the power system (PS), the loss of excitation and the following drop-out of these turbogenerators belong to significant failure conditions of turbogenerators of high unit power. The electric protections of turbogenerators play an important role in systematic failure elimination [2], [14]. A complex solution of the protecting system of the most important devices of power plants (turbine, alternator, block transformer) taking into account various operation states faces a problem of dealing with the protection system at forbidden frequencies [9]. The frequency or angular velocity is one of important parameters of operation of the PS [10]. At transition processes the frequency of voltage in PS affects not only the frequency of the fault current but its magnitude as well. An increase in angular velocity has also a negative effect on the static and dynamic stability of PS. The paper presents a calculation of the setting and selectivity of selected turbogenerator protections.

K e y w o r d s: turbogenerator, excitation, turbine, frequency, static and dynamic stability of PS

1 INTRODUCTION

Sometimes, there are situations of undesirable failures in the operation of alternators. We distinguish between internal and external failures of alternators [1], [5], 14].

The internal failures include:

- *Insulation failures of the stator* (*eg*internal short circuit, external short circuit, interwinding short circuit, first earth connection, second earth connection),
- *Insulation failures of the rotor* (*eg*interwinding short circuit, first earth connection, second earth connection, bearing currents) [3].

The external failures include:

- *Anomalous stator working conditions* (*eg*current overload, overvoltage, selfexcitation of the alternator, subsynchronous speed) [2],
- *Anomalous rotor working conditions* (*eg*loss of excitation of the alternator, current asymmetry from the stator),
- *working conditions of the alternator drive* (*eg*backward flow of the active power, oversynchronous speed, rotor shift, turboaggregate oscillation, mechanical faults of the turbine, steam generator or boiler faults) [15], [16].

It is apparent from what has been mentioned above that there are a number of possible failures of the alternator. From the point of view of stability of the PS of the Slovak Republic (SR) and its connection to UCTE (Union of the Coordination and Transmission of Electricity), it is necessary to consider the position and significance of nuclear power plants (NPP). The new conditions for the operation of PS in SR, which are in compliance with technical conditions for the connection to UCTE [17], create pressure on monitoring all the required parameters in the sense of limits and conditions of operation of NPP.

2 PROTECTION OF GENERATOR AGAINST LOSS OF STABILITY AND UNDEREXCITATION

The protection against stability loss indicates exceeding the allowed temperature rise of the front faces of the stator and overrunning of the underexcitation limit from the point of view of static stability in the case of failure of the limit guard of underexcitation of the regulator of excitation [4]. This protection works on the principle of impedance measuring with offset characteristic , Fig. 1.

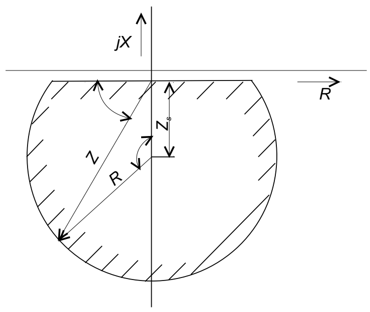

Fig. 1. Characteristic of the protection against loss of stability.

The protection works if these two inequalities hold at the same time:

$$Z \cos\varphi \leq R \sin(180-\Psi) = R \sin\Psi \qquad (1)$$

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$$Z \sin\varphi \le Z_s + R \cos(180 - \Psi) = Z_s - R \cos\Psi \quad (2)$$

where Z is the measured impedance, R is the circle radius of the characteristic, Ψ is the angle (see Fig. 1), φ is the angle of the Z impedance vector.

After elimination of Ψ and further manipulation we get the equation of protection switching for different angles φ of the measured impedance Z.

$$Z \le Z_s \sin\varphi + \sqrt{R^2 - Z_s^2 \cos^2\varphi} \quad (3)$$

where Z_s is the actual impedance.

In the generator mode, φ is from the range 0 - 90°. The radius of the impedance circle is

$$R = \frac{x_d + x_s}{2} \frac{I_{1PTP} U_{ng}}{I_{ng} U_{1PTN}} \quad (4)$$

$$Z_s = \frac{x_d - x_s}{2} \frac{I_{1PTP} U_{ng}}{I_{ng} U_{1PTN}} \quad (5)$$

where x_d is the relative longitudinal synchronous reactance of the generator, x_s is the relative reactance of the network, I_{1PTP} is the primary nominal current of instrument current transformer, U_{ng} is the nominal voltage of the generator, U_{1PTN} is the primary nominal voltage instrument voltage transformer, I_{ng} is the nominal current of the generator.

2 PROTECTIONS OF THE GENERATOR AGAINST THE LOSS OF EXCITATION WITH AUTOMATICS FOR POWER CONTROL

The loss of excitation of a generator in operation may occur due to interruption of the excitation circuit, due to an outage of the exciter, by activation of protections in the excitation circuit, *etc*. The outage of excitation of an alternator with high unit power is very dangerous for the stability of the power system. Furthermore, a marked drop occurs of the voltage on the terminals of the involved alternator caused by taking-off reactance power from the network. The stator current overruns its nominal value. The operation of turboalternators gets changed severely. The machine gets into asynchronous operation. Its revolutions exceed the synchronous values. As a tool against this condition of the generator, protection is used with an impedance measuring element having a "polarized mh0" characteristic shifted towards $-jX$ axis (Fig. 2). This protection measures the impedance by which the generator is loaded or through which the machine is fed. The value of this impedance depends on the load of the machine and on excitation. The static stability boundary of a synchronous machine with a constant terminal voltage (thus when the load angle is $\vartheta = 90°$), represented in the impedance plane, is a circle with diameter equal to the transverse reactance of the generator in saturation x_q (Fig. 2) [10].

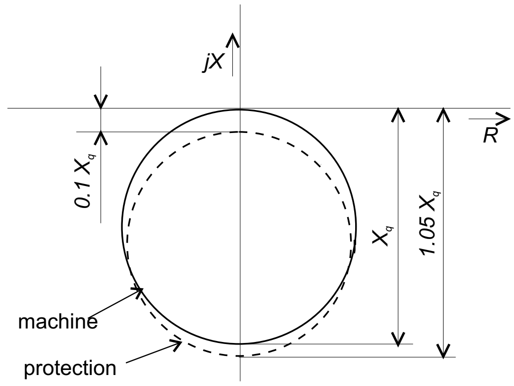

Fig. 2. Characteristics of the protection and of the machine in the impedance plane.

For the transversal axis of the machine in steady state it holds

$$x_q I_q = U \sin\vartheta \quad (6)$$

where I_q is the transversal stator current, U is the terminal voltage of the machine, x_q is the relative transversal synchronous reactance of the machine, ϑ is the load angle.

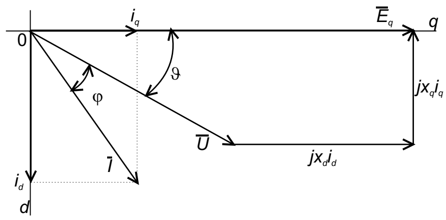

Fig. 3. Vector diagram of the synchronous machine.

For the longitudinal axis one can write

$$E_q - x_d I_d = U \cos\vartheta \quad (7)$$

where E_q is the open voltage x_d is the relative longitudinal synchronous reactance of the generator, I_d is the longitudinal stator current. Since $\bar{I} = I_q + jI_d$ and for the limit of static stability $\vartheta = 90°$, the impedance vector "seen" from the machine terminals can be written as

$$\bar{Z} = \frac{\bar{U}}{\bar{I}} = \frac{\bar{U}}{\frac{\bar{E}_q}{x_d} + j\frac{\bar{U}}{x_q}} \quad (8)$$

which for varying excitation corresponds to the circle in Fig. 4. If there is additionally x_ν reactance between the machine terminals and the hard voltage, then

$$\bar{Z}_v = \frac{\bar{U}}{\frac{\bar{E}_q}{x_d + x_v} + j\frac{\bar{U}}{x_q + x_v}} \quad (9)$$

where Z_v is the vector of impedance "seen" from the machine terminals, x_v is the reactance between the terminals of the machine and the hard voltage, and the impedance circle of static stability is larger. However, the terminal voltage is not $\bar{U}$, but $\bar{U} - jX_v\bar{I}$, hence on the terminals of the machine, where the protection is connected, the vector of impedance is

$$\bar{Z}_q = \frac{\bar{U} - jX_v\bar{I}}{\bar{I}} = \frac{\bar{U}}{\bar{I}} - jX_v = \bar{Z}_v - jX_v \tag{10}$$

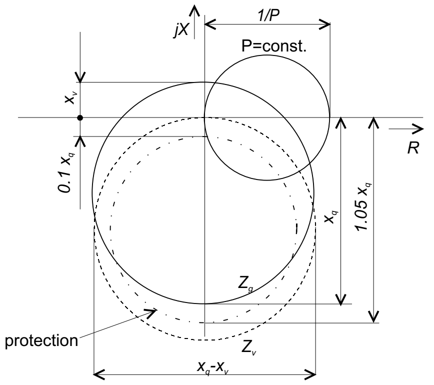

Fig. 4. Characteristic of protection against loss of excitation.

Reactance x_ν is very difficult to find and it depends on the operation of the network. Furthermore, in larger turbogenerators x_ν has a weaker influence because their reactance is usually high. For turbogenerators, $1.5 \le x_q \le 2.2$, while $x_q \le 1$ for machines with pronounced poles. It is necessary to bear in mind that this protection works when the circle is large enough even when machine oscillations occur because when the machine approaches the stability limit, it is actually underexcited. Nevertheless, this activity is undesirable and it is better to adjust the protection to x_q (Fig. 4). In the case of loss of excitation the machine gets quickly through the stability boundary and enters the area of functioning protection. However, at the beginning it moves along the V-curve projected into the impedance plane as a circle P=const. If the protection is set to x_q, it will work in any case of loss of excitation, no matter whether the load is small (point 0, $-jx_q$, remains unchanged for any x_ν) or large (the machine passed beyond the Z_v circle, it will quickly traverse onto the circle of protection). Under this situation the protection will be little sensitive to swinging and dynamic shocks. Turbogenerators can stand asynchronous operation for some time (given by the producer) and after recovering excitation they become synchronized again. Therefore it is recommended to connect the protection to a switch and a field break switch with delay, while signalling should indicate the state without delay for the operator or excitation regulator to have time to act. In this way, unnecessary disconnection of the machine from the network is avoided. Unless the producer states another time, we can give a period of 30 seconds as an appropriate time delay. The protection is adjusted according to the saturated transversal synchronous reactance X_q of the machine. Usually protections have two levels. The first one lowers the generators power output and launches the automatics of asynchronous operation. The other level, alike impedance adjusted, depends on the decrease of the voltage on terminals of the generator and gives impulse to switch off the generator from the network without time delay. Protection for the case of loss of excitation can be blocked with an undervoltage element. Protection is further completed with automatics for the loss of generator excitation with a cascade "time - power output" characteristic. This automatics controls the allowed time of duration of asynchronous operation [6], [7].

The diameter of the impedance circle is adjusted to

$$x_{qr} = x_q \frac{I_{1PTP} U_{ng}}{I_{ng} U_{1PTN}} \tag{11}$$

where x_{qr} is the diameter of the impedance circle. The impedance setting will be:

$$V = \frac{1}{x_{qr}}. \tag{12}$$

Adjustment of the undervoltage element:Considering the operation experience, it is recommended to set 0.5 0.6 U_n Protection setting at asynchronous operation:

Allowed durations of operation at excitation loss are shown in Tab. 1.

Table 1. Allowed duration of operation at a loss of excitation in dependence on the generator output.

Generator oputput	Allowed duration of operation t_{off} (min)
$P > 0.5P_n$	1
$0.3 < P < 0.5P_n$	2
$P < 0.3P_n$	15

Single levels of automatics are adjusted according to the following relation:

$$P_r = P\ \frac{U_{ng}\ I_{ng}}{U_{1PTN}\ I_{1PTP}} \tag{13}$$

where P_r is the setting of automatics, P is the actual power output.

In the case of a fault in the PS (short circuit, drop-out of the alternator, *etc.*) which would bring about a loss of dynamic stability in a part of ES, a loss of synchronism of alternators operating in PS would occur. In such a case the PS is divided in two or more groups, thus the system disintegrates. Each of these disintegrated parts will have its own frequency (this mode is called the insular operation of PS) [14].

If this situation were accompanied also by a loss of excitation of the alternator, the frequency - being not held by the system any more - could rise or fall beyond the allowed limits and cause a failure or even destruction of power plant devices (turbine, alternator, block transformer) [6].

3 FREQUENCY OPERATION OF THE TURBINE

At very high speeds, disruption of the turbine and subsequent leak of high pressure steam may occur resulting into machine destruction. Since the speed rise above the allowed limits may take place within 50 ms after the loss of load, it is not possible to forestall this event by the actions of the operator. Therefore, there is a need for reliable automatic systems.

The operation of a turbine - from the point of view of frequency - can be classified as normal or extraordinary. These modes are discussed in [13]. The normal mode is defined within the frequency range from 49.0 to 50.5 Hz. The operation modes with other frequencies are considered to be extraordinary [18]. The turbine can be permanently operated in the range from 48.5 to 50.5 Hz (a condensing turbine up to the nominal electric power output, a turbine with heat take-off up to the maximum attainable electric power output in dependence on the heat power taken off in accordance with the take-off diagram). It is possible to regulate the power output of the turbine during operation according to the need of the PS, possibly also according to the system taking off the heat, in a regulation range from the nominal power output to the output corresponding to the technical minimum of the block, and within the regulation range according to the operation principles. In turbines with heat take-off it is additionally necessary to obey the operation modes in accordance with the take-off diagram.

For frequencies below 48.5 Hz, the operation of the turbine is time-limited, its maximum electric power being given in Tab. 2.

At frequencies above 53.0 Hz, the block must be put out of operation immediately.

P_n (MW) is the nominal electric power output of the turbine or the maximum attainable output of the turbine with heat take-off in dependence on the heat power taken off according to the take-off diagram.

At frequencies below 46 Hz, the block must be shutdown immediately. At frequencies above 50.5 Hz the operation of the turbine is time-limited and the maximum electric power output is given in Tab. 3.

Table 2. Operation of the turbine at a reduced speed.

Frequency range (Hz)	Maximum turbine power ($\%P_n$)	Maximum duration of a single case (min)	Total duration within 12 month of operation (min)
48.5 - 48.0	100	30	360
48.0 - 47.0	100	20	120
47.0 - 46.0	70	5	10

Table 3. Operation of the turbine at an increased speed.

Frequency range (Hz)	Maximum turbine power ($\%P_n$)	Maximum duration of a single case (min)	Total duration within 12 month of operation (min)
50.5 - 51.0	100	30	120
51.0 - 52.0	100	10	30
52.0 - 53.0	70	5	10

4 FREQUENCY OPERATION OF THE ALTERNATOR

The allowed frequency operation of alternators depends on the frequency as well as on other parameters such as terminal voltage, power output, current of stator and rotor and cooling. Permanent and short-run operations of a generator P_n=220 MW used in NPPs in SR are shown in Figs. 5 and 6.

5 FREQUENCY OPERATION OF THE BLOCK TRANSFORMER

The domain of normal operation in which the transformer can be permanently loaded is determined by the voltage band $(0.95°1.1)U_n$ and the frequency band 49.5°50.5 Hz. In addition to this, a condition holds that the maximum permissible operation voltage on the output side of the transformer at normal operation must not be exceeded [9].

It is possible to permanently load the transformer with the nominal power output also outside this domain even at frequencies lower than 49.5 Hz as well as higher than 50.5 Hz. The zone of extraordinary operation with a nominal power output is limited by the maximum permanently allowable value of magnetic induction, by the maximum permanently permissible current, by the highest permissible total losses, and by the highest permanently permissible operation voltage.

At frequencies exceeding 50.5 Hz it is allowed to permanently load the transformer with a nominal power output in the voltage range 0.95°1.1 U_n.

At frequencies lower than 49.5 Hz it is allowable to permanently load the transformer with a nominal power output in the area limited by the voltage $U = 0.95U_n$ and $(U_1 \times 50)/(U_{1n} \times f) = 1.1$.

At frequencies lower than 46 Hz and voltage lower than 0.95 U_n it is allowable to permanently load the transformer with a reduced power output, which means that at the extraordinary operation the maximum allowable current $I_n/0.95$ must not be exceeded.

Total losses of the transformer depend on the current, voltage and frequency. Their total must not exceed the

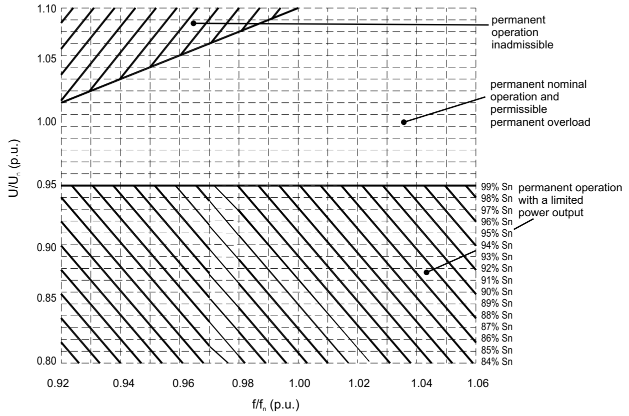

Fig. 5. Permanent operation of the generator with tolerances of U and f.

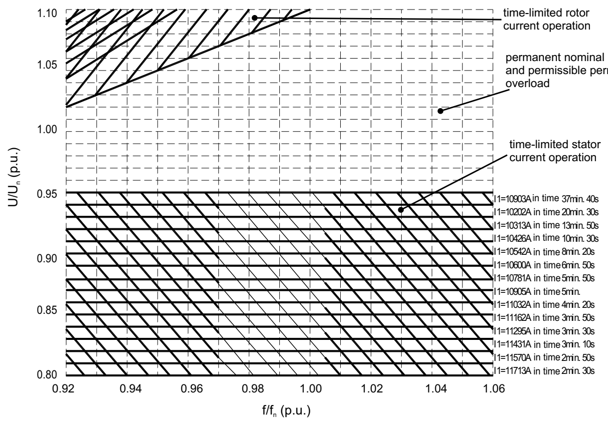

Fig. 6. Short-run operation of the generator with tolerances of U and f.

allowable total losses which can be led off by the cooling system of the given transformer. At reduced and increased frequencies it is essential to comply with the maximum values given in Tabs. 4 and 5.

Table 4. Zone of extraordinary short-run operation of the block transformer at increased frequency.

U_1/U_n	1.3	1.19	1.15	1.12	1.115
duration (min)	2	5	10	20	60

Table 5. Zone of extraordinary short-run operation of the block transformer at reduced frequency.

$b = \frac{U_1 \times 50}{U_{1n} \times f}$	1.3	1.19	1.15	1.12	1.115
duration (min)	2	5	10	20	60

The total duration time of all extraordinary operation conditions must not exceed a triple of single duration times during a period of 12 month.

6 FREQUENCY OPERATION FROM THE POINT OF VIEW OF NPP DEVICES

The requirements upon frequency operation from the point of view of the whole PS are discussed in [12]. If an NPP receives simultaneously the signal "increased frequency in the PS" from the Slovak Energy Control Centre (SECS) and from the local frequency relay (FR), it assures:

- automatic disconnection from the central regulator U by SECS in the LFC terminal (device for distance regulation of voltage and reactance power output from SECS),
- reduction of power output of the turbogenerator at a rate of 2 % P_n/min in dependence on frequency.

In case the frequency returns back below the 50.2 Hz limit, the lowering of the power output of the turbogenerator stops until the frequency enters the band $f = 50 \pm 0.05$ Hz. In the case of a repeated frequency increase the reducing of the power of the turbogenerator in NPP will repeat. The power output reduction in NPP will be controlled according to the local frequency meter provided that no instruction is given by SECS. If necessary, NPP will lower the power of turbogenerators down to the allowable minimum output. The operation of NPP in the case of breakdown changes is summarized in Tab. 6.

The measures summarized in Tab. 6 take into account the requirements upon the quality of energy supply, fully in accordance with UCTE regulations. The criterion of automatic disconnection of turbogenerators and their transition to the auxiliary system by far does not meet the requirements of producers regarding a secure operation from the view of frequency. The allowable frequency operation of a single NPP block must take into account the limitations of producers of all devices operating in the block.

Since the allowable operation of the alternator and of the block transformer in the frequency range of 46 to 53 Hz depends on other parameters than frequency, the requirements on the frequency operation of the turbine will be considered as the strictest criteria (Fig. 7).

As shown in Tab. 6, at a frequency of 50.1 Hz the NPPs disconnect automatically from the PS and switch to auxiliary system. At the first look, this criterion assures also the fulfilment of requirements on other devices. In fact, this is not true. The situation is shown on the example of Block 3 of NPP V2 in Jaslovské Bohunice. A similar project solution is used in every nuclear block in SR. The frequency relay which secures disconnection of the block from the system at 51.0 Hz takes its input signal from the voltage transducer placed behind the outlet circuit breaker. The initial signal from the relay causes disconnection of the outlet circuit breaker thus insulating the block from the PS.

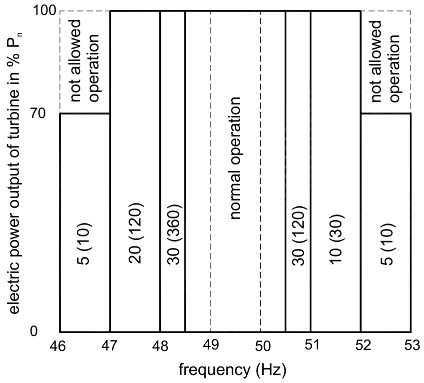

Fig. 7. Operation diagram of a steam turbine from the point of view of frequency.

At the same time, the FR gives a signal to the outlet circuit breaker V 043 in the Bošáca substation which secures disconnection in the case of a failure of the circuit breaker in NPP. Simultaneously, transition of the block power to auxiliary system is initiated. This means that although the block is disconnected from PS, the systems of NPP devices are still loaded because NPP continues working into its auxiliary system. For these devices also the operation for auxiliary system at non-nominal frequency may be a serious threat. Both designed and non-designed conditions may occur in which the frequency relay is blocked. The existing solution does not secure a proper protection of devices at non-nominal frequencies satisfying the requirements of their producers. For this reason, satisfying the requirements upon allowable operation of devices in respective frequency bands in Fig. 7 must be assured separately. Since the requirements given above can be met by none of the existing protections, it is necessary to develop a new system of protection.

Complex frequency protection of devices in PS, regarding their safe operation and the requirements of producers and operators of devices, is a new problem which requires special solutions. The close connection between the technological devices of production and the electric devices demands progressive protections which will secure appropriate protection of energy producing facilities as a whole. In the future it will be necessary to design disconnecting algorithms which will, provided they have been chosen appropriately, prevent operation conditions at increased frequencies. Despite all measures we can not completely eliminate these conditions. It is therefore necessary to pay attention to complete technical solutions of protecting the devices in energy producing facilities. Though this contribution refers mainly to nuclear power plants and takes some of their specifics into account, it is possible to generalize its contribution to all types of power plants.

Table 6. Measures at breakdown changes of frequency in NPP.

F (Hz)	Measure	Delay (s)
49.5	Manual increase of NPP turbogenerator power if a margin is available	
47.5	Automatic disconnection of turbogenerators and their transition to auxiliary system	1
50.2	Manual reduction of turbogenerator power at a rate of 2% P_n /min in dependence on f if NPP simultaneously receives the signal "increased frequency in the ES" from SECS and and from the local FR	
51.0	Automatic disconnection of turbogenerators #11,12,31, 32 in NPP EBO and turbogenerators #11,12 in NPP EMO and their transition to auxiliary system	5
	Automatic disconnection of turbogenerators #21,22,41, 42 in NPP EBO and turbogenerators #21,22 in NPP EMO and their transition to auxiliary system	10

CONCLUSION

From the viewpoint of stability of the power system of Slovakia, its connection to UCTE and fulfilment of the imposed technical conditions it is necessary to put strong emphasis on a secure and reliable operation of NPPs.

One of the most important devices in a power plant is the alternator. It is therefore important to perfectly manage its protection against all possible failure conditions. As mentioned in the introduction, there are a plenty of alternator failures which may occur during operation. We pursued the analysis of two chosen failures, a loss of excitation of the generator and non-synchronous running of the generator with a frequency dangerous to the devices of NPP.

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