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Modelling of Electrical Power System Equipment on Program and Technical Complex RTDS for Testing and Configuration of Relay Protection and Automation Devices

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1 INTRODUCTION

Program and technical complex RTDS (Real Time Digital Simulator) is the progressive solution in the sphere of modeling which combines advantages of mathematical and physical models and makes great opportunity for testing relay protection and automation devices in different easy and complex electric modes. By means of RTDS it becomes possible to use rather exact models of network elements, controllers, to carry out shift operations or regulation of mathematical model modelled in real time from operation signals of the checked device connected with analog and digital inputs and outputs of RTDS complex. By means of RTDS the research-and-production enterprise EKRA, Ltd. Created a mathematical model of an electric power system on which microprocessor (MP) devices of the research-and-production enterprise EKRA, Ltd. tests: power swing protection (PSP) and relay protection of a generator against out-of-step running and asynchronous mode on the program confirmed by SO UPS.

2 TESTING OF RELAY PROTECTION AND AUTOMATION DEVICES

Often in modern MP PSP the algorithms already existing on electromechanical or microelectronic base of out-of-date devices are realized. But some principles have the further development and perfection as, for example, in PSP of EKRA. PSP manufactured in EKRA fixes change of a transmission angle in the course of an asynchronous mode, has three steps and is capable to function in the conditions of essential unbalance of current and pressure, in particular, in tightened pause of single-phase autoreclosing. When selecting settings the calculations are reduced to a minimum and consist of characterization of a protected line. The device is capable to function correctly at big slip frequencies up to 12 Hz that is provided with the internal technical organization of algorithm.

In the course of working out of PSP device corresponding to up-to-date requirement specifications, two primary goals are solved:

1. PSP Algorithm selection providing simple configuration and reliability of functioning.
2. Offset from errors of the measuring units of PSP appearing at frequencies of entrance analog signals, distinct from nominal industrial.

The chosen algorithm based on modeling of pressure on the ends of the protected site, has been realized for the first time in typical panels ShDE2601 and ShE2707, developed in All-Russian

Research Institute in the 80s and issued in Cheboksary Electric Apparatus Plant [1]. The functioning principle is explained on fig. 1.

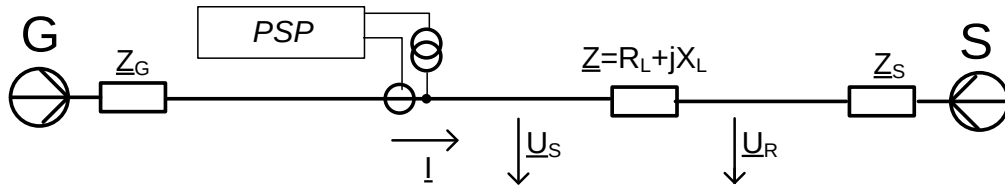


Fig. 1: Illustration to the principle of functioning

On fig. 1 the scheme of connection of PSP device to the current and voltage transformer of a line. $\underline{U}_S$ and $\underline{I}$ – voltage and a current in the place installation of PSP, $\underline{Z} = R_L + jX_L$ – impedance of a protected line. Knowing currents and voltage at the beginning of a line and line impedance the voltage $\underline{U}_R$ in the end of line is calculated $\underline{U}_R = \underline{U}_S - \underline{Z} * \underline{I}$, and knowing the voltage at the beginning and in the end of the line it is possible to define a transmission angle $\delta = \underline{U}_S \wedge \underline{U}_R$. Asynchronous mode comes to light according to a transmission angle value which should be $\pm 180^\circ$. Depending on a sign of the first derivative of a corner various operating signals stand out: asynchronous mode with positive slip, asynchronous mode with negative slip. Upon achievement by a transmission angle of values $\pm 180^\circ$ turns in the course of asynchronous mode are counted.

Block diagram of PSP is presented on fig. 2. Designations on fig. 2: ADC – the analog to digital converter; FHF – fundamental harmonic filter, PSF positive sequence filter, NSF – negative sequence filter.

Solving of the second problem demands understanding of the nature of errors in measuring units of PSP in the course of asynchronous mode. An original cause is frequency departure of entrance analog signals from nominal industrial 50 Hz. Difference of expected and actual frequencies leads to distortions of the signal received as a result of work of Fourier filter [2] that can cause errors of operation of the first and second sort [3], and also bring an additional calculated error.

In the developed PSP device three mechanisms of reduction of errors of measuring units are realized:

- decimation;
- application of quantity of positive sequence similar to IIIЭ2707. The calculation of positive sequence is actually averaging which allows lowering of a distortion level. Also it is necessary to notice that fact that positive sequence voltage in the conditions of essential asymmetry most correctly reflects the position of a rotor of the equivalent generator [4]. This moment is rather important at revealing of asynchronous mode in the conditions of tightened pause of a single-phase autoreclosing;
- double averaging – averaging of the average amplitudes renewed by orthogonal components, which are behind from each other on a quarter of the settlement period.

The result of application of these three mechanisms is shown on fig. 3.

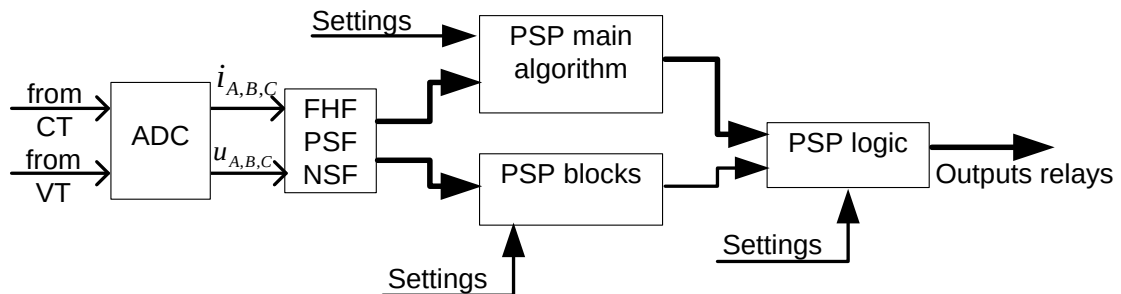


Fig. 2: Block diagram of MP PSP

The other MP device tested on the developed model of an electric power system is relay protection of the generator from asynchronous mode and out-of-step running.

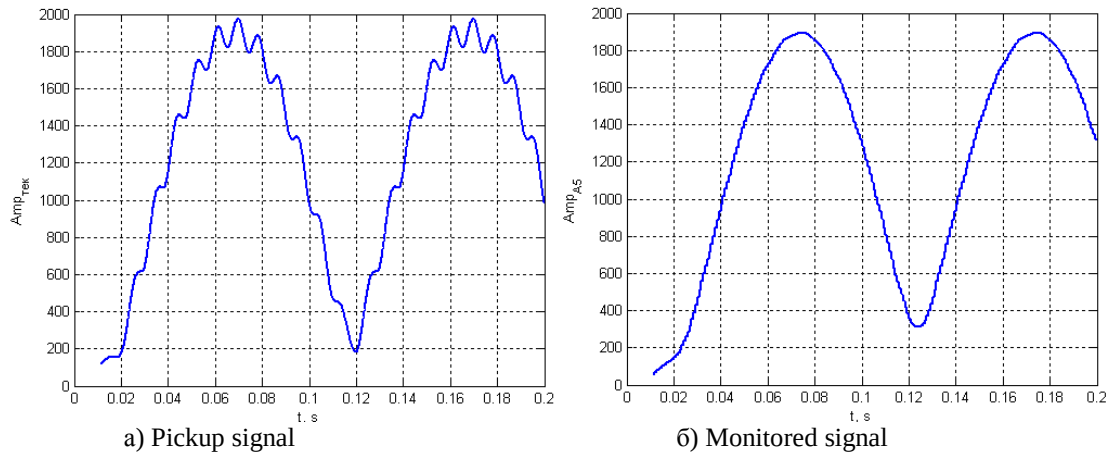


Fig. 3: – The result of swing turning of current vector in the process of asynchronous mode

In [5] it was shown that the devices widely used for protection of modern turbogenerators and hydrogenerators when using asynchronous mode because of loss of excitation and in occurrence of out-of-step running of generator because of reduction of its excitation below the level sufficient for preservation of synchronous operation is inefficient. It works reliably only in the field of stable asynchronous mode which comes after off-loading of the generator below 70-60 % of its nominal rating power while the primary goal of this protection is giving the command for such off-loading and (or) timely tripping of the generator.

In particular asynchronous pole slipping at heavy load is most dangerous for modern highly used generators. From [6] it can be seen that in occurrence of asynchronous mode with closure of the winding excitation on rectifier converter valves of excitation system the excursion of active power of the generator in each period of slip can exceed its nominal rating power in 1,5 times. There are cases when the highest value of slip at its wide fluctuations appearing in each period due to 2-3 multiple reductions of damper properties of a rotor drum of modern turbogenerators in comparison with cars of former execution, reduction of their inertia constant and uniaxiality of the winding excitation, already on the 2nd second reached the pickup setting of the automatic transfer switch of the turbine which is the last protection against its dispersal and destruction. Thus there was blackout of power units.

The most dangerous are cases of occurrence of out-of-step running of the excited generators when at periodically opening rectifiers in the course of asynchronous pole slipping, in winding excitation besides current induced from the stator, the forced current from the activator runs. It doesn't remain constant and depends on the character of parametric variation to which the automatic regulator of excitation reacts. In [5,6,7] the oscillograph of a turbogenerator's asynchronous mode included in a powerful power supply system from which it can be seen that in this case the excursion of active power in 3-3,5 times exceeded turbogenerator's nominal rating power, periodically varying from -1,25P_n to +2P_n; rotor acceleration reached 80 rad/s², the stator current periodically exceeded nominal value in 3,7 times, and stator pressure (accordingly on feed bus of unit own needs too) decreased below 50 % of the nominal. Due to lag effect of system of speed regulation of rotation of the turbine, within 2,5 seconds there occurred three such asynchronous slippings. Only after that under the influence of a speed regulator of the unit there was its braking, but at reduction of frequency of rotation the regulation opened valves of an admission of steam in the turbine again and the described process repeated in a new cycle. The similar data were received at test on the actual unit of turbogenerators of capacity 165, 200, 300 and 500 MVt.

The physical essence of these processes is shown in [6]. From the told the necessity of protection from out-of-step running and asynchronous mode during the first turn of a rotor concerning the field of a stator, i.e. before achievement of the first maximum of a throw of active power and other parameters of a mode is obvious. For this purpose the protection should influence immediately on switching-off of excitation system, field discharge of the generator with excitation winding closure on equivalent circuit and the following fast decrease in loading of the generator and (or) its switching-off from a network. However for offset from transitive modes and power swing in an electrical power system known for us protection devices from out-of-step running and asynchronous

mode are carried out with a delay of 2-3s or with the account of cycles of asynchronous turn. In [5,7] it is shown that the protection device, executed for example on a principle of measurement of the generator resistance which has operation delay, in general can fail to operate as the module of generator impedance during a cycle of asynchronous turns of a rotor periodically leaves an operative zone of such a device, and it will lead to dump of operation of its reacting part.

The aforesaid means that protection of powerful turbo - and hydrogenerators from asynchronous mode at loss of excitation and more over from out-of-step running of excited generator, should be high-speed, hence, it should be selective by mode of functioning. In this sense out-of-step running of the raised generator is boundary by virtue of the fact that the character of parametric variation is most similar to the character of their changes at power swings or parametric variation in electrical power system when special protection system should operate, and excessive actions of individual relay protection of generators can lead to simultaneous tripping of several generators of a power station and aggravate an emergency situation in an electric power system.

It is known that the characteristics of out-of-step running in an electric power system, the simplified equivalent loading diagram of which is on fig. 4 and, are following[8]:

- Periodic change of a corner δ between nonsynchronous electromotive force from zero to 2π rad. with slip frequency (fig. 4,);
- Periodic, with slip frequency, pressure excursion in all points of an electricity transmission, thus in the electric center out-of-step running pressure changes from the maximum value at $\delta = 0$ and $\delta=2\pi$ radian to zero at $\delta = \pi$ (fig. 4r);
- Periodic, with slip frequency, current excursion in all elements which connecting nonsynchronous electromotive force, thus the current has the minimum size at corners $\delta = 0$ and $\delta=2\pi$ and reaches the maximum value at $\delta = \pi$;
- Periodic, with sine change with double slip frequency, change of active power of generators.

It is obvious that out-of-step running of the excited generator is an especial case of out-of-step running in an electric power system and that differentiation of an operative zone of relay protection of the generator from out-of-step running and operative zones of system automation should be defined by the position of the electric center of out-of-step running. Concerned relay protection should operate on condition that electric center of out-of-step running is inside of the given concrete generator. In case when the electric center of out-of-step running is out of the generator the rotor doesn't do full turns concerning the field of its own stator, undergoing only power swings, and the considered protection shouldn't operate, but special protection system should operate.

Researches on models, and natural tests have shown that if the exciting current of the separate generator is insufficient for its deduction in synchronism, so at asynchronous turns of a rotor of the excited machine concerning a stator field which has network frequency, i.e. when the electric center is in the generator, electromotive force directed in the excitation winding from stator, periodically with slip frequency counterbalances or exceeds electromotive force, caused by the voltage of the exciter:

$$e_{f\text{ind}} = -d\Psi_f/dt \geq e_f(U_f) \quad (1)$$

Thus the current in excitation winding periodically passes through zero, and there are valves in the chain of excitation winding they are periodically locking.

In cases when asynchronous mode of the generator occurs because of loss of excitation the current directed from the stator to the excitation winding in the short circuit of it on the equivalent circuit on an armature of the cross-field exciter, has sign-variable character and periodically with double slip frequency also passes through zero, and at opened chain the excitation winding is equal to zero. At closing of excitation winding on valves the current in its chain periodically changes from some positive value when valves are open to zero at their lock-out. At last, at loss of synchronism of the excited generator the condition (1) is carried out, if the sliding reaches such great value that the generator, despite the forced excitation, can't be involved in synchronism, and electromotive force inducted in excitation winding becomes periodically more than electromotive force, caused by pressure of the activator. Only then valves locking. If $e_{f\text{ind}}$ doesn't exceed $e_f(U_v)$, lock-outs of valves won't occur also there won't be rotor turns concerning a stator field and a corner of a departure of a rotor after reaching certain value begins to decrease, i.e its periodic power swings will occur. It is possible only in case when the level of excitation of the considered generator is high enough and the electric center of out-of-step running (fig. 4a) is within x_r towards the line.

At the same time in all synchronous modes admissible for the generator and at occurrence of short circuits in a network the current in chain of excitation winding of the generator doesn't decrease to zero. The exceptions are the generators which system of excitation possesses inverting possibility. Forced excitation system at periodic increase of pressure in process power swings or out-of-step running in an electric power system can give a command order on inverting and a current in the excitation winding of the generator can short moment decrease to zero. Proceeding from these features, some updatings of the devices providing selective operation of protection on the first asynchronous turn of a rotor of the generator rather a field [7, 9] have been developed, executed and checked widely up.

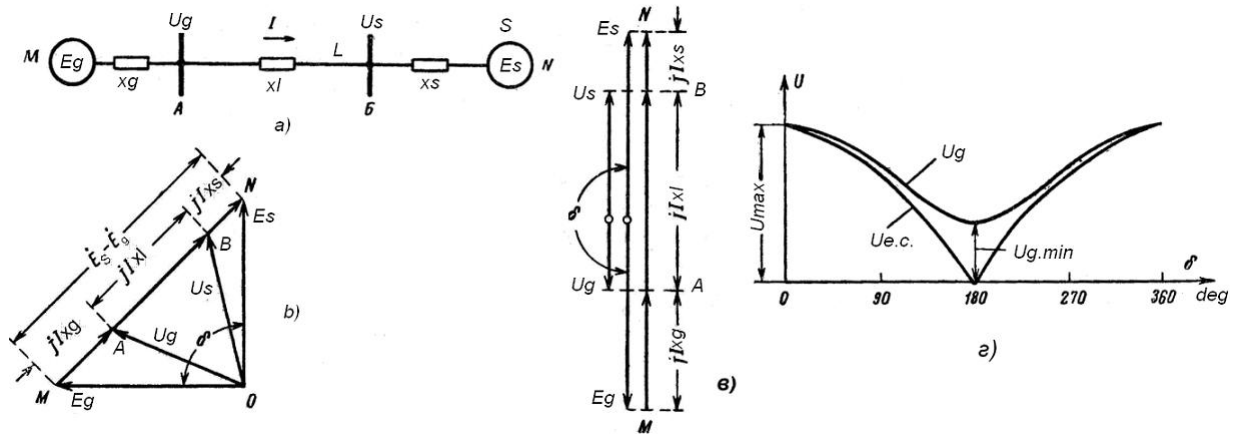


Fig. 4: The loading diagram and the vector diagram of electromotive force and transmission voltage
 a) the equivalent loading diagram of power plant operation on a reception electric power system;
 b) the vector diagram of electromotive force transmission voltage at $E_s = E_g$, $\delta = 90^\circ$;
 c) the same at $\delta = 180^\circ$, $E_s - E_g = jI x_g + jI x_l + jI x_s$;
 d) change of pressure in the process of out-of-step running at $E_g = E_s$

Both above described MP devices pass through tests on the developed model of an electric power system (fig. 6) which structure is shown on fig. 5. A Considerable quantity of library models of generators, their controllers, turbines, power lines, power transformers, electric load, engines, current and voltage transformers allow creating on RTDS the models of power unit of various complexity and configuration. The control of model can be carried out in real time. RTDS allows examination of a static operating mode of a primary network, and also electromagnetic and electromechanical transients in it.

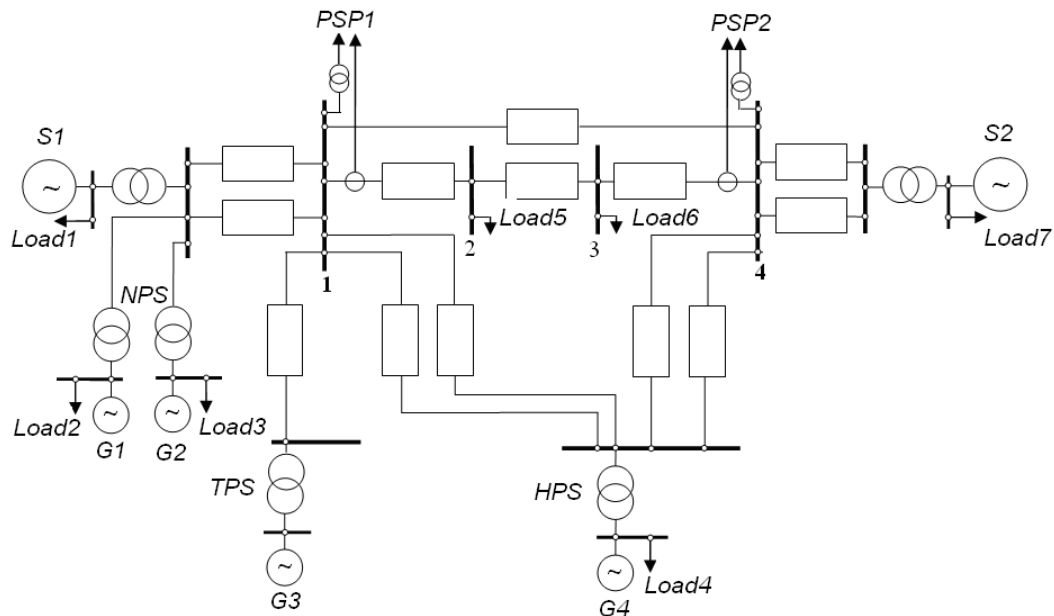


Fig. 5: Electric power system diagram

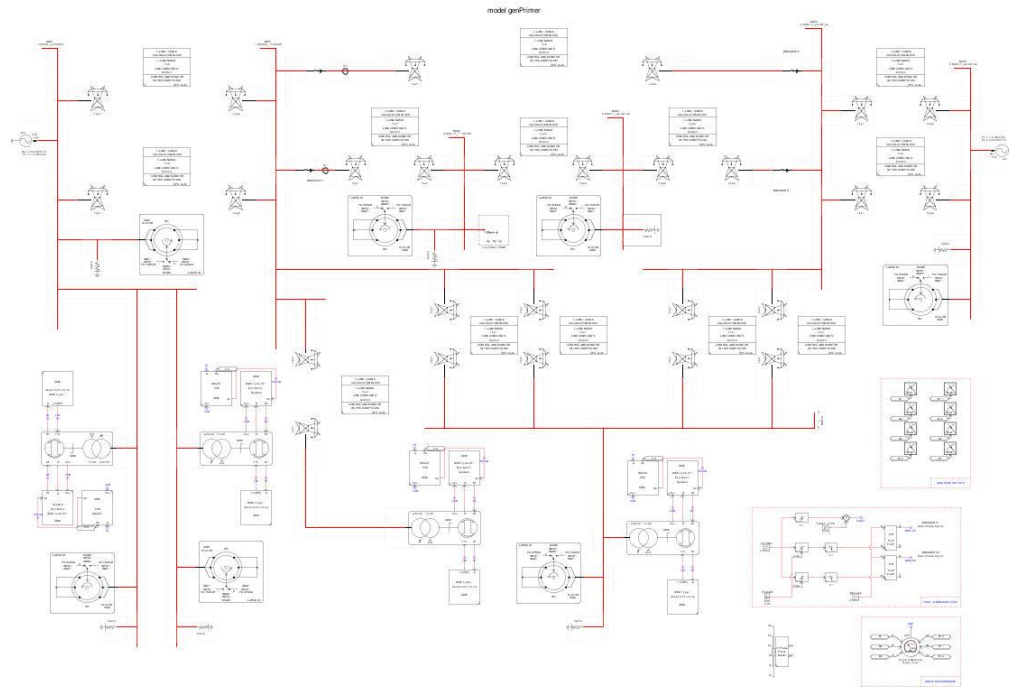


Fig. 6: The model of electric power system on RTDS

The model of an electric power system (fig. 6) includes 4 synchronous generators and also their block transformers, 7 complex electrical loads and 14 power lines. Generators G1 and G2 model an nuclear power station, G3 – thermal power station, G4 – hydro power station, models of equivalent electric power systems S1 and S2 are represented as ideal voltage sources. The power unit is presented by mathematical model of the synchronous generator, the turbine with speed governor, system of excitation and the block transformer. The model of the synchronous generator allows to consider the following mechanical and electric parameters: capacity of the machine, rated voltage of the machine, nominal frequency, quantity of rotor damper windings, a constant of inertia of the machine, synchronous mechanical damping, D-axis(Q-axis) Unsaturated Reactance, D-axis(Q-axis) Unsaturated transient (sub-transient) Reactance. The variety of parameters allows modeling of various types of generators. Standard library of RTDS contains various types of systems of excitation of generators of proportional and strong action. In model (fig. 6) generators are equipped by forced excitation system. The block transformer is presented by a model of the three-phase transformer with the type of windings connection Y_0 / Δ . Power lines with the level of pressure 330 kilowatt are presented by models with the distributed parameters. RTDS possibilities allow to set the following parameters of power line: Type of wires, type of phase splitting, type of a wire, distances between wires, type of support, sagging of wires of phases. Complex loadings are simulated by a complex of the active shunt and the asynchronous engine.

PSP devices were connected to tires «1» and «4». The site of a network (1-2-3-4) (fig. 5) was supervised. By switching-off of separate lines, generators and loadings the initial was led to various test schemes. Generators of stations were deduced from stability by short circuits. During tests the following emergency modes has been simulated:

- Emergency modes with an arrangement of section of out-of-step running on a protected site of a network without intermediate power takeoff;
- Emergency modes with an arrangement of section of an asynchronous course out of a protected site without intermediate power takeoff;
- Emergency modes with an arrangement of section of an asynchronous course on a protected site with intermediate power takeoff.

On fig. 7, for an example, current magnitude, voltage, an angle degree and also active and jet capacities in experience of short circuit in «A» phase on a site (1-2-3-4) near to tires «4» with switching-off short circuit and the subsequent tightened pause of single-phase autoreclosing are shown. During the pause of single-phase autoreclosing owing to previous short circuit the stability is

broken. The electric center of power swings is on the site 1-2. On the oscillogram it is possible to see the correct functioning of all three steps which have been adjusted on operation after 2, 4 and 6 turns of, PSP device connected to tires «1».

Generator protection was tested in modes of out-of-step running and asynchronous mode with the position of the electric center within the generator of a nuclear power plant and out of it, and also in case of external out-of-step running and deep power wings. Input protection quantity is field current and voltage on the excitation winding of the generator. On fig. 8, for an example, it is shown out-of-step running with the electric center in the generator. Apparently from drawing, at the moment of a turn the current in the excitation winding passes through a zero, therefore protection works.

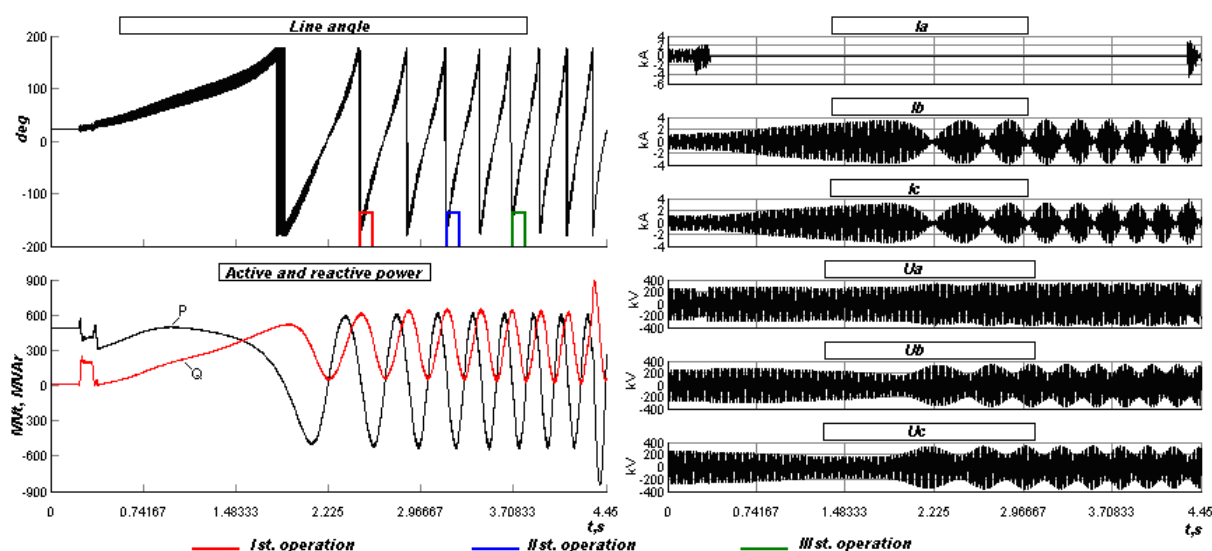


Fig. 7: Loss of stability during the pause of single-phase autoreclosing

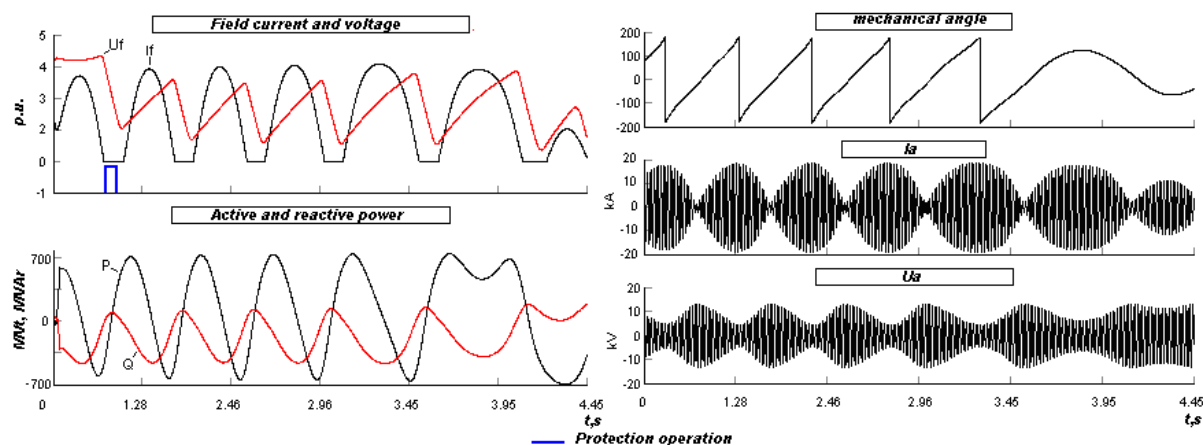


Fig. 8: Out-of-step running with the electric centre in a generator

3 CONCLUSION

For difficult projects with programmed MP relay protection it is possible to guarantee working capacity of relay protection complex of an object with high probability only having made its check in the conditions as much as possible close to real, on the basis of tests with imitation of the basic of tests with the imitation of main calculated errors on the object that allows to reveal engineering errors and errors at feature determination and a configuration of MP relay protection. One of the advanced means of carrying out of complex tests of MP relay protection is the program and technical complex RTDS which allow to use rather exact models of network elements, controllers, to switch back and forth between or to control the mathematical model modeled in real time from operation signals of the checked device connected to analog discrete inputs and outputs of RTDS complex.

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