Full Scale Experiment of the East-West Interconnection

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Abstract – **The paper focuses on the feasibility of conducting a full-scale experiment of the East – West Interconnection, which could be carried out under short-term preliminary connection of UCTE and IPS/UPS. If the experiment was fulfilled with sufficient supply of Digital Fault Recorders (DFR) along the whole 12.000 km transmission system, it would provide enough information for improving the transmission system control. Some aspects of possible work on the interconnection are discussed based upon the full-scale experiment carried out in the Siberian Interconnected Power System**

Keywords – Interconnection – Full-scale experiment – Modeling – Simulation

I. INTRODUCTION

Today the geographical size of the UCTE power grid, from Portugal to the eastern boundary of Poland, amounts to about 3.000 km. If the East-West interconnection project was realized, the distance from the outermost eastern to the utmost western points of the interconnection could reach 9.000 km, and taking into account the power systems of Russian Far East, and those of North Africa and Middle East (TESIS), it could exceed 12.000 km. Such interconnected power system will have pronounced wave characteristics. One of these characteristics consists in that the wave of frequency, caused by emerging of a large active power imbalance in one part of the power grid, will be moving, at a finite speed, along the transmission system. Under some conditions, this wave of frequency can give rise to continuous low-frequency oscillations. The investigation of this phenomenon presents both scientific and practical interest.

In order to fulfill the investigation properly, it is necessary to form a group of international experts who could apply their skills and modern research tools jointly. There are several ways to put this idea into practice. One of them consists in forming a consortium around the experts who took part in the full-scale experiment made in the Siberian Interconnected Power System in November 2002. The experience obtained during these tests could become a good base for preliminary investigation of the feasibility of the East-West interconnection. Indeed, the experiment is the first step in order to certify the dynamic model of the IPS/UPS network. Certification of the dynamic model is a requirement for the East-West interconnection. Some results of the experiment will be discussed here.

II. OBJECTIVES OF THE SIBERIAN TESTS

The origin of this exploration was the necessity to make sure that the program and the power plants` equipment models being used for more than 10 years for long-term stability assessment in power systems, simulate dynamics properly. The second motive to execute the full-scale experiment is the start of processes of deregulation in the power industry and the absolute necessity to guarantee that the frequency control in Russian power systems can satisfy the European standards. One of the actions to achieve this consists in an evaluation of the frequency-control capacity of the individual power plants.

Simulation of long-term dynamics in large-scale power systems is another aspect of this exploration. This paper presents the conditions of preparation, realization and the results of simulation of the processes which existed during the experiment.

III. DESCRIPTION OF THE TEST

The Siberian Interconnected Power System was separated from the Russian Power Grid during the experiment, and it included 9 regional power systems as shown in Fig. 1 taken from [1-2].

The experiment consisted in making series of trials (5 trials in total) with incremental active power imbalances and in recording active power and frequency in different points of the power systems. The 110 kV and 220 kV transmission lines which shunt a two-circuit 500 kV transmission line at the Krasnoyarsk Hydro Power Plant (6000 MW, 12x500 MW), were disconnected. One of two 500 kV section circuit breakers at the Krasnoyarsk Hydro Power Plant's bus bar was opened. Thus, the eastern and western parts of the Siberian interconnected power system became connected only by one 500 kV circuit breaker. Prior to the experiment, Bratsk Hydro Power Plant (4500 MW) was removed from frequency regulation. After having switched off the section circuit breaker, the frequency was not adjusted for 5 minutes. At 6th minute, a control order for synchronization on the section circuit breaker was given.

Besides the recording of active power and frequency by power plants` measurement instrumentation, two BEN5000 DFR produced in Belgium were exploited. They were

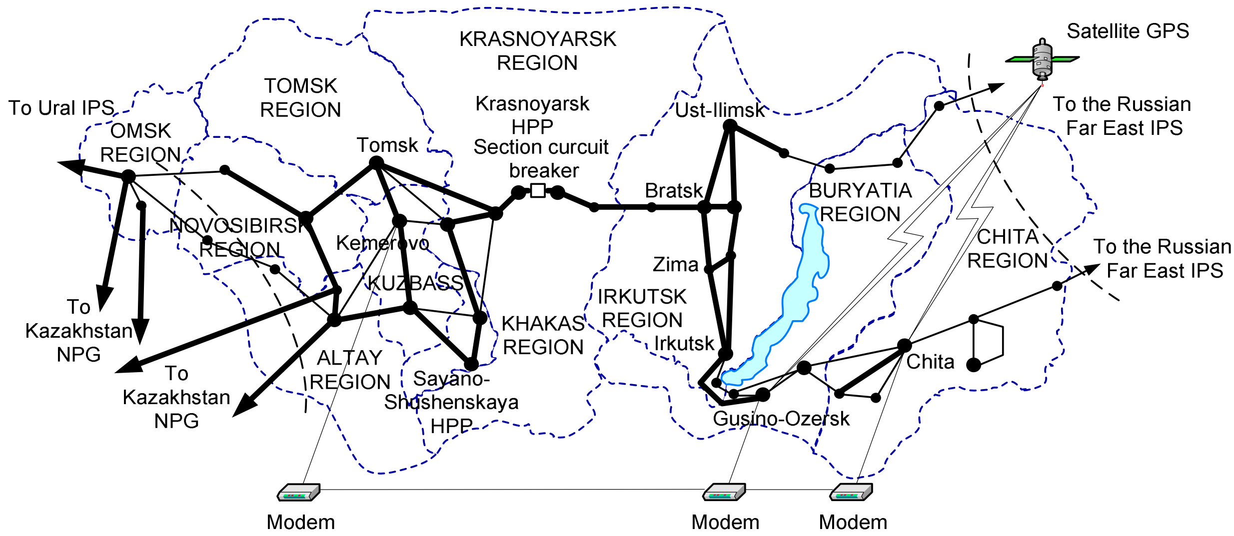


Fig. 1. Configuration of the Siberian Interconnected Power System. IPS- Interconnected Power System, NPG- National Power Grid, HPP- Hydro Power Plant, SPP- Steam Power Plant

deployed at two locations remote from the power grid's separation site by hundreds of kilometers away: Gusinoozersk Steam Power Plant and Chita Heat Power Plant. Fig. 2. shows the training of Russian specialists in Novosibirsk by one of the paper's author, LEM Elsis expert.

The power plants` measurement instrumentation recorded the parameters of power systems such as active power of separate generators, total stations` active power, bus frequency at high speed (1 centimeter/second) and at slow speed (1 millimeter/second). The BEN5000 DFR recorded at high speed (5000 samples/second) the current and voltage from generators and at slow speed (50 samples/second) the rms voltages, power and frequency.

During the experiment, the power flow (in both directions) through the circuit breaker was made such that, on its disconnection, a frequency deviation of ± 0.3 Hz in each part of the power grid was reached.

Fig. 2. Digital fault recorder BEN 5000

The GPS signal reception couldn't be guaranteed prior to dispatching the units to the remote locations. Therefore, "Timed Trigger" function was programmed in each unit to force in advance, recording at the precise time of the induced system events. Twelve triggering (six in each sub-BEN, slow and fast recording) at each BEN5000 were programmed to capture data before, during and after the expected events times at 12:00, 13:00, 14:00, 15:00, 16:00 and 17:00. The recording times were set at 16 seconds in the fast sub-BEN and about 180 seconds in the slow sub-BEN. As a matter of fact, the GPS antenna of the BEN5000 installed at Gusinoozersk Steam Power Plant could not be deployed to capture the satellite signal and that recorder's real time clock ran on its own. One should note that the "Timed Trigger" function did not prevent the BEN5000 from triggering on its own detection and for variable times.

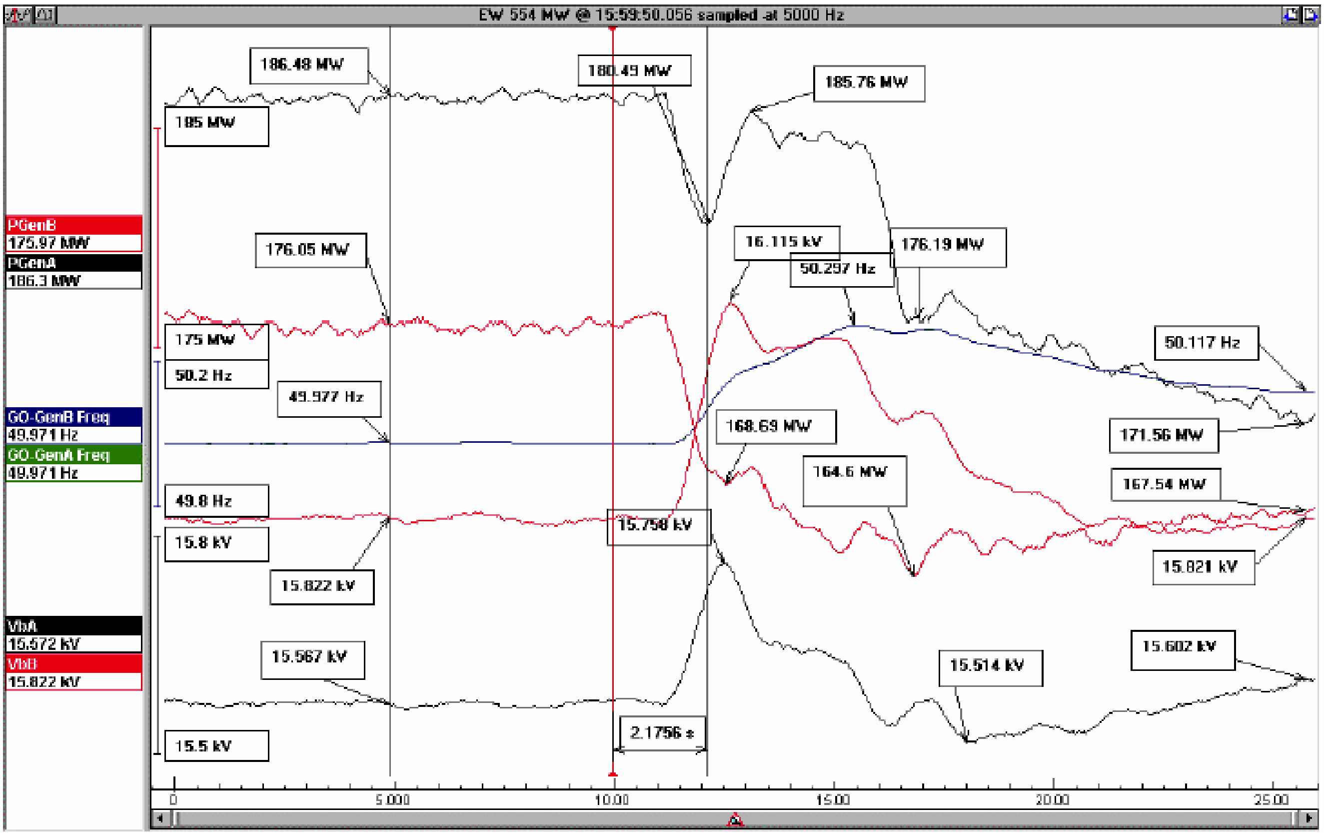
IV. ANALYSIS OF RECORDED CHARACTERISTICS

Two of many oscillograms obtained during the tests are shown in Fig. 3. The results of analysis of the oscillograms are gathered in Table 1.

The following abbreviations are used in Table 1:

- K-MW - MegaWatt variation at Krasnoyarsk station (in MW)
- LocalMW - MegaWatt variation at the site ("GO" or "Chita") (in MW)
- D MW @ deepest pt. - MegaWatt variation at widest Frequency variation point (in MW)
- D Freq @ deepest pt. - Frequency variation at its deepest point (in Hz)
- D MW @ T0+16s. - MegaWatt variation ± 16 seconds after event (in MW)
- D Freq @ T0+16s. - Frequency variation ± 16 seconds after event (in Hz)

(A)



(B)

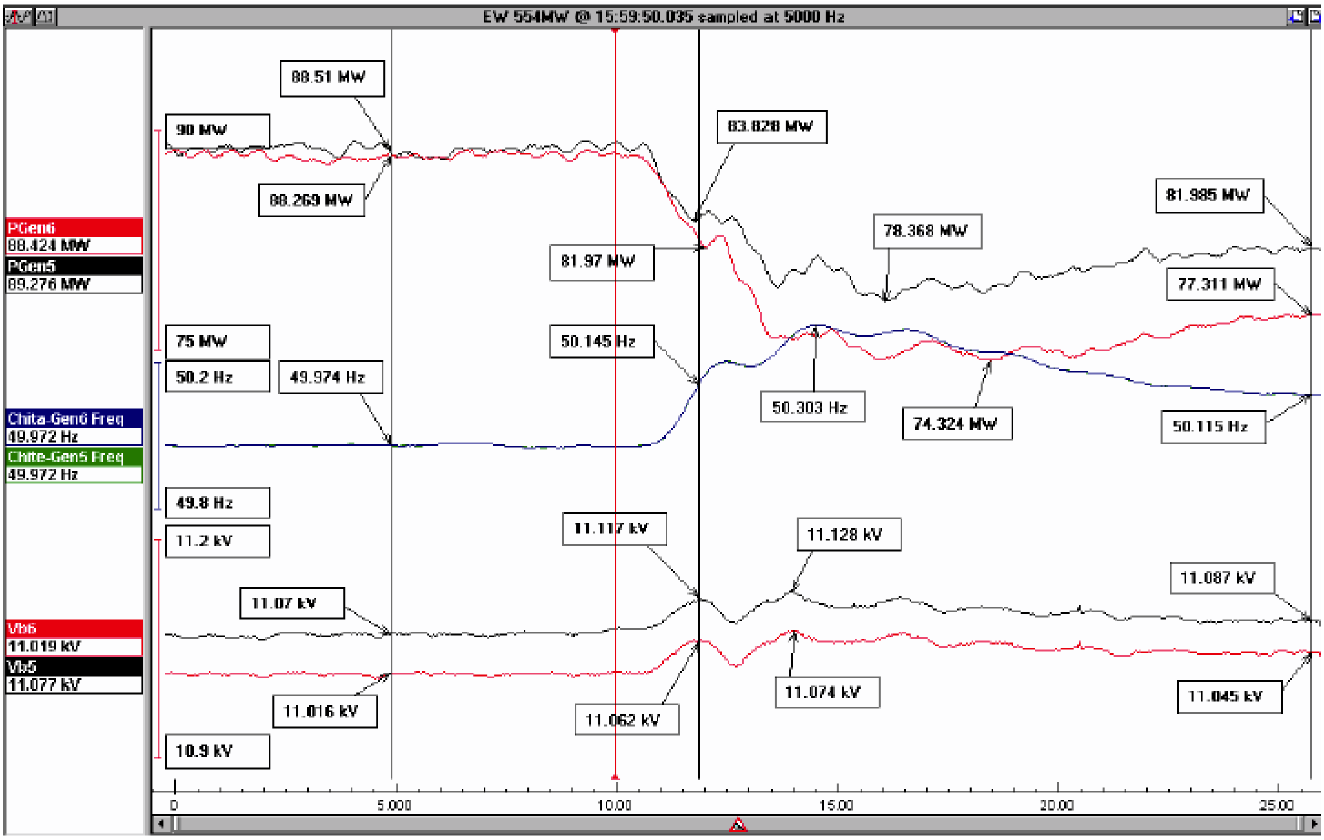


Fig. 3. Dynamics of parameters during Event № 5 recorded using BEN Digital Fault Recorder:
(A) at the Gusinoozersk Steam Power Plant; (B) at the Chita Steam Power Plant

Table 1

The ratio of the Frequency variation in Hz to the % of Power variation at the generator (or site when both generator results are compounded)

EVENT#	#1	#2	#3		#4	#5
MW	200	360	540		300	554
GO Gen A @ deepest	-0.2164	-0.63517	-36.5599		-8.8278	-0.265784539
GO Gen A @ To+15s	-0.78269	-0.70575	2.212109		-3.86352	-0.017609913
GO Gen B @ deepest	-0.05572	-0.06394	-0.08928		-0.05693	-0.059280823
GO Gen B @ To+15s	-0.03358	-0.03431	-0.05083		-0.02805	-0.028773213
Total / plant						
GO A+B @ deepest	-0.08967	-0.11849	-0.18214		-0.11579	-0.098744777
GO A+B @ To+15s	-0.06559	-0.06689	-0.10653		-0.05702	-0.021697952
Chita Gen 5 @ deepest	-0.18839	-0.11676	-0.11456		-0.04027	-0.039491621
Chita Gen 5 @ To+15s	2.047643	-0.13534	-0.08881		-0.02154	-0.018973728
Chita Gen 6 @ deepest	-0.02249	-0.01898	-0.01359		-0.0244	-0.023435484
Chita Gen 6 @ To+15s	-0.01174	-0.01331	-0.00978		-0.01102	-0.011460838
Total / plant						
Chita 5+6 @ deepest	-0.04461	-0.03586	-0.02699		-0.0305	-0.02942539
Chita 5+6 @ To+15s	-0.02706	-0.02698	-0.01961		-0.01465	-0.014294801

Since it appears that two generators of the same plant may have reacted differently upon a similar event it has been decided to compound the values together as it has been suspected for some inter-generators interaction. Some other generators in the plant yet running may also have influenced the transitory response. One can note from the analysis of the curves, displayed in Fig. 4, that some different behavior between generators can be signed upon the occurrence of an event. See the level at which the generators A and B of Gusinoozersk Steam Power Plant are leveling after Event №3.

All the records (except the one of event №5) show a long term variation smaller for the generators A (Gusinoozersk) and 5 (Chita). In an unexpected fashion, after the event №5, the generator A of Gusinoozersk Steam Power Plant shows a unsteady behavior later ending with a power variation for Generator A (-14.7 MW) unusually larger than the one of Generator B (-8.4 MW). It is shown in the Fig. 5.

Since the BEN Sensors cannot compute the Virtual channels of the Real and Reactive Power based on the phase-to-phase Voltage, it was decided to make the equivalent Calculated Channels in the Fast Sub-BEN records based on the equations of Table 2 (so-called 2-Wattmeter method). One can see from these equations the computation of the following intermediate quantities:

Table 2

Creation of Calculated Channels

Channel	Unit	Equation
PabA	MW	@RealPower("11A1:GO-GenA Vr","11A5:GO-GenA Ir ")/1000
PbcA	MW	@RealPower("11A2:GO-GenA Vs","11A7:GO-GenA It ")/1000
PGenA	MW	"E1:PabA"-"E2:PbcA"
PabB	MW	@RealPower("12A1:GO-GenB Vr ","12A5:GO-GenB Ir ")/1000
PbcB	MW	@RealPower("12A2:GO-GenB Vs ","12A7:GO-GenB It ")/1000
PGenB	MW	"E4:PabB"-"E5:PbcB"
VbB	kV	@TrueRms("12A2:GO-GenB Vs ")
VbA	kV	@TrueRms("11A2:GO-GenA Vs")*1

- PabA - Real Power based on V_{ab}, I_a for Generator A
- PbcA = Real Power based on V_{bc}, I_c for Generator A
- The resulting total 3-phase power by the 2-Wattmeter method: PGenA.
- PgenB is computed similarly to PGenA.

V. SIMULATION PROCEDURE

The simulation of the above mentioned full-scale experiments in the Siberian Interconnected Power System were done with the use of PAG software tool, developed by the Siberian Electric Power Research Institute and EUROSTAG software package, developed by Tractebel and Electricité de France[3].

During preparation of the Siberian Interconnected Power Systam base model, the attention has been given to the following items:

- the number of generators in model have to be equal to actual number of generators during every test
- conformity of the value of a rotating power reserve to the real value in the power system
- correspondence of the block transformers' quantity to the real value in the power system.

Adequacy of the dynamic model of any power system depends on the level of its simplification. The fullness of the model may become an imperfection, as convergence problems may emerge. It is conditioned on the insufficiant computing capacity of the applying software tools and on uncomplete range of data about objects. Furthemore, some software tools limit the model fullness by their own restrictions. For instance, PAG software tool applying for simulation of dynamics in the Siberian IPS has the following restrictions on quantities:

- buses - 300;
- branches - 500;
- synchronous machines – 100.

In view of mentioned above restrictions the Siberian Interconnected Power System model was decreased and included 220 buses, 275 branches, 58 generators. The same model was investigated using EUROSTAG software package. Previously all data were converted into IEEE data exchange format and then into EUROSTAG format applying the converting subprogram of this package.

In order to take into account identical dynamic behavior of load in both program the following relations were utilized:

$$P = P_0\left(\frac{U}{U_0}\right)^{\alpha} \cdot \left(\frac{\omega}{\omega_0}\right)^{\delta}$$

$$Q = Q_0\left(\frac{U}{U_0}\right)^{\beta} \cdot \left(\frac{\omega}{\omega_0}\right)^{\gamma} \qquad (1)$$

$\alpha=2 \quad \beta=2 \quad \delta=0 \quad \gamma=0$

Thus, load behavior was not depended on frequency.

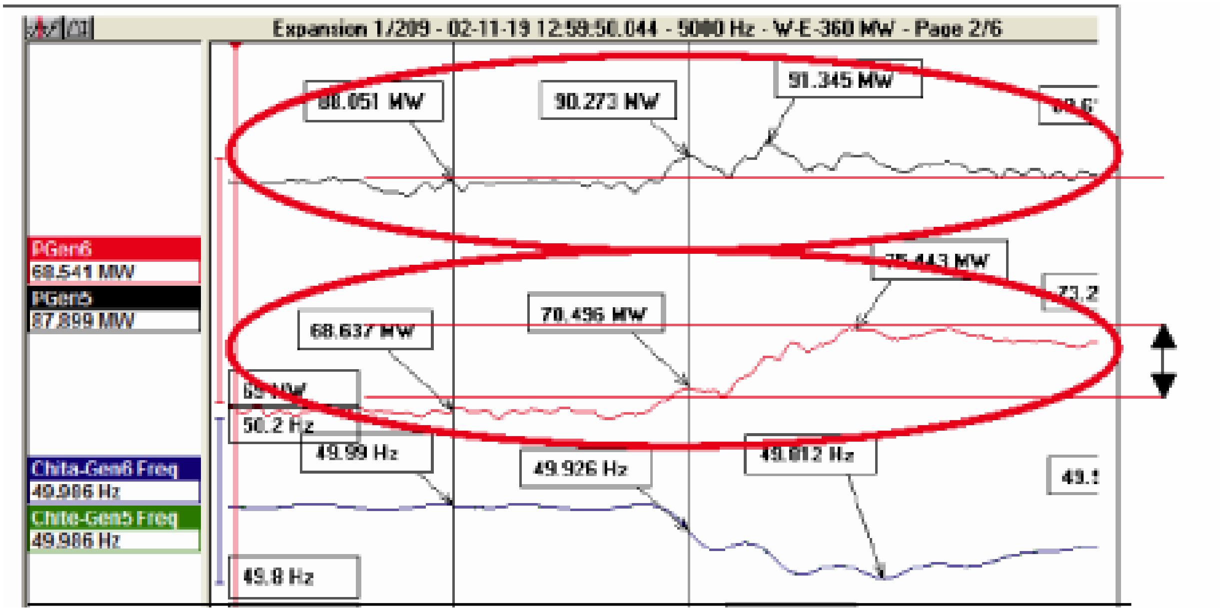


Fig. 4. Differences in generators behavior during Event №3

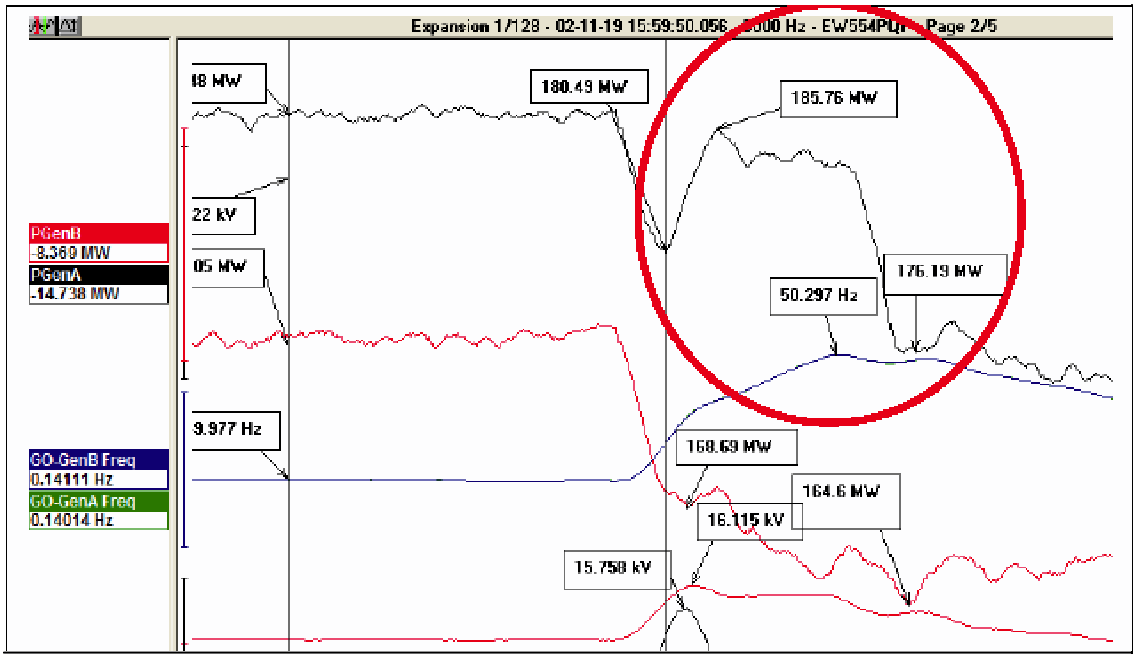


Fig. 5. Unsteady behavior of the generator A at the Gusinoozersk Steam Power Plant

PAG software tool contains its own models of turbines, both steam and hydraulic, control systems, speed and voltage regulators. EUROSTAG package includes a graphical pre-processor which uses elementary block schemes. The user may specify his own models - macroblocks. With the use of this facility, PAG models of equipment have been adapted to EUROSTAG.

The Siberian Interconnected Power System model has been supplied by the following types of macroblocks:

- for steam power plant equipment that includes steam turbine, boiler, governor, power regulator, pressure regulator submodels
- for hydro power plant equipment that includes hydraulic turbine, governor, power regulator submodels
- for power plants` voltage regulator system that includes voltage regulator and exciter system submodels.

The primary frequency control implies the governors response during the emergence the active power imbalances in the power system. Therefore, parameters of governors were analyzed with great care. The governors` parameters which had been used in simulation are pointed in Table 3.

Table 3

Parameters of governors, used in simulation

Parameter	Steam Power Plants	Hydro Power Plants
Permanent droop, %	4; 4.5; 5.0	6; 8; 10
df, %	0; 0.25; 0.3, 0.5	0; 0.1; 0.25
T_+ , sec	1	2; 3; 10
T_- , sec	0.3	2; 3; 10

Fig. 6 shows the results of simulation of reduced model of Siberian Interconnected Power System with the use of the parameters displayed at the Table 3.

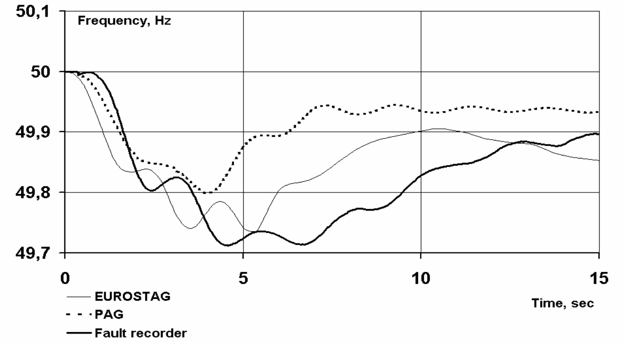


Fig. 6. Comparison of simulation results and real frequency characteristic during Event №3 at the Chita HPP bus-bar

It is easy to note considerable differences between simulated characteristics. Some reasons of such distinctions were discussed in [1-2].

The following investigation were started in order to get more adequate simulated characteristics using EUROSTAG software package. Firstly, it was decided to use more complete model of the Siberian Interconnected Power System, containing 532 buses, 577 transmission lines, 267 transformers and 95 synchronous machines. Such researches are possible with the use of EUROSTAG software package. The results of the dynamic simulation of frequency behavior at the Gusinoozersk Steam Power Plant and Chita Heat Power Plant are displayed in Fig. 7. One can see satisfactory similarity of the curves with the same curves in Fig. 3.

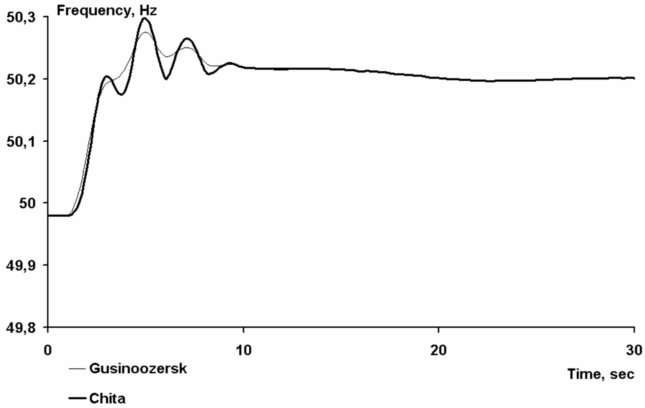


Fig. 7. Frequency dynamic during Event № 5

VI. INITIAL STEPS OF VALIDATION OF THE DYNAMIC MODEL

The final aim is to support the decision process about East-West interconnection. This requires first "proofs by simulations". To make these simulations possible, adequate models of TESIS (UCTE+CENTREL) and IPS/UPS systems must be set-up. The objective consists of modelling the UPS system. This model must be, to a certain extend, certified by comparison of simulation results with measurements. These latter imposes the installation of suitable digital recorders in the UPS system.

This certification will be based on two complementary actions. The first part of that specific work will be devoted to the preparation of a fully documented dossier about data, mathematical model of power plants and networks of the Russian power system. The second part will be based on information from the digital fault recorders to assess the power/frequency control operation of the Russian system and to allow a certification of power system models, including load models.

VII. BUILDING AND VALIDATING THE ENTIRE UPS/IPS MODEL

A. Ways and Means

These works must be realised beyond those made in the framework of the Tacis Project EREG 9601: "Synchronous Interconnection of the TESIS and UPS Networks - Requirements and Feasibility".

The objective is the set up of additional information necessary to assess the operation of the interconnection of Eastern and Western systems. The ways and means necessary to reach this goal can be summarised as follows:

- Definition of the suitable Data Quality (D.Q.) approach in the preparation of the models and parameters;
- The set-up of the "right" system model which must be as complicated as necessary, but must remain as simple as possible. The basic dynamic models for UPS power plants simulation will be those developed during the Tacis Project ERUS 9411 "Stability of Operating Regimes at Power Stations";
- The preparation of the specific dossier including the certified models and parameters for the different power plants and the networks;
- The installation of digital fault recorders in the UPS system to get the basic information allowing the certification of the global UPS model.

B. Methodology

The comprehensive certification of all power plant models, of all parameters implies huge efforts beyond the scope of this investigation. Hence the method which should be used for certifying power system models, at least in the domain considered, should be based on the comparison of simulation results with recordings made following real incidents, or possibly specific tests.

To be effective, such a procedure imposes the use of well built simple models, taking into accounts the basic physical characteristics of the different control systems and processes. Data and models for UPS system should be Data quality (D.Q.) procedures described hereunder

The methods should be specific to each domain considered: the modelling of power-plants and the modelling of networks based on works realised during previous projects. Some aspects should be reconsidered in the frame of system model certification.

The measurements will be realised by suitable digital fault recorders which have to be installed for that purpose in the UPS system. Similar devices have been installed in Western Europe by different companies. For these latter published results will be used to check the system response.

C. Data Quality

Data quality (D.Q.) procedures should be developed in details at the beginning of the project. The main idea behind them is as follows. In a first step, each significant item within the system model should be identified: the origin and the validity of the model used as well as of its parameters. Then, in a second step, the user should decide in full knowledge of the facts those for which complementary investigations could be necessary to guarantee for the model and its data a sufficient quality.

The methods will be specific to each domain considered: the modelling of power-plants and the modelling of networks.

D. Modelling of Power Plants

A library of models has been built for Automatic Voltage Regulators, speed governors and boilers in service in UPS, in the framework of the Tacis Project ERUS 9411. The different units in the system should be modelled using this model's library and the corresponding sets of parameters.
If some units are equipped with prime movers or controllers which are not yet modelled, specific models could be proposed and developed to complete the Russian models library.

To set-up the D.Q. procedures for the power plants modelling, the analysis of the following information sources should be considered:

- The procedures used when putting power plant into service;
- The procedures in application after power plant servicing;
- Tests made on a regular basis during power plant life.

The results of these investigations should permit to comprehensively describe where the actual control parameters are coming from. In case of doubts about some parts of the developed model, specific investigations could be proposed for tuning the related parameters, like for example the application at model level of the practical rules used for setting control parameters in real situation (for example the gains setting of additional signal loops in AVR, whose function is equivalent to Power System Stabilizers).

E. Modelling of Networks

In the framework of the Tacis Project EREG 9601, a system model valid for the year 2005 has been proposed. The D.Q. procedures should analyse globally the origin of data for the different components of the model: analysis of reception tests (like those of transformers), field tests, measurements before putting devices into service (like line parameters), and computations based on physical descriptions etc.

The technical procedure used previously for "equivalencing" the lower voltage parts of IPS should be evaluated taking the best suited IPS as example.

Similar models should be set-up in due course for studying specific situations. These should be suited for checking real world events detected by the digital fault recorders. Prospective simulations considering the East-West interconnection should use a global model including TESIS and UPS.

F. Digital Fault Recorders

Measurements realised during perturbations should be used for checking the validity of the model set-up for UPS system, in the domain of low frequency oscillations. This is necessary to limit the uncertainties related to load behaviour, to system "equivalencing" of generating sets connected at lower voltage levels and not explicitly represented, etc.

The proposed method consists of using planned tripping or real events which take place at random in the system and to record them in different sites. Hence to simulate the identified events, considering the data sets prepared as described above, and to compare measurements and simulated results. Some iterations could then be necessary to refine the modelling and finally to assess the quality of the model (the same method has been used by RWE and REE to prove the quality of their modelling of UCTE and TESIS).

This supposes the installation of digital fault recorders, hence:

- The preparation of technical specifications for these devices;
- The determination of the number and locations where they will be installed, in the frame of a specific budget;

- The acquisition and installation;
- The preparation of the procedures which will be used to collect the recorded data (stored in digital fault recorders) and the additional information about the corresponding initiating perturbation.

G. Simulations

Simulations should be used for performing investigations on the recorded incidents. The steady-state stability of the interconnected system should be investigated. These simulations should be realised considering:

- Linear analysis around an operating point. This should be made using EUROSTAG to generate the linear model, and a specific module based on Arnoldi method to analyse the less damped modes of oscillation;
- Time domain simulations of the full detailed model, to account for possible non linear oscillations.

The size of the dynamic model imposes the use of a powerful computer and a specific version of EUROSTAG. These computations would be realised on a powerful multiprocessors server.

VIII. RECOMMENDATIONS FOR FURTHER TESTS – FULL SCALE TESTS

The immediate task which must be solved in order to accomplish UCTE-IPS/UPS interconnection consists in preparing and carrying out several full-scale experiments, similar to those fulfilled in the Siberian Interconnected Power System, in the specially defined zones of IPS/UPS. These zones could be constructed from some Interconnected Power Systems bordered upon each other. These investigations could be realized in the near future.

After confirmation of the IPS/UPS network dynamic models, the trial synchronization (some minutes) of UCTE and IPS/UPS could be fulfilled. Taking into account the Siberian tests, it may be suggested to produce a 500-1000 MW imbalance in the Siberian Interconnected Power System making generation rejection at the Bratsk Hydro Power Plant as one of possible contingencies. In this case, the wave propagation will take place from the East to the West [4-5]. The methodical approach demands to make the same imbalance in the western part of the interconnection in order to direct the frequency wave from the West to the East.

IX. CONCLUSIONS

The international team that is represented by the authors of the paper is ready to proceed with the certification of IPS/UPS network model which has to precede the East-West Interconnection. This team may head the full-scale experiment which may be needed before the East-West synchronization.

In order to synchronize the East-West power grids in time, not late 2008-2010, the consultation between IPS/UPS and UCTE officials has already started. The interaction and integration of the system protection schemes for the East-West Interconnection may become a discussion topic too.

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