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Smart Grid Technologies Simulation Experience at Russky Island

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Abstract—The paper deals with a power network model for examination of Smart Grid technologies at Russky Island, the end part of the Russian Far East at the Pacific coast. Possible configurations of a Virtual Power Plant, which could be created at this Island, are discussed. Several possible combinations of different energy sources as well as energy storage units are examined. Also examined the dynamics of this smart grid. Use of Fuzzy Controller is shown as an example of control under loss of a link with the main grid. The paper describes a direction of the future studies on the base of this model.

I. Introduction

The current power supply infrastructure of Russky Island is a very convenient object for the Smart Grid concept examination in Russia. Indeed, Russky Island is located at the edge of continental Russia at the Pacific Coast. After recent modernization timed to the forum of Asia-Pacific Economic Cooperation (APEC) 2012, three neoteric Combined Heat and Power (CHP) plants have been put into operation there. Another CHP plant is to be put into operation in the near future. This area of Russia is known as a place with a very rich potential of wind and solar energy. This is why there is a very good opportunity to create so-called virtual power plant (VPP) at this Island. A diagram of an existing power system of Russky Island is shown in Fig.1A. Here the black solid lines show two circuits of 35 kV cable lines, while the yellow solid line denotes 220 kV double cable line that may connect power network of Russky Island with the power system of Vladivostok city.

Another motivating factor for the present analysis is creation of the Far East Federal University at Russky Island. There is an agreement between industry and this Federal University about development of a Microgrid test field on the base of the university campus. In our opinion, it may become a convenient platform to study solar energy production in combination with energy storage devices. Popov Island, the structure of the electricity network might become such shown in Fig. 1B. Here the red dotted line denotes possible 110 kV transmission line.

Taking into account very convenient location of Russky Island for wave energy production and considering Fuel Cells technology as one of most promising smart grid directions, future structure of Russky Island power network might look as shown in Fig. 1C. Here black dotted lines denote possible 35 kV transmission lines.

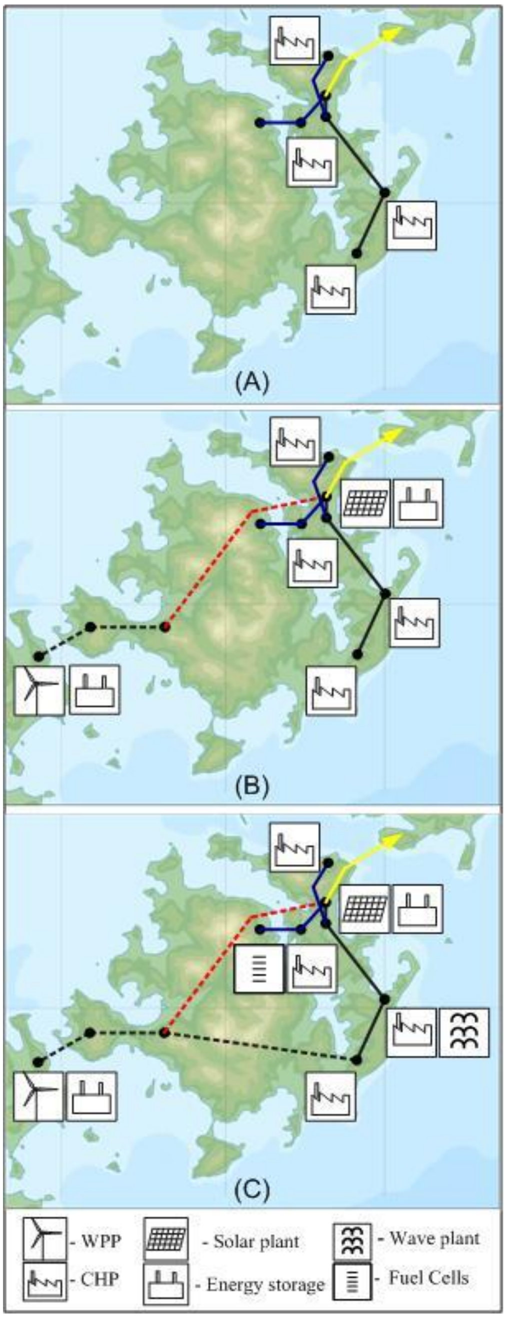

Figure 1. Possible Phases of Evolution of Russky Island Power Network

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II. STATEMENT OF PROBLEM

A. Models and Conditions for Modeling

A virtual power plant (VPP) may include so-called controlled load as one of it's components. Usually, the controlled load is a means to control steady state condition of a power system. In our view, nothing prevents us from using it as a tool to control transients. This is because VPP usually includes different energy storage devices. From the point of view of transients' control, the main requirement for energy storage devices is to provide a quicker response to changing power system conditions. Among other possible energy storage devices meeting this conditions are super capacitors, production technology of which have been recently mastered in Russia. These devices are a combination of a high-power rechargeable battery and a powerful capacitor. There are also other types of energy storage devices such as a superconducting energy storage system, flywheel, etc., which can be used for controlling transients in smart grids.

A characteristic feature of a VPP that can be created on the basis of the power supply network of the Island, is the possibility to use this network as a means of System Integrity Protection Schemes (SIPS). SIPS ensuring the integrity of power systems usually perform automatic load shedding in different networks including Vladivostok region. Switches of load feeders used by SIPS system are not quick enough. This requires excessive switch off the consumers in the framework of emergency control. Two 220 kV lines linking the Island to the mainland have modern circuit breakers. The speed of these circuit breakers is higher than the speed of load feeder switches. In case, of active power flow from the mainland to the Island, this VPP may significantly increase SIPS efficiency if it is used for load shedding. Power shortage, which appearing in the power supply grid of the Island, can be eliminated by the use of Under Frequency Load Shedding (UFLS) in combination with controlled load.

A mathematical model of VPP should be adequate to explore all aspects of emergency control in the VPP. Since the use Smart Grid components the instruments of SIPS requires careful study, we attempted to create such model. We believe that the variety of transients occurring in different VPP components have to be examined using different software packages with diverse calculation possibilities. At the initial stage of the research we created, the power supply model of Russky Island on the basis of two software packages, such as EUROSTAG 5.1 and MATLAB / Simulink / SimPowerSystems. The choice of EUROSTAG 5.1 was determined by the need of further exploration of various processes in the Russian Far East Power Grid consisting of one or several VPPs as components of a Smart Super Grid.

This version of EUROSTAG 5.1 with a function for interaction external software can become a very attractive tool for Smart Grid simulation. On the other hand, certain features of MATLAB / Simulink / SimPowerSystems make this software a very convenient tool to study many ways to control steady and transient modes in Smart Grids. This two software packages can be used for further improvement of methods for Smart Super Grid simulation in the Russian Far East, including VPP at Russky Island.

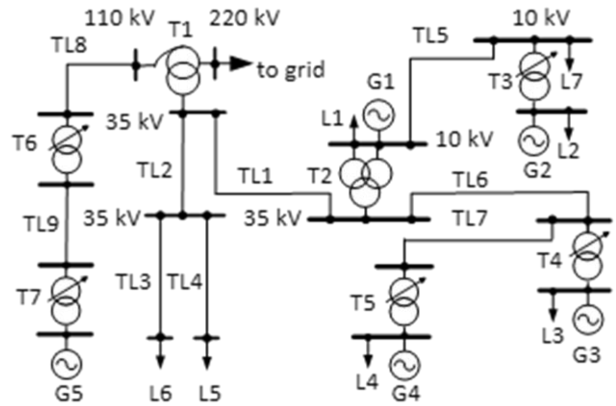

Figure. 2. Proposed Equivalent Model of the Russky Island Power Network

The power supply network of Russky Island is isolated from Vladivostok city grid, and constitutes an autonomous power system. 220 kV transmission lines connecting this electric network to mainland power grid will be put into operation in the nearest future. Possible creation of Wind Power Plant (WPP) will certainly require a high rated capacity Battery Energy Storage System (BESS) at the Island power network. In turn, creation of the above-mentioned micro-grid on the base of the university campus will undoubtedly stimulate use of solar energy together with BESS or some other type of energy storage plants. These factors will make it possible to refer the power network of Russky Island to the class of Virtual Power Plants.

This paper examines the power network of Russky Island, shown schematically in Fig. 2. In the real world, all power transformers as well as transmission lines in this power network were built as double circuit objects, except 35 kV cable transmission lines TL3 and TL4, as well as 110 kV overhead transmission line TL8.

Table I lists the scheme parameters (column "Name" and column "N x Pr, MW"), where N is "number" and Pr is "rated active power of unit". We assume that the electric load L1 consists of two parts. The first part is constant, while the

TABLE I. SCHEME PARAMETERS

Generation			Load		Transmission lines	
Name	N x Pr, MW	N x Pw, MW	Name	P, MW	Name	L, km
CHP1-G	5 *x* 6.6	5 *x* 6.6	L1	34,5	TL1	0,15
CHP1-D	2 *x* 1	0	L2	0,4	TL2	5
CHP2-G	2 *x* 1.8	2 *x* 1.8	L3	16,1	TL3	1
CHP2-D	2 *x* 1	0	L4	2,1	TL4	1
CHP3-G	2 *x* 6.6	2 *x* 6.6	L5	16,3	TL5	2
CHP3-D	2 *x* 1	0	L6	6,3	TL6	6
CHP4-G	2 *x* 1.5	2 *x* 1.5	L7	4	TL7	3,7
CHP4-D	2 *x* 0.4	0	∑	79,6	TL8	11,1
WPP	5 *x* 2.3	5 *x* 2.3	Import	14.5	TL9	4,7
∑	73,1	66,3				

second one can be controlled during transients. Parameters of the transformers and the generators are listed in the Appendix.

This power network model was examined using both types of the above-mentioned software. The difference between models is in the way of representation of generation units at CHPs and WPP. Detailed layout of the model was made in the EUROSTAG 5.1, while an equivalent model was examined using MATLAB/Simulink software package.

B. Power Network Model in Simulink format

At this stage of the research, comparison of simulation results showed absolute identity of transients obtained with the using these two software packages. This is why only Simulink model in shown in Fig. 3.

Each of four CHPs consists of two equivalent generators (green rectangles in Fig. 3). One of the units is a gas-turbine block and another one is formed by several diesel-generators. Power transformers are shown in gray, while transmission lines are represented by blue color rectangles. Symbols of resistance and reactance seven denote loads. It is assumed that all seven have constant resistance. Two parallel transmission lines connect the power network of Russky Island with the mainland part of the grid (denoted as “Inf. Bus”). The load shown in yellow color is a special type of load that aslo includes above-mentioned electrical load whose structure is shown in Fig. 5.

In this diagram, the loads at the voltage level 35 kV include a distribution network with rated voltage of 10 kV and less, but some of them are combined with equivalent generators nodes with rated voltage 10 and 6.3 kV.

C. Generation Unit Model in Simulink format

Each of these synchronous generators was modeled on the basis of conventional sixth order model. A typical Simulink model of AGC (automatic generation control) as well as parameters of automatic voltage regulation were included in this study. A well-known Rowen’s model [1]-[2] for a gas turbine was used in this analysis, however only one control channel was used for simulation. An advantage of this

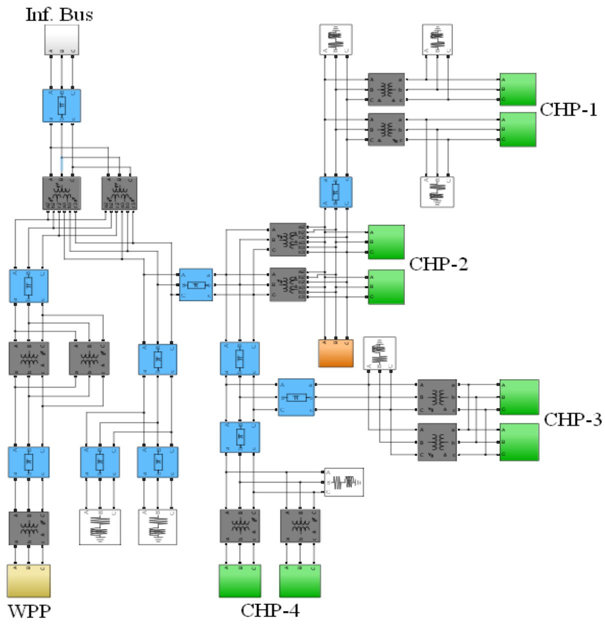

Figure 3. VPP model in Simulink format

approach is neglecting the channels of exhaust gases temperature control and acceleration loop. Fig. 4 demonstrates a Simulink model of the gas unit used in this study. The UFLS automation has the following parameters: 48.8 Hz is the frequency threshold triggering it, the frequency deviation step for each next activation of load shedding is 0.01 Hz. It was assumed that all of 35 kV substations have UFLS automation. Each unloading step means switching 5 percent of the total power consumption at Russky Island.

Moreover, several assumptions were made in order to model the existing mini-grid at Russky Island. First, it was assumed that this electricity network is connected with the Vladivostok city power network. Second, the diesel-generators, being reserve power units at each CHP, were not been taken into account. Third, the load demand level corresponds only approximately to the real one because there is no reliable data about consumption in power system at present.

Sudden loss of connection to the main power grid as well

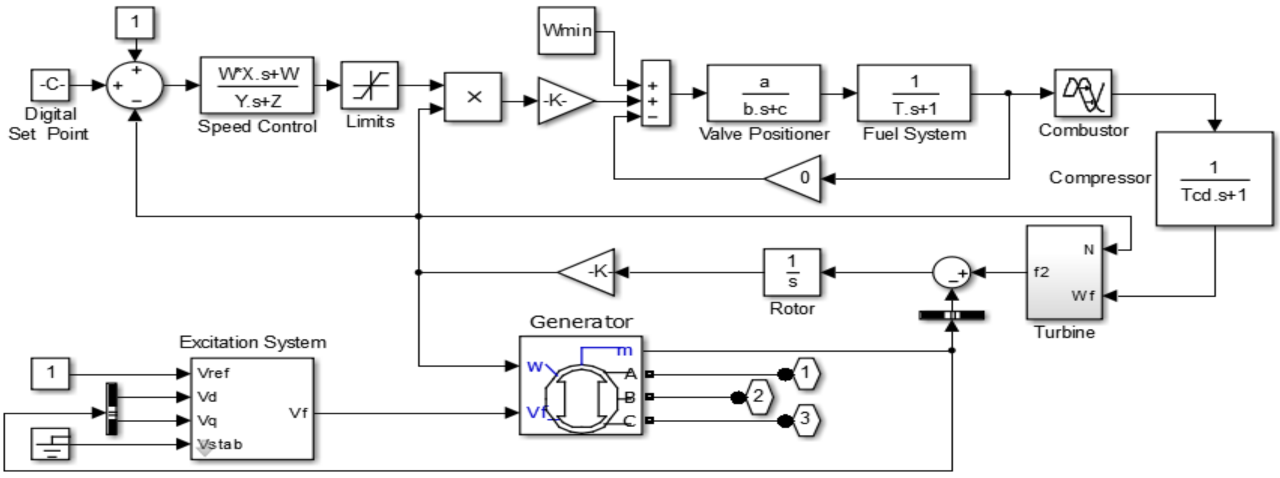

Figure. 4 Simulink model of gas-turbine and generator unit

as subsequent power shortages may be taken as one possible disturbance in the VPP. In such case, a traditional instrument of emergency control is the use of Under Frequency Load Shedding automation (UFLS). However, taking into account possible use of different types of energy storage devices in the micro-grid of the university campus we may suggest that at least a share of the load can be used for damping frequency oscillations as well as for emergency control. It is assumed that 70 percent of the load shown as L1 in Fig.2, constitutes the consumption of the university campus.

Meanwhile, 30 percent of it can be designated for continuous control using a Fuzzy Controller. A small part of the campus micro-grid is shown in Fig.5. The models of both PV module and BESS do not require further development because they already exist in MATLAB. The correlation principle of the controller is explained in Fig. 6.

Fuzzy Logic transformation was made based on Mamdani's Fuzzy Inference System (FIS). For the fuzzification one input variable is normalized. Two membership functions such as triangular and trapezoid are used as shown in Fig. 6. For fuzzy inference, "IF-THEN" rules were designed for a fuzzy variable process, and the "MINMAX" method is applied for fuzzy rule implication and aggregation.

MATLAB FIS editor was used to create this controller and Simulink Fuzzy Logic Toolbox / Fuzzy Logic Controller

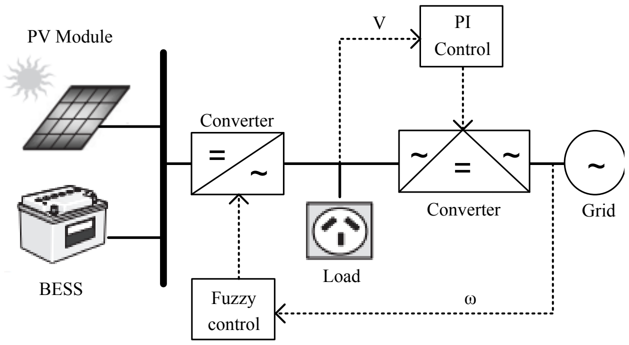

Figure 5. Structure of Part of Controlled Load: V is voltage, ω is frequency

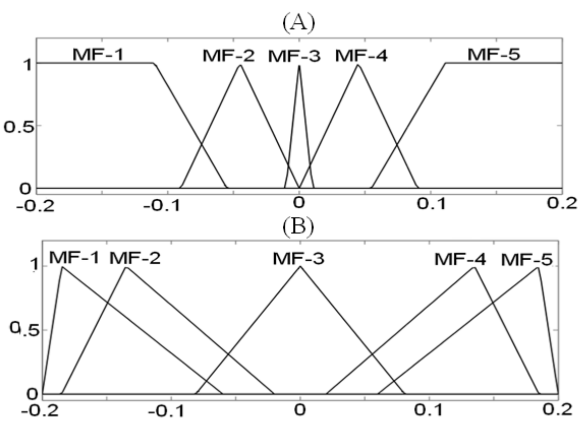

Figure 6. Fuzzy Controller Logic: (A) is inputs, (B) is outputs

calculated control signal for UFLS automatics in the model based on all equivalent gas turbines mean angular speed error.

Recently the technology of coupling the battery energy storage system (BESS) with a capacitor energy storage plant jontly referred to as a super-capacitor system has been mastered in Russia. This is way we can assume that such super-capacitor system could be used to damp low frequency oscillations in micro-grids and therefore in Smart Grids.

D. Load Resistors for DFIG control

Another examined situation here is the condition of Fault Ride-through (FRT) for WPP. This problem in distributed generation can with time become a very important subject for Russky Island power networks. For instance, in order to meet FRT conditions it was recently suggested to use the so-called series dynamic braking for wind turbines coupled with induction generators [3]. Special solutions were proposed for wind turbines coupled with DFIG [4]-[5]. This paper once again examines technical solution to provide for FRT conditions for DFIG-coupled wind turbines. This solution involves so-called loading resistors similar to series dynamic resistors, but having different physical properties.

The effect of loading resistors inclusion (LR) into stator circuits of DFIG during hard faults consists in prevention of bus voltage dropping lower than the threshold triggering a protective relay. It's assumed that this feature prevention disconnection of large quantity of wind turbines. If the above-mentioned WPP at Russky Island is based on the DFIG type generation unit the FRT conditions might be met for example by using the series braking resistors as one of the possible emergency control tools, which can become another level of power systems integrity protection.

The model of DFIG turbines includes a stator protection device with the following algorithm: the wind turbine has to be disconnected when voltage drops below the threshold (0.75 p.u.) and remains below this threshold for a certain time (0.08 sec). In case of close faults loading resistors can be used as protection for wind turbines in a power system.

Fig. 7 shows the operating principle of a load resistor, which is used in this study.

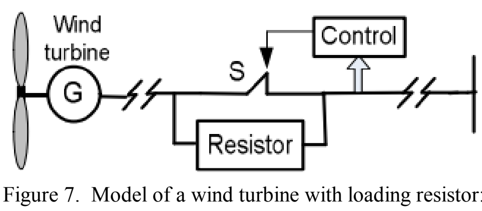

Figure 7. Model of a wind turbine with loading resistor: G is generator, S is a bypass switch

III. Simulation Results

Two situations were examined in order to demonstrate the potential of the developed power network model. The first one implies emergency isolation of Island Russky power network from the mainland grid. This case can happen if the 220 kV transmission lines to the main grid are denergized. Another situation can arise upon three-phase fault on 110 kV overhead transmission line with subsequent clearing and automatic reclosing of the transmission line.

These transmission line's disconnections are modelled for different operating modes and power network configurations. Basic generation and consumption mode is shown in Table I (columns "Generation, N*Pw", and "Load, P"), where symbol "Pw" denotes "working power". Transients in different modes in this diagram has shown the likelihood of low frequency oscillations initiation. In order to demonstrate this, one more mode was examined here, with 5.5 MW generation at CHP-1 of and 22 MW power import.

Simulation results of emergency disconnection of 220 kV transmission lines in both modes are shown in Fig. 8. The results UFLS automatics operation during these transients are listed in Fig. 9. It can be see that use of such controlled load with intelligent control algorithms can become an extremely effective instrument both for low frequency oscillation damping and for decrease in the volume of consumer load disconnection as a result of activation of system protection schemes.

Efficiency of loading resistors was shown by simulation of following sequence of events: a fault occurring on 110 kV transmission line is modelled for the case when WPP power is transmitted both via overhead 110 kV transmission line and 35 kV cable lines as it is shown in Fig. 1,C. This is a good case to demonstrate opportunities of LRs and the benefits for a transmission system.

In this study the rated power of each resistor is assumed to be 30 percent of the wind turbine rated power. It is assumed that this WPP consists of 5 so-called Double Fed Induction Generators (DFIG) each of which has rated power of 2.3 MW. The control law is without feedback, and repeats action of bypass switch shown in Fig. 7 with the delay of 0.04 sec. Table II demonstrates the sequence of events in this computational experiment, while Fig. 10 illustrates the results of simulation for such sequence of events. One can see benefits of WPP based on DFIG technology for FRT.

TABLE II. Event Sequences

Event Time (sec)	**Events Sequences for Simulation**
1.0	3-phase fault at 110 kV transmission line
1.04	load resistor insertion
1.2	fault clearing and transmission line opening
1.24	load resistor bypass
3.2	autoreclosing of transmission line

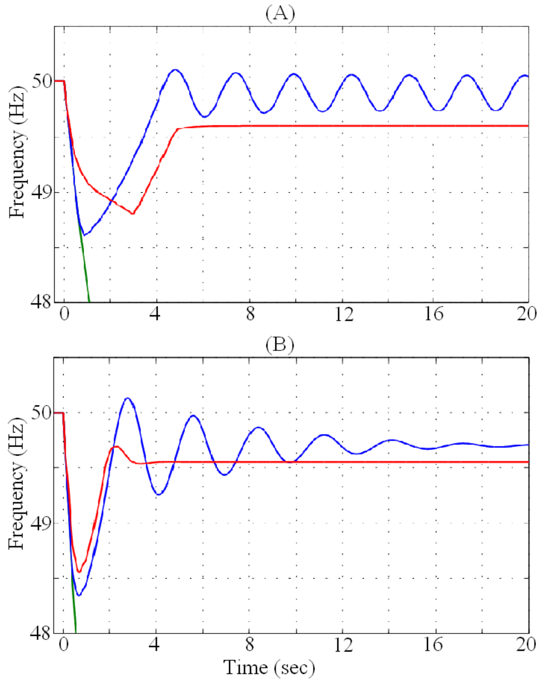

Figure 8. CHP-1 bus frequency. (A) in extreme regime, (B) in base regime: green line – without control actions, blue line – with UFLS, red line –with UFLS and Fuzzy Stabilizer actions

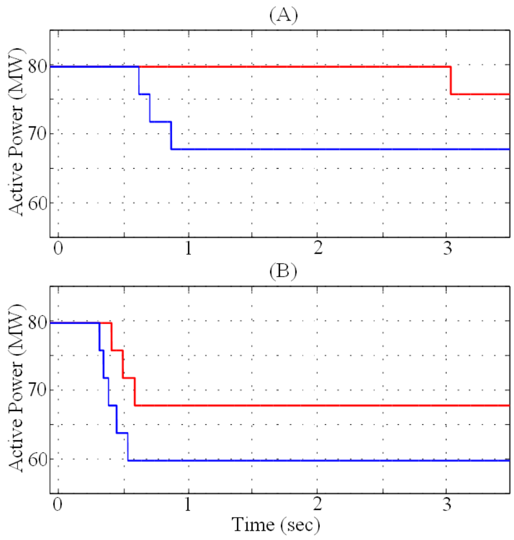

Figure 9. Results of UFLS actions. (A) in extremely regime, (B) in base regime: blue line – with UFLS, red line –with UFLS and Fuzzy Stabilizer actions

IV. Direction of Future Investigations

Three main tasks need to be solved in Russky Island power network. The first one is to develop models for distributed generation that are missing from EUROSTAG and MATLAB/Simulink software packages. The second is to provide for interaction of these programs to calculate different types of transients using instantaneous values and phasors. The third is explore the possibility of keeping the integrity both of possible VPP at Russky Island and the Russian Far East Power System based on such interaction. These tasks are going to be solved in the near future by one of the fifteen Centers of Research, Education and Innovation in Russia that

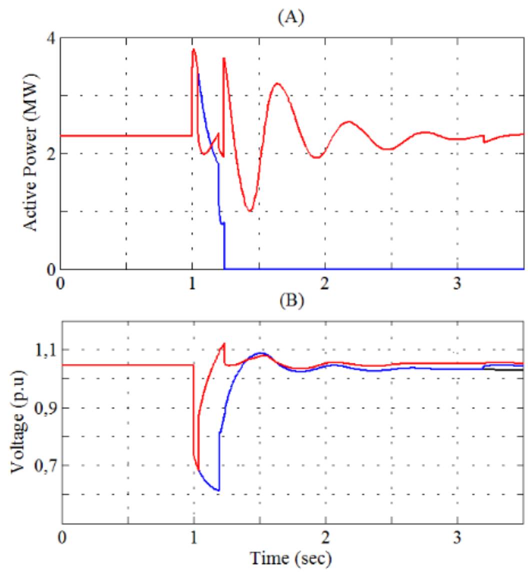

Figure 10. DFIG active power (A), voltage at WPP bus (B). Blue line – without resistor insertion, red line– with resistor

will be created by Skolkovo Institute of Science and Technology (SkolTech) together with Massachusetts Institute of Technology (MIT). This center will focus on smart grid technologies. The power networks of Russky Island will become one of the subjects for international exploration with based on the model presented in this work. The project is called "Modeling and Control of Power Electronics and Systems for Smart Grids". Its objective is to prepare the conditions for realization of such construction plans. This project is financed in the framework of the SkolTech/MIT program for "SkolTech Seed and Ramp-up Team Funding". It is implemented by a group of experts from the U.S. and Russia. Their future studies will use Russky Island power network model for examine the Russian Far East Power Grid that might become the first place in Russia with the virtual power plant.

As it has been already noted above, Russky Island is a very convenient place to simulation and explore new technologies for power generation and energy storage, such as wind power plant, photo voltaic cells, solid oxide fuel cells, battery and flywheel energy storage systems, super-capacitors etc. Such approach might be useful for popularization of new technologies among Russian companies in the power industry. This model can be used to study dynamics of power system's applying new energy sources as well as their technical and economic feasibility. Exploration of power factor of regulated load influence on the behavior on a virtual power plant is planned in the near future. In addition, examination of the potential role of nonintrusive load monitoring in developing sophisticated models for assessing power system stability and power plant operation, as applied to the Island Russky power network particularly in the context of distributed generation will be done in the frame of the above-mentioned international cooperation.

APPENDIX

TABLE III. SCHEME PARAMETERS

Symbol	G1	G2	G3	G4
Number	5	2	2	1
S_n, MVA	7.33	2	7.33	1.8
P_n, MW	6.23	1.8	6.23	1.62
U_n, kV	10	6.3	10	10
cos φ	0.85	0.9	0.85	0.9
f, Hz	50	50	50	50
Speed, rpm	1500	1500	1500	1500
Reactances in p.u.				
X_d (%)	238	238	238	375
$X_{d'}$ (%)	33.6	33.6	33.6	26.7
$X_{d''}$(%)	24	24	24	14.8
X_q (%)	121	121	121	225
$X_{q''}$(%)	23	23	23	15
X_l	18	18	18	20
Time constants				
Td0' (s)	9.67	9.67	9.67	2.6
Td0'' (s)	0.05	0.05	0.05	0.019
Tq' (s)	0.337	0.337	0.337	0.267
Tq'' (s)	0.029	0.029	0.029	0.010
Inertia constant (s)	1.19	1.19	1.19	3
Resistances				
Stator resistance (pu)	0.003	0.003	0.003	0.003

TABLE IV. TRANSFORMER DATA

Symbol	2 x T1	2 x T2	2 x T4	2 x T3	2 x T5	2 x T6	2 x T7
S (MVA)	63	25	a25	16	6.3	25	2 x 16
Ratio	220/110/35	35/10	10/6.3	35/10	35/10	110/35/10	35/0,575
P_{cu} (kW)	215/-/-	120	110	85	46.5	140/-/-	85
U_k (%)	11/35.7/22	10.5	10	10	7.5	10.5/17.5/6.5	10

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