

A Multi-Agent Approach to Electric Power Systems

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1. Introduction

Electric power systems are rather complicated objects for modeling, investigation and control because of many elements and complex structure. Comprehensive multi-functional software is necessary to study multi-dimensional systems of the kind. The problems of current state estimation should be solved for monitoring of electric power system operation conditions.

Emergency control actions are required to improve stability of electric power systems. A multi-agent approach can be used to solve such complex problems of electric power systems.

The chapter deals with the following important areas of modeling, investigation and control of large electric power systems:

- Effective construction of comprehensive software by using the multi-agent approach;
- Decomposition of state estimation problem for large electric power system by using phasor measurement units and the multi-agent approach;
- Multi-agent approach to coordination of emergency control devices against voltage collapse.

The effectiveness of multi-agent approach for solving the above problems is illustrated by test examples.

2. Effective construction of comprehensive software by using the multi-agent approach

2.1 Methodical approach to multi-agent software development

Traditionally, there are active complex research of energy systems (electrical power system, natural gas industry, mineral oil providing system, carbon providing system, heat supply system), Fuel Energy Complex (FEC) and energy security problem of Russia in Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS). Results of researching the branch energy systems often are input data for FEC research. And results of researching the developing trends of FEC must be taken into account while analyzing developing process of the branch energy systems.

It is necessary to co-ordinate input and output information to get grounded conclusions and recommendations which are prepared for outer organizations. That is why we must create

integrated informational and computational environment for investigating i.e. IT-infrastructure (infrastructure based Informational Technologies) of research activities. IT-specialists of the Institute have proposed the project of creating such IT-infrastructure taking into consideration the specificity of power engineering researches and up-to-date tendencies in the development of Informational Technologies (Massel et al., 2008).

We interpret **IT-infrastructure** as a combination of Hardware, Software, Dataware and Telecommunication for supporting research activities; technologies of their making and using; both inner and outer standards for making informational and program products in the field of energy researches, exchange of them and outsourcing at the informational market. On the one hand, IT-infrastructure is integrated informational and computational environment for energy researches implementation. On the other hand, it creates preconditions for stage-by-stage transition to the creation of distributed data bases and program complexes; distribution and parallelization computations; outsourcing on the base science intensive informational and computational products (creation of Web-services).

There is an active work that deals with method of software that supports energy research to become intelligent.

One of possible way is to integrate multi-agent technologies, ontologies and service-oriented architecture as a platform for intelligent software development for energy research. Using the multi-agent systems conception based on Service-Oriented Architecture (SOA) implementation, where the problem of knowledge representation solved with a help of ontologies had been proposed by authors. Such knowledge representation gets additional advantage when designing software with Model-Driven Architecture (this approach is developed and used in ESI SB RAS).

Conception of creating programs, which can exist autonomously and interact with each other in independently manner perfectly combines with technical abilities which SOA gives. Usage of software agents, particularly, intelligent software agents, is good, because experts could delegate their authorities for solving complex tasks to such agents. Intelligence is a feature of software agents that contains in their ability to knowledge processing. One of the modern technologies of knowledge representation is using ontologies. At first time, SOA had been used to create applications in commercial area and later it becomes more popular in scientific research and other subject areas.

Implementation of IT Infrastructure of science research in ESI SB RAS created the necessary prerequisites for using such modern and available technologies as Web-services. One of the main ideas of ES problem research support is increasing the intelligent and adaptation level of software tools (Massel et al., 2009). Using the Web-services technology per se can't influence increasing the intelligent level of software tools for supporting research. Therefore, using the multi-agent technologies, which were conceived from intersection of systems theory and artificial intelligence and became popular nowadays had been proposed by authors (Fartyshev et al., 2009).

The original author's methodical approach to multi-agent software complexes development for energy research includes:

- the method of designing and implementing the multi-agent software complex which can be used for the new generation software for energy research support;
- by using Service-Oriented Architecture of multi-agent software it is possible to consider the agents as the Web-services, application is built from;
- data models and algorithm of data processing are the base of universal software components which can be used while multi-agent software constructing.

The author's method is a direction which combines agency conception and object-oriented approach to software development. Following this direction it is possible to implement the multi-agent software complex. The method consists of the following generic stages:

1. Formulating purposes of the development.
2. Formalizing the use cases of multi-agent software.
3. Defining the agents structure and their main and auxiliary functions.
4. Defining the type and main properties of agents environment.
5. Specification the agents structure and distribution the functions among agents. Choosing the agents architecture.
6. Defining base interactions (relations) among agents.
7. Defining possible agents actions (operations).
8. Designing and implementing multi-agent software complex architecture.
9. Testing implemented multi-agent software.
10. Integrating the multi-agent software into the IT-infrastructure of energy research.

Service-Oriented Architecture is one of the key concepts in the whole implementation plan of multi-agent software complex. Considering separate agents in the view of Web-services gives certain advantages like using mutual assistance, parallelism, high degree of reusing and so on. Multi-agent software complex is implemented in distributed client-server architecture where the application server is the central component (Fig. 1).

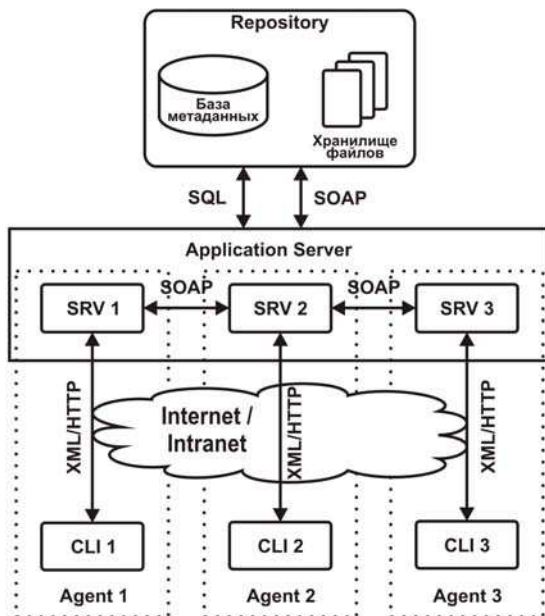


Fig. 1. Architecture of multi-agent software

Thus, agent is a certain application consists of client (service consumer) and server (service provider) at the physical implementation view point.

The main task of the agent client part is providing the user-friendly interface which is used to access the agent's features mainly implemented in its server part. Agents can work with

data and knowledge by connecting the Repository through the Simple Object Access Protocol (SOAP) or by using the Structured Query Language (SQL). Agents can connect to each other also by using the SOAP. However, there can be used other similar to SOAP technologies that could transmit XML data through the Hyper-Text Transfer Protocol (HTTP), for instance XML-Remote Procedure Call (XML-RPC), to provide the agents interconnection.

There is need to use all three components of SOA: service provider, service consumer and register of services in implementation of the multi-agent software complex based on SOA. Register of services is the component that cares about service publication and providing the links to the services that are already registered in it. Register is used for service discovery and publication accordingly by service consumers and service providers. The existing Repository of IT-infrastructure of science research (Massel et al., 2008) is used in service register role.

The universal system components compound the base of multi-agent software complex are the following:

- the new standard for storing and representing the information models of FEC, that are one of the key elements in ES problem research;
- service for uploading and downloading information models of FEC into the Repository of IT-infrastructure;
- agents messaging services;
- agents integration services;

Developed method and architecture were used to design and implement multi-agent software INTEC-M for energy security problem research.

2.2 Multi-agent software INTEC-M

Design and implementation of the multi-agent software INTEC-M for supporting the ES problem research were done based on author's method and in accordance with developed architecture.

There is distribution of functions between different agents in the idea of INTEC-M software implementation. Such software is a compound of mentioned above system components and specific intellectual and traditional agents for specific solving of certain subject area problem.

The common scheme of agents working process in accordance with computational experiment in researching the developing trends of FEC considering energy safety requirements is shown at Fig.2.

Every implemented agent solves the certain task that corresponds to the certain stage of computational experiment. One of the main advantages of proposed approach is independence of hard-coded sequence of computational experiment stage that is accomplished by such agent's properties as autonomy and mobility.

The main purpose of *Agent of extraordinary situations modeling* is fusion of human-readable wordings of extraordinary situations scenarios with its digital interpretation in model. The agent gives a researcher an opportunity to store, classify, configure and apply different types of extraordinary situations in the computational experiment process.

Agent of development scenarios of FEC modeling is a software tool allowing a researcher to form the FEC development variants tree which is the main base during the computational experiment process.

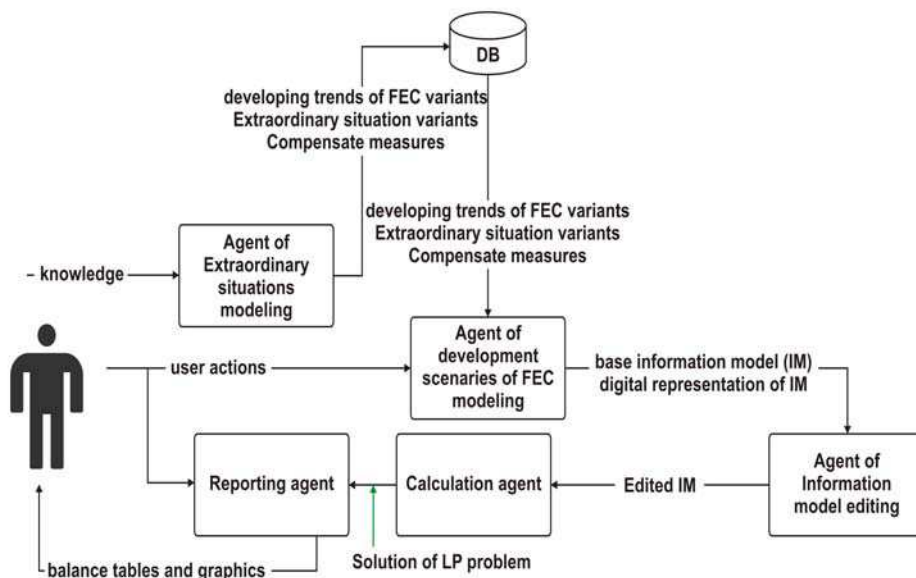


Fig. 2. The common scheme of agents working process

Agent of FEC information models editing gives a researcher accessible and effective software tools for working with FEC information models including its creation from the beginning.

Calculation agent is an open source software tool (Ip_solve) for solving Mixed Integer Linear Programming (MILP) problems implemented by third-party. It was included in INTEC-M software, because the common linear programming problem is traditionally solved in FEC development trends research considering energy safety requirements.

The main purpose of reporting agent is to create and then analyze different table reports and its graphic representations of computational experiment results. The agent gives an opportunity to a visual comparing of summary and detailed computational experiment data.

Agents get the additional property of mobility which is valued agents property in multi-agent systems by using such modern and standardized technologies as Java and XML.

The main advantages of INTEC-M software are the following:

- The uniform ideology and technology of development;
- Adaptive to changing behavior of computational experiment scheme;
- Cross-platform;
- Trends to parallel data processing;
- IT-infrastructure integration.

The joint computational experiment of evaluation of possible deficits fuel and energy resources and measures for its to compensate in extraordinary situations was processed. As the extraordinary situation it was taken cold winter in Central Federal District of Russia.

Effectiveness of using implemented INTEC-M software for ES problem research of Russia and its regions is implied in useful, psychologically comfortable work that improved by many experts.

3. Decomposition of state estimation problem for large electric power system by using phasor measurement units and the multi-agent approach

3.1 Decomposition of state estimation problem

State estimation of electric power systems (EPS) is an important procedure that allows on-line calculation of state variables for a current scheme of electric network on the basis of teleinformation. The obtained calculated model of power system is then used to solve various technological problems to effectively control electric power system.

The calculations for a large system encounter the problems related to the inhomogeneity of calculated schemes, large volumes of various data to be processed and the requirement for high speed software. Besides, the need for online state estimation of such systems increases the burden on the available computing resources in the EPS Control Center. The distributed data processing at decomposition of the state estimation problem is an effective method of solving these problems.

Until recently state estimation in Electric Power Systems was mainly based on the SCADA (Supervisory Control and Data Acquisition) measurements: voltage magnitudes, branch power flow, nodal power injections and, occasionally, current magnitudes. The advent of WAMS (Wide-Area Measurement System) that contains phasor measurement units (PMU) as the main measurement equipment makes it possible to synchronously and accurately control the EPS state and essentially improve the results of state estimation. The use of PMU measurements offers new possibilities in decomposition of the state estimation problem.

The distributed approach to state estimation applies *decomposition* and *aggregation* procedures. The SE procedure thereby consists of the following stages:

1. Division of the calculated scheme into subsystems by one or another method at the decomposition stage.
2. State estimation for each subsystem.
3. Solution of the coordination problem consisting in calculation of the boundary variables and check of the boundary conditions. If the conditions are not met, the subsystems are recalculated with new values of boundary variables.
4. Formation of the general solution for the whole scheme by combination of solutions for individual subsystems and solution of the coordination problem at the aggregation stage.

In large-scale interconnections that consist of EPSs operating in parallel and have no single control center, the aggregation stage may be neglected. The calculation terminates by solving the coordination problem at the solution coordination center, resulting in the estimated state obtained for each subsystem that is balanced in the boundary regions with the states of neighboring subsystems.

Flow chart of distributed state estimation is shown in Fig.3.

Decomposition of the state estimation problem proposed by authors is based on structural (by subsystems) and functional (by the problems solved) decomposition. The structural decomposition is made by dividing the calculated scheme into subsystems by one or another method. The functional decomposition is made in accordance with the problems solved within the SE procedure. The main of them are: analysis of network topology (formation of current calculated scheme); analysis of observability; analysis of bad data; calculation of estimates and calculation of steady state with regard to the estimates obtained.

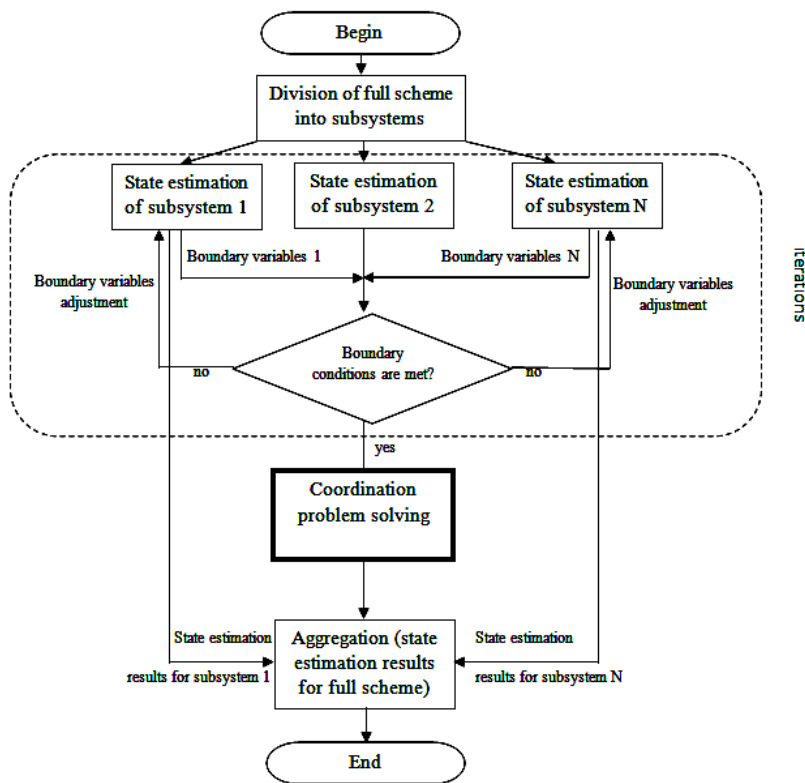


Fig. 3. Flow chart of distributed state estimation

3.2 Algorithms of the calculated scheme division into subsystems

The calculated scheme can be divided into subsystems by the following techniques: decomposition utilizing geographical characteristics, decomposition by boundary nodes, by tie-lines, based on the structure of gain matrix, by Danzig-Wolf decomposition algorithm and others.

The main algorithms of state estimation problem decomposition suggest dividing the calculated scheme into subsystems whose boundaries are either nodes or branches.

As boundary conditions at decomposition with boundary nodes the equality of voltage magnitudes and phases at these nodes for the i, j, \dots, k -th subsystems should be met (Gamm, 1983):

$$U_i = U_j = \dots = U_k ; \tag{1}$$

$$\delta_i = \delta_j = \dots = \delta_k ; \tag{2}$$

Besides the boundary balance relationships should be met. For example for boundary node l , common for the i, j, \dots, k -th subsystems

$$P_l + \sum_{s=i,j,\dots,k} \sum_{m \in \omega_s} P_{lm}(U_l, \delta_l, U_m, \delta_m) = 0; \quad (3)$$

$$Q_l + \sum_{s=i,j,\dots,k} \sum_{m \in \omega_s} Q_{lm}(U_l, \delta_l, U_m, \delta_m) = 0, \quad (4)$$

where ω_s - a set of nodes of the s -th subsystem, that are adjacent to the l -th node.

As boundary conditions at decomposition with boundary branches the relationships for active (5) and a reactive (6) power flows should be observed:

$$P_{ij}(X_i, X_j) = -P_{ji}(X_i, X_j) - \Delta P_{ij}(X_i, X_j), \quad (5)$$

$$Q_{ij}(X_i, X_j) = -Q_{ji}(X_i, X_j) - \Delta Q_{ij}(X_i, X_j) + Q_{gij}(X_i, X_j), \quad (6)$$

where P_{ij} and Q_{ij} - power flows from i -th subsystem to j -th subsystem, $\Delta P_{ij}(X_i, X_j)$, $\Delta Q_{ij}(X_i, X_j)$, $Q_{gij}(X_i, X_j)$ - aggregate losses of active and reactive power and aggregate power of section links, X_i, X_j - state vectors for i -th and j -th subsystems.

For boundary branch m - l

$$U_m^2 - (U_l - \frac{P_{ml}r_{ml} + Q_{ml}x_{ml}}{U_m})^2 - (\frac{P_{ml}x_{ml} - Q_{ml}r_{ml}}{U_m})^2 = 0, \quad (7)$$

$$\delta_m - \delta_l - \arctg \frac{P_{ml}x_{ml} - Q_{ml}r_{ml}}{P_{ml}r_{ml} + Q_{ml}x_{ml}} = 0. \quad (8)$$

Decomposition of calculated scheme with boundary branches is more often used.

3.3 PMU measurements usage for the solution of decomposition of state estimation problem

For decomposition of power system state estimation problem it is necessary to maintain accurate values of voltage magnitudes and phases at boundary nodes of subsystems for iteration-free solution of coordination problem. A simple but not an optimal solution is placement of PMUs at all boundary nodes. Based on the measurements to be received from the placed PMUs the voltage magnitude and phase at a neighbor node can be calculated using the electrical circuit equations. The phasor voltage measurement obtained by the equations further will be named as "calculated" PMU.

The study shows that the accuracy of parameters of the "calculated" PMU practically equals the accuracy of measurements of the physical PMU (Kolosok et al., 2009). With an optimal combination of physical and "calculated" PMU at all boundary nodes of subsystems it is possible to determine voltage magnitudes and phases required to coordinate the solutions obtained for individual subsystems.

In order to minimize the number of PMUs authors analyze not only the list of boundary nodes but the list of internal branches within subsystems that are incident to these nodes as well. The boundary nodes may happen to belong to one and the same subsystem and bound one and the same branch. Then it is enough to place a physical PMU at one end of the branch and a "calculated" PMU at the other.

Installation of PMU in boundary nodes allows to fix boundary variables U and δ on the values metered with high accuracy. In this case:

- boundary conditions (1), (2) are fulfilled automatically, and
- solution of a coordination problem consists in calculation of node injections in boundary nodes on (3), (4), using estimations of branch power flows, received from results of separate subsystems.

Thus state estimation of separate subsystems can be calculated in parallel, independently from each other, accomplishment of iterative calculations on subsystems is not required.

When decomposition of calculated scheme into subsystems with boundary branches PMU is installed in one of nodes of a boundary branch then a "calculated" PMU can be received on other end of a branch. In this case:

- the combination of measurements from physical and "calculated" PMU in an incident node provide accomplishment of boundary conditions (7), (8) in boundary branches,
- as PMU, installed in a node, allows to receive or calculate measurements (pseudo-measurements) of power flows of all branches departing from a node the boundary conditions (5), (6) also will be fulfilled.

In this case SE of separate subsystems also can be calculated independently from each other, accomplishment of iterative calculations on subsystems is not required.

For coordination of phase angles of the voltages received from local state estimation only one PMU measurement of phase angle is enough in each subsystem. Such node is appointed for subsystems reference node. PMU measurements coordinate results of state estimation of separate subsystems. In one arbitrary selected subsystem the reference node with a zero angle is traditionally set. Actually, the zero value of an angle of a reference node does not correspond with the PMU metered angles of other nodes. Therefore it is necessary to install PMU device in a reference node or to appoint the node with PMU as a reference.

Bad data detection in telemetry, or validation of measurements, is one of the most important problems in EPS state estimation. In this work bad data detection is based on the test equation method. This method makes it possible to carry out validation of information prior to solving the SE problem. Solving the problem of state estimation for EPS with low redundancy of measurements we face the problem of validating the critical measurements and critical sets. It is impossible to detect uniquely gross errors in these measurements. One of possible approaches for solution of this problem is the use of PMU measurements. Optimal placement of PMU increases the redundancy of SCADA measurements and eliminates critical measurements and critical sets, i.e. allows detection of all bad data in measurements.

Accurately synchronized measurements provided by PMU placed near boundary nodes essentially increase the redundancy of measurements and efficiency of methods for detection of bad data in boundary regions.

3.4 A two-stage algorithm for decomposition of the calculated scheme into subsystems in state estimation

The idea of decomposing the state estimation problem with PMU placement at boundary nodes is rather attractive. In reality, however, due to high cost of PMUs they can only be used when the number of boundary nodes is small.

To calculate large inhomogeneous schemes the authors propose a method of dividing the calculated scheme with respect to voltage levels (Gamm et al., 2007 (a)). This method

decreases essentially a negative impact of inhomogeneity of calculated scheme and telemetric information in calculation of subsystems of one voltage class but for the complex scheme inevitably leads to a large number of boundary nodes. Therefore, the paper proposes a two-stage algorithm to decompose the calculated scheme into subsystems that combines the positive features of both approaches.

At the first stage the scheme is divided into rather large areas with minimum number of intersystem ties and boundary nodes. This decomposition can be made on the basis of administrative division, for example, the entire scheme of Russia's Unified Energy System is decomposed into regional power subsystems of large regions in the country that operate in parallel or it can be decomposed artificially into separate areas by special algorithms (Gamm & Grishin, 1995). PMUs are placed at the boundary nodes of the areas. Highly accurate measurements obtained from PMU make it possible to register the values of magnitudes and phases of nodal voltages at the boundary nodes and make calculations for the areas in parallel.

At the second stage the calculated scheme of each area in turn is divided into subsystems that correspond to the levels of nodal voltages. The calculations start with the subsystem of the highest voltage level (750-500 kV). Normally this part of the scheme is well provided with highly accurate telemetry and contains a basic node. Then the calculations are made successively for the rest of the subsystems. The subsystems are ranked by voltage levels (220 kV, 110 kV, etc.). Every time the node bordering the subsystem of higher voltage level is chosen as a basic one. After calculations of lower voltage levels of large areas the coordination problem is solved, which include calculation of node injections in boundary nodes or calculation of power flows in boundary branches.

The functional decomposition of the state estimation problem is performed in accordance with the problems solved within the state estimation procedure. The main of them are: analysis of network topology; analysis of observability; analysis of bad data; calculation of estimates and steady state by the estimates obtained.

The current calculated scheme is formed for the entire scheme. Bad data analysis and calculation of estimates and steady state are performed by the test equation technique for each subsystem of a certain voltage class before solving the state estimation problem (Gamm et al., 2007 (b)).

State estimation is made according to two criteria: the method of weighted least squares and the robust criterion that allows the estimates to be obtained and bad data to be suppressed simultaneously.

Control is transferred to one or another state estimation program depending on operation of the bad data detection program. In case of bad data detection or their absence the program for calculation of estimates operates on the basis of the least squares method. However, if it is impossible to detect erroneous measurements and, hence, identify bad data the program operates according to the robust criterion. State estimation is made starting at the upper level of the structural decomposition.

3.5 Full algorithm

The full algorithm for solving the state estimation problem based on structural and functional decomposition is as follows.

1. The complete calculated scheme of EPS is decomposed into rather large areas. Phasor measurement units are placed at the boundary nodes of subsystems. PMU device is placed in the basic node of full scheme.

- 1A. PMU devices are placed in the boundary (not transit) nodes of subsystems. In the subsystems that have no basic node of the complete scheme one of the boundary nodes with PMU of the highest voltage class is chosen as a basic one. Measurements of nodal injections at boundary nodes are excluded from the vector of measurements.
- 1B. If the boundary nodes of two or more subsystems are transit, the decomposition with boundary nodes is used. PMU is installed in one of nodes of a boundary branch then a "calculated" PMU can be received on other end of a branch. While calculating the first subsystem the measurements of node injections of second subsystems are excluded from the vector of measurements, and vice-versa.
2. At the second stage of decomposition the calculated scheme of each area is divided into subsystems that correspond to the levels of nodal voltages. The boundaries of the subsystems are the nodes adjacent to the nodes of the voltage class of this subsystem. For example for the 750-500 kV voltage class subsystem the nodes with the voltage of 220 kV are boundary nodes and vice-versa.
3. The calculation starts with the subsystem of the highest voltage level (750-500 kV) for each subsystem. Normally this part of the scheme is well provided with highly accurate measurements and contains a basic node. The state estimation algorithm for subsystems with boundary nodes is as follows:
 - 3.1. For each subsystem that contains boundary nodes the problem of bad data detection is solved by the test equation technique.
 - 3.2. In case of bad data detection or their absence the state estimation is made according to least squares method.
 - 3.3. In the event that erroneous measurements cannot be detected and hence it is impossible to detect bad data, the state estimation is made according to the robust criterion (bad data suppression).
4. The rest of the subsystems in the scheme are successively calculated. They are ranked by voltage level (220 kV, 110 kV, etc.). Every time the node bordering the subsystem of higher voltage level is chosen as a basic node. The estimates of the boundary variables of the state vector that are obtained at the upper level of decomposition are registered.
5. The injections at boundary nodes between the subsystems of different voltage class are calculated.
6. After all subsystems of the first level of decomposition have been calculated similar problem is solved for the boundary nodes with PMU, if these nodes are transit, power flows in the boundary branches are calculated.
7. Due to obtain general solution for full scheme the results received from subsystems and results of coordination problem solution are aggregated.

3.6 Multi-agent approach

The multi-agent approach to the power system state estimation is based on the structural and functional decomposition of state estimation problem described earlier.

For each agent the subsystem of a certain voltage class is used as an object to be modeled. To implement the algorithm of state estimation by the test equation technique a multi-agent system (MAS) has been developed (Fig.4).

Functionality of agents:

- MAS_0 – a common MAS, that contains all subsystems and all agents.

- A_{DE} - a decomposition agent, that makes decomposition of the calculated scheme into subsystems by voltage level;
- A_{AG} - an aggregation agent, that aggregates data received by coordination agent from subsystems, and forms the full scheme regime;
- $MAS_i, i=1, \dots, n$ - a MAS's, that contain subsystems of first decomposition level;
- MAS_{ij} - an agent of i -th subsystem of the j -th voltage level (Fig.5) that transfers the values of voltages and phase angles at its boundary nodes to a lower level. It contains a local multi-agent system that consists of three agents:
 - A_{BD} - an agent of bad data that detects bad data and, depending on results of its operation, starts either agent A_{SQ} or agent A_R ;
 - A_{SQ} - an agent of state estimation by the least squares method, started by the agent A_{BD} if bad data are found or there are no bad data;
 - A_R - an agent of state estimation in accordance with the robust criterion. It is started by the agent A_{BD} if it is impossible to identify bad data;
- A_K - coordination agent that coordinates calculations in big subsystems, and calculates boundary variables (active and reactive powers in boundary nodes and power flows in boundary branches);
- A_k - coordination agent for voltage level areas, that calculates active and reactive powers in boundary nodes of these areas;

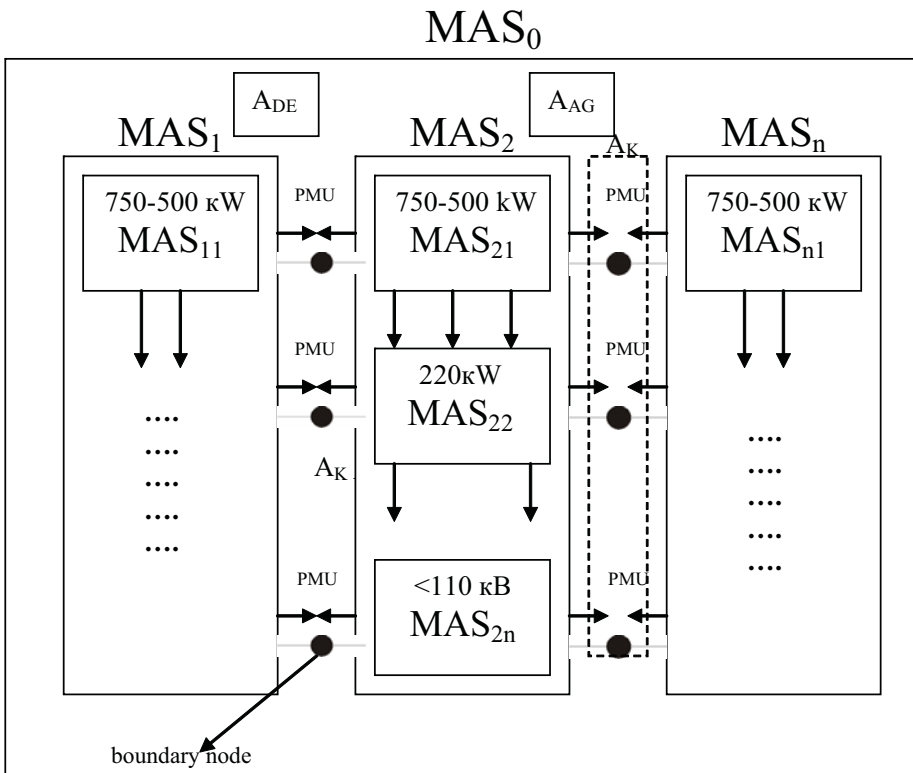


Fig. 4. Architecture of multi-agent system

Agents A_k and A_k may be mobile agents, and can move between subsystems, collecting data for further calculations.

Usage of multi-agent approach to distributed state estimation allows following advantages:

1. To organize a flexible choice of a method of solving different problems of state estimation for each subsystem;
2. To coordinate and quickly exchange data between tasks which are solved in different levels and distributed territorially (mobile agents).

MAS_{IJ}

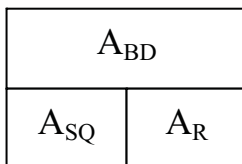


Fig. 5. Structure of agent of i-th subsystem of the j-th voltage level

3.7 Case study

In order to test the efficiency of the suggested decomposition algorithm of state estimation the calculations of a real scheme consisting of 107 nodes and 175 branches were made (Fig.6). The calculations were based on real measurements. The efficiency of the algorithm was assessed by comparing the results of calculations made for subsystems to the results of the calculation made for the entire scheme.

At the first stage the genetic algorithm was used to divide the entire scheme into two subsystems containing 55 and 52 nodes with 6 boundary nodes in which the PMU data (measurements of magnitudes and phases of nodal voltages) were modeled. The calculations of these subsystems were carried out in parallel which reduced the time of solving the SE problem almost twice: from 0.49 s to 0.27 s.

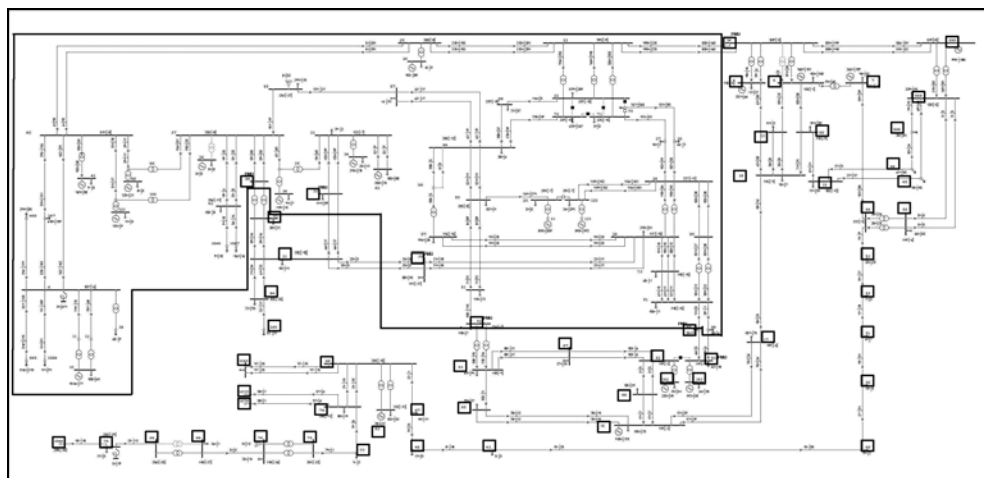


Fig. 6. EPS scheme fragment

At the second stage of decomposition each of the subsystems in turn was decomposed into three areas corresponding to the voltage levels of 500 kV, 220 kV, 110 kV and lower. The calculation of these areas according to the above algorithm was made successively, therefore the full time of solution could increase. However, owing to the improved convergence of the iteration processes in the calculation of areas of the same voltage class the total time of the calculation for all the three areas practically did not change.

More efficient operation of bad data detection algorithm and application of the robust criterion of state estimation for two of six areas improved considerably the results of state estimation: the value of the state estimation objective function at the point of solution decreased almost by a factor of 6 and the estimates at boundary nodes were noticeably improved.

Decomposition by voltage levels and usage of PMU measurements in boundary nodes allow to considerably improve the effectiveness of bad data detection methods. Table 1 shows the comparison of calculation results in voltage level areas with calculation results by full subsystem. Apparently from the table, while calculations are made by subsystems and PMU devices are used, number of critical measurements and groups of the doubtful data is essentially reduced.

	500 kV area	220 kV area	110 kV area	Full subsystem
Number of nodes	5	25	30	55
Number of branches	7	24	44	80
Measurements	31	98	133	265
Not observable nodes by δ/U	no/no	4/0	5/1	9/1
Redundancy	3,44	2	2,06	2,43
Unchecked data without PMU	2	23	17	35
Unchecked data with PMU	2	7	13	24
Doubtful data groups without PMU	0	0	4	6
Doubtful data groups with PMU	0	0	4	5

Table 1. Comparison of calculation results in voltage level areas with calculation results by full subsystem

4. A multi-agent approach to coordination of emergency control devices against voltage collapse

4.1 Emergency control problem

Power Industry spends a lot of money to protect a power system against different severe disturbances. Nevertheless, large interconnected Power Systems throughout the world are

frequently subjected to widespread blackouts which interrupt millions of consumers and cost billions of dollars.

Analysis of the recent blackouts showed, that the most severe interruptions occurred in highly loaded interconnected power systems due to EHV line disruption followed by multiple contingencies.

These accidents highlighted the deficiency of the existing protection systems that cannot maintain the integrity of the transmission grid during multiple contingencies (Lachs, 2002).

Power system behavior in an emergency state is characterized by complex interaction between discrete and continuous control devices. Continuous control devices are automatic voltage regulators, turbine governors, FACTS devices, etc. Discrete control devices are different protection relays, under load tap changers, etc. Currently both continuous and discrete control devices substantially use local signals only and do not coordinate their actions with each other. Absence of coordination between discrete and continuous control devices is the shortcoming of the existing protection system and may lead to blackout.

The paper presents a control system based on the multi-agent approach. The control system provides coordination of different discrete and continuous control devices to prevent voltage collapse of the power system during the post-disturbance period.

4.2 Voltage instability mechanism

To understand the importance of the discrete and continuous control devices coordination, one should understand the mechanism of voltage instability that may occur any time after the first severe contingency and lead to blackout.

Existing practice shows that if protection system works correctly, most power systems have sufficient stability to withstand the first heavy disturbance in EHV transmission system. The post-disturbance phase represents a deceptively calm period that lasts several minutes with a normal level of frequency and then voltage collapse that lasts seconds (Lachs, 1992).

The first heavy disturbance leads to increase in the reactive power losses and reactive power output of rotating units in the vicinity of the affected region. So, the first disturbance effects influence only the affected region, being initially a local problem. But sometime after, the lack of reactive power in the affected region might increase considerably, leading to voltage collapse in the neighboring regions and even in the whole system. This happens because if the disturbance is not dealt with timely, the after-effects spread out through the EHV transmission network and actuate different control devices such as automatic voltage regulators, automatic transformer tap changers, current protection relays, etc. These control devices act at the different speed, respond to changes in the immediate vicinity and act without coordination with one another. Their actions in response to the post-disturbance conditions are actually the main cause of power system breakdown; consequently, the timely control of the discrete and continuous control devices under the post-disturbance conditions is the only means to prevent voltage collapse of the whole system. Undoubtedly, the absence of different control actions coordination during the post-disturbance period can cause different types of instability. But first of all, one should cope with voltage instability because it was the main cause of the recent blackouts. New system protection system philosophy has to be proposed to prevent voltage instability during the post-disturbance period.

4.3 System protection philosophy

A new system protection philosophy is needed to control the post-disturbance phenomenon. A new protection system must detect the critical situation and coordinate the

work of control devices to exclude any possibility of voltage instability. So, how can the new protection system identify the critical situation and what kind of control actions should the system use to control the capacity of available reactive power resources?

A. Parameters-Indicators

The main symptoms that precede the voltage collapse are considerable reduction of transmission voltage levels and increase of reactive power outputs on rotating units (Makarov et al., 2005; Taylor & Erickson, 1997). Reduction of voltages and increase of rotating unit excitation were proposed in different papers to indicate the proximity to voltage collapse. Thus, these two criteria may be used to detect the critical situation appearance and activate protection system.

B. Control Actions

Power industry has already used the philosophy of load shedding by selecting non-essential load to prevent frequency reduction. The analysis of recent blackouts showed that the rapid load shedding is usually the only way to prevent the collapse of the whole system. On the one hand, load shedding should be as fast as possible, on the other hand, it should be optimal. The optimal load shedding scheme can be realized by using different optimization procedures, but it is hard to solve optimization problem for any possible situation in advance, because the number of situations is too big. This means that some optimization computations should be made during the post-disturbance period. In spite of the fact that there is a number of optimization techniques that can be used to calculate emergency control actions quickly, the amount of input data required to solve the problem is usually too big. The state estimation alone can take from tens of seconds to minutes. However, load shedding under the post-disturbance conditions has to work faster. Hence, load shedding procedure has to use less complex methods to control post-disturbance phenomenon. The following simple countermeasures to control post-disturbance phenomenon were proposed in (Lachs, 1992):

- Countermeasure 1. Fast tap changing on transmission substation transformers.
- Countermeasure 2. Raising terminal voltage on selected synchronous condensers and hydro generators.
- Countermeasure 3. Fast tap changing on selected generator transformers.
- Countermeasure 4. Strategic load shedding at selected transmission substations only if voltage levels and reactive outputs do not meet the requirements, or some transmission lines are overloaded.
- Countermeasure 5. Re-arranging generator MW outputs. Connecting part of the disconnected load.

Countermeasures 1 - 3 have approximately the same execution time and their main purposes are to impede the sharp increase of series reactive power losses, to increase transmission line charging and to inhibit tap changing on subtransmission and distribution transformers. Load is shed (Countermeasure 4) only after countermeasures 1 - 3. This will decrease the amount of the load to be shed. Countermeasure 5 considers an optimization procedure. The optimization procedure takes much more time in comparison with countermeasures 1 - 4 and provides post-emergency operation optimization.

Thereby, countermeasures 1 - 4 provide fast control of the post-disturbance phenomenon to avoid voltage collapse and countermeasure 5 provides long-time-period post-emergency operation optimization.

The proposed control principles can be applied to various parts of the grid that work independently.

Briefly, the control actions aim to control the capacity of the available reactive power resources and do not let reactive power demand of the affected region increase beyond their sustainable capacity to exclude the possibility of voltage instability.

The proposed control system can be built by using distributed intelligence principles. The distributed intelligence is taken to mean the multi-agent system (Panasetky & Voropai, 2009).

4.4 Multi-agent control system structure

Current overload of the network elements in postdisturbance period is a serious problem, which can lead to cascade line tripping. However, the proposed MAS does not solve the problem of the current overload, except current overload problem of the generator excitation system, which directly influences the reactive power output of generator. The proposed multi-agent control system provides reactive power control to prevent generator tripping and preserve load bus voltages within the normal range. Current and ohm relays coordination problem is the further work goal.

A power system presented in Fig.7 is used to illustrate the main principles of the proposed multi-agent approach.

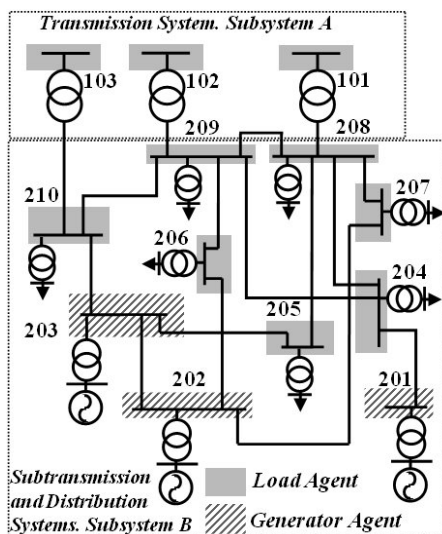


Fig. 7. A part of the modified IEEE One Area RTS-96 system

This power system is a part of the modified 24 bus IEEE One Area RTS-96 system. It is divided into two subsystems - Subsystem A and Subsystem B that correspond to transmission and subtransmission plus distribution systems respectively.

The proposed MAS consists of two types of agents: Load Agents and Generator Agents (see. Fig.7). Any agent at any time has the following set of local data:

- Local state variables (primary and secondary voltages, power flows, etc.).
- Operating characteristics of the local equipment (generator terminal voltage, tap range of the tap changer, excitation current of the generator, etc.).

Any agent has two goals:

- Local goal. It consists in maintaining local state variables and equipment operating characteristics within the normal range.
- Global goal. It consists in voltage collapse prevention.

To make different parts of the proposed MAS system work independently, each agent must know only about the limited number of agents, which influence his activity most. For instance, Load Agents, installed at Bus101 – Bus103 in Subsystem A must know much about the agents in Subsystem B, because all these agents can influence them. On the other hand, in spite of the fact that agents in Subsystem B could know much about one another, they must know only about three agents in Subsystem A: Load Agents, installed at Bus101 – Bus103, because these three agents can only influence them. In this case, subtransmission system produces minimal influence on transmission system.

A. MAS Ontology

Agents communicate with each other, by using some communication language. According to FIPA standards, messages exchanged by agents have a number of fields and in particular: sender, receiver, communicative intention (also called "performative"), content, language, ontology and some fields used for control. Ontology is the vocabulary of symbols and their meanings. For the effective communication, both the sender and the receiver must ascribe the same meaning to symbols. Ontology can include different elements such as agent actions, terms, concepts, etc. Agent actions indicate actions that can be performed by some agents. Terms are expressions identifying entities (abstract or concrete) that "exist" in the world. For voltage control purposes, the following simple Voltage Control Ontology can be proposed:

Agent actions of the Voltage Control Ontology:

- Increase Reactive Power.
- Stop Reactive Power Increase.
- Start Load Shedding.

Terms of the Voltage Control Ontology:

- Owner.
- Voltage Rate.

The Voltage Control Ontology usage principles will be given in the next sections.

B. Generator Agent

Generator Agent obtains local information about excitation current of the generator, primary and secondary voltages at the generating substation, active power flows and transformer tap ranges. If excitation current goes beyond of its normal range, Generator Agent tries to decrease it to exclude the possibility of the generator tripping. Generator Agent sends messages to other agents that can decrease the shortage of the reactive power in the affected region. The sent messages apply FIPA Request Interaction Protocol and include Increase Reactive Power action of the Voltage Control Ontology. The sequence diagram for the Request Interaction protocol used by the Generator Agent is depicted in Fig.8.

Before sending a message, Generator Agent could use a rule set to identify whether receiver is able to help him. In our research, we used the following simple rule: Generator Agent do not send Request message to another agent if electric coupling between them has become too weak. For instance, if Bus202 – Bus203 active power flow is equal to zero, Generator Agent at Bus 203 does not send Request message to Generator Agent at Bus 202.

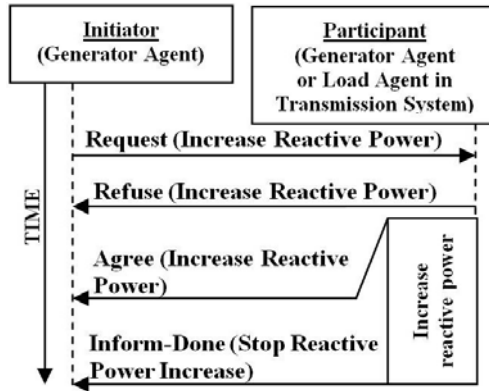


Fig. 8. Request Interaction protocol used by Generator Agent

In response to his request, Generator Agent can receive either Refuse or Agree message. Agree message means that Request Interaction protocol participant starts to increase reactive power. Sometime later, Generator Agent will receive Inform-Done message with Stop Reactive Power Increase action, which means that the participant stopped increasing reactive power (see Fig.8). Thus, Generator Agent always knows when reactive power increase in his subsystem is stopped. If reactive power increasing is stopped, but Generator Agent is still overexcited, it starts Load Shedding procedure.

FIPA Contract Net Interaction Protocol is used in Load Shedding procedure. In this protocol, the initiator wishes to optimize some function that characterizes the Load Shedding Procedure. We use minimal voltage rate function, but of course, it could be function, which includes some economic aspects. Generator Agent sends n Call for Proposal messages to Load Agents and solicits from them m proposals and k refuses (see Fig.9). The proposals contain voltage rates at primary buses of the Load Agents. After that, Generator Agent accepts j proposals and sends j Accept-Proposal messages to those Load Agents which have the lowest voltage rates at their primary buses. When Load Agent receives Accept-Proposal message it starts to shed the load until its primary voltage will not increase up to the specified value.

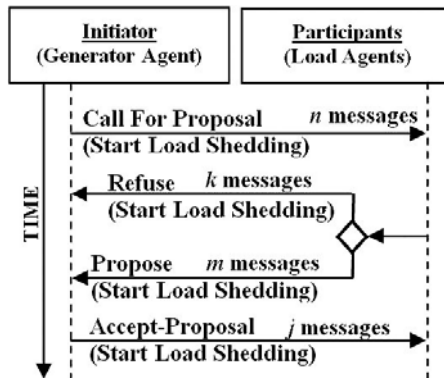


Fig. 9. Contract-Net Interaction protocol used by Generator Agent

C. Load Agent

Load Agent obtains local information about primary and secondary voltages at the substation, transformer tap ranges and active power flows. Load Bus agent takes part in Load Shedding procedure (see Fig.9). It also can shed the load independently in case of critical voltage drop. If it is installed at transmission system substation, Load Agent can take part in reactive power regulation (see Fig.8). In this case, Load Agent changes transmission transformer tap ratio until primary voltage will not decrease or secondary voltage will not increase up to specified values. Changing transmission transformer tap ratio, Load Bus agent must coordinate its actions with generators in transmission system.

Now consider situation when Generator Agent receives Request message. First, it analyzes operating characteristics of the generator and if they are within the normal range it starts to increase reactive power output according to the algorithm, presented in Fig.10.

Where U_{GEN_SV} - generator secondary voltage, U_{GEN_TV} - generator terminal voltage, I_f - excitation current, I_{f_MAX} - the highest possible excitation current.

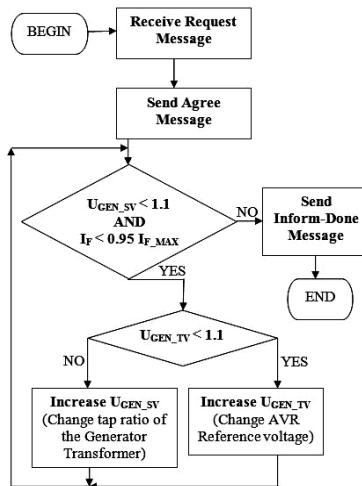


Fig. 10. Reactive power output increasing algorithm of Generator Agent

4.5 Multi-agent control system implementation

The success of multi-agent system mainly depends on the availability of appropriate technology (development tools, programming languages) that allows its implementation. Any kind of programming language could be used for MAS realization, but object-oriented languages are more suitable, because the concept of agent is close to the concept of object.

The computer model of the proposed MAS for power system voltage stability control was implemented in JADE. JADE has become a firm favorite with researchers in power engineering in recent years. JADE implements a famous object-oriented language Java (Bellifemine et al., 2000). Agents, developed for the JADE platform consist of three basic layers: a message handling layer; a behavioral layer; a functional layer. Message handling layer is responsible for the sending and receiving of messages from other agents. The behavioral layer provides control of when an agent has to implement some task. The functional layer embodies the action the agent can perform.

Necessary power flows and time domain simulations were carried out in Matlab/PSAT environment. Java capabilities of the JADE environment were used to implement communication between Matlab/PSAT and JADE, Fig.11.

To provide communication between Matlab and JADE, Box Agents are used. Box Agents are Java objects that contain different data structures. During Time Domain Simulation, information about power system operating conditions at each integration step passes from Matlab environment to JADE by means of Box Agents. After that, agents inside JADE environment process this information, produce control actions if needed, put information about control actions inside Box Agents and pass Box Agents back to Matlab environment.

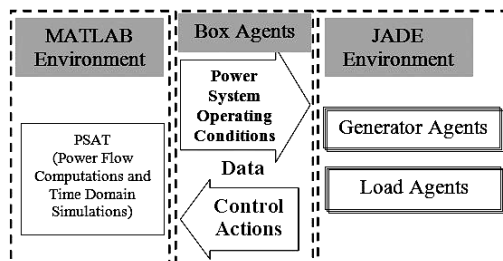


Fig. 11. MAS implementation

Thus, there is no need to use computer hard disc during the simulation, all computations are performed inside the main memory and simulation process is faster. The proposed MAS software realization allows one to use complex Matlab/PSAT routines and to model complex behavior of the agents.

4.6 Case study

A. The Test System

Modified IEEE One Area RTS-96 system is used as a case study. Initially this test power system contained 24 buses and had no dynamic elements. During modification, the following changes in the test system structure were made:

- To explore the influence of the ULTCs actions during low voltage conditions, transformers equipped with ULTCs were installed between subtransmission system and distribution system loads.
- Each load was modeled as 50% constant impedance and 50% constant current for both active and reactive components.
- Each generator was modeled by six order dynamic model and was equipped with Type I Turbine Governor (TG) and Type II Automatic Voltage Regulator (AVR).
- Three machines connected to Bus201 - Bus203 in subtransmission system (see Fig.6) were equipped with over excitation limiters (OXLs).

After modification, IEEE One Area RTS-96 system contains 42 buses. Parameters of the unmodified 24-bus test system can be found in PSAT test folder. For better understanding of the transient process, agents were installed only at the buses depicted in Fig.7.

B. Disturbance

To test the proposed MAS for an extreme contingency, the following sequence of disturbances is examined:

- 2 seconds after the simulation starts. Loss of the generator connected to the Bus 201.

- 40 seconds after the simulation starts. Loss of Bus208 – Bus207 line.

C. Preliminary remarks to the simulation process

During the simulation process, two types of automatic systems are considered:

- Automatic system based on conventional principles
- Automatic system based on multi-agent principles.

Both automatic systems do not provide for decentralized Under Voltage Load Shedding (UVLS) scheme. Undoubtedly, decentralized ULVS scheme is an effective means of preventing voltage collapse and it should be provided for both conventional and multi-agent automatic systems. However, the main purpose of the simulation is to demonstrate the MAS advantages in relation to reactive power sources coordination for the purpose of generator tripping prevention. It should also be mentioned, that the proposed centralized multi-agent ULVS scheme (see Fig.9) differs from conventional centralized ULVS scheme, because it is actuated without time delay in case when there is no available reactive power in a subsystem.

D. Dynamic simulation for automatic system based on conventional principles

Conventional automatic system includes the following set of the decentralized devices:

- TG and AVR at each generator.
- OXLs at the generators, connected to Bus201 – Bus203. OXLs maximum field currents for generators connected to Bus202 and Bus203 are 3 and 2.5 respectively. OXLs maximum voltage output signal is 0.1.
- ULTCs are installed at the subtransmission substations Bus204 – Bus210. ULTC time delay for the first tap movement is 20 seconds. ULTC time delay for subsequent tap movements is 5 seconds. ULTC tap range is ± 12 steps.

Voltage reductions at load substations during the simulation are shown in Fig.12. The change of rotor currents during simulation is represented in Fig.13. The change in AVR reference voltages during simulation is given in Fig.14.

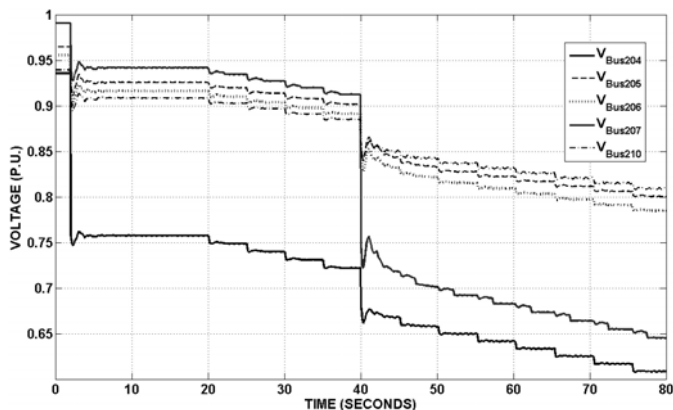


Fig. 12. Changes in HV substation voltage level

After the first disturbance, rotor current of the generator, connected to Bus203, reaches its thermal limit, and AVR reference voltage of the generator starts to decrease. 20 seconds after the first disturbance, ULTCs on all transformers at the affected subtransmission substations starts to work. This leads to further decrease of generator 203 AVR reference voltage.

Compensating reactive power shortage, generator 202 increases its excitation current. After the second disturbance, rotor current of generator 202 reaches its thermal limit and rotor current of generator 203 exceeds its thermal limit. AVR reference voltages of both generators continue to decrease and after a while, this will lead to generator 203 tripping and to the voltage collapse.

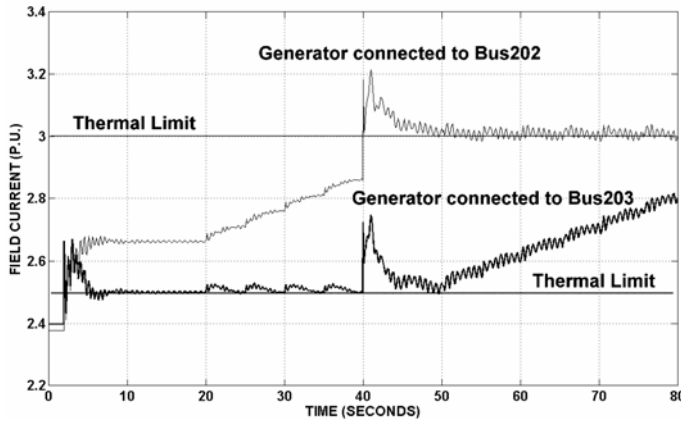


Fig. 13. Rotor current change

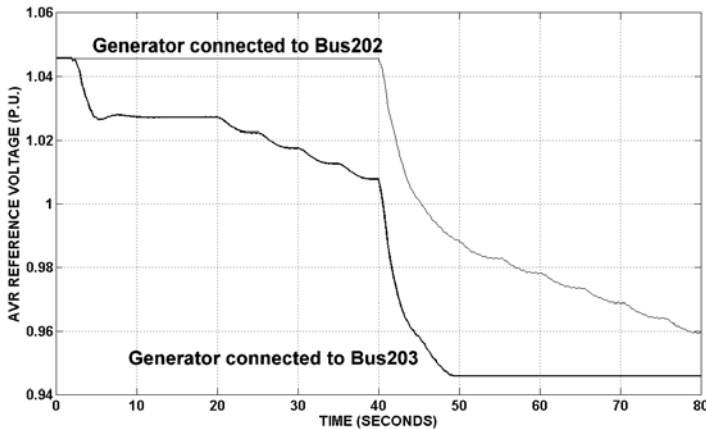


Fig. 14. AVR reference voltage change

E. Dynamic simulation for automatic system based on multi-agent principles

In addition to the set of local devices, represented for conventional automatic system, multi-agent automatic system also includes ULTCs for transmission transformers at Bus101 – Bus103. Trying to exclude generator tripping, multi-agent automatic system coordinates the work of local devices. Voltage reductions at load substations during the simulation are shown in Fig.15.

After the first disturbance, rotor current of the generator, connected to Bus203, reaches its thermal limit and the generator sends request message to generator 202 and to the

transmission transformers, connected to Bus101 – Bus103. Transmission transformers at Bus101 – Bus103 as well as generator 202 are trying to decrease reactive power shortage of the subsystem. Their joint actions decrease generator 203 excitation current. Excitation current becomes lower than its thermal limit, and generator 203 AVR reference voltage starts to increase. After the second disturbance, rotor currents of both generators reach their thermal limits and generators send request messages to each other and to transmission transformers at Bus101 – Bus103, but in this case, the generators receive refuse messages and immediately start load shedding procedure. Thus, during the transient process, rotor currents of the generators remain within the normal range. This fact excludes the possibility of the generator tripping.

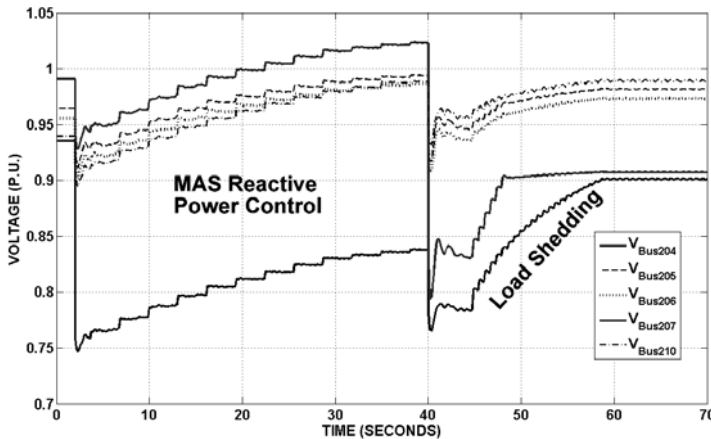


Fig. 15. Changes in HV substation voltage level

The change of rotor currents during simulation is presented in Fig.16.

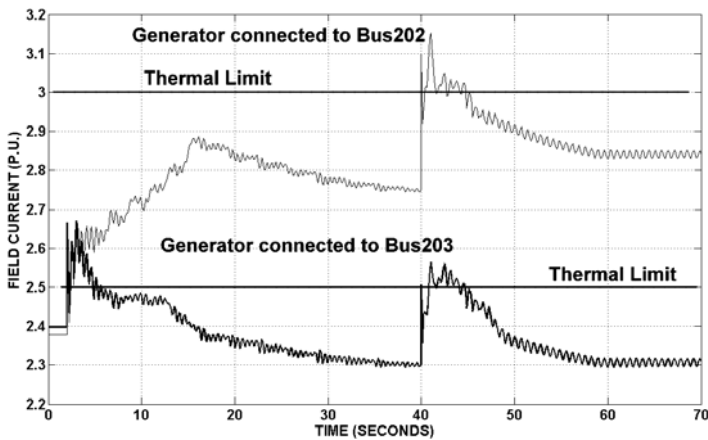


Fig. 16. Rotor current change

The change in AVR reference voltages during simulation is given in Fig.17.

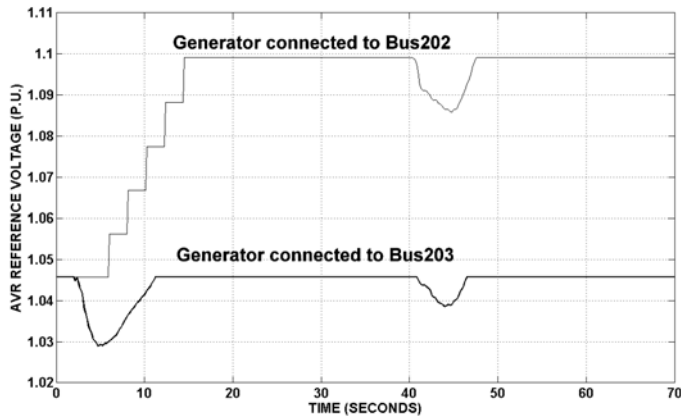


Fig. 17. AVR reference voltage change

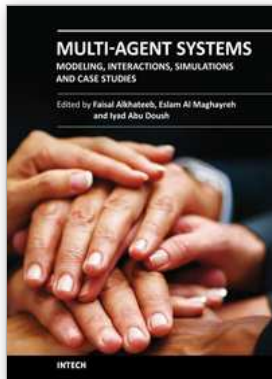
5. Conclusions

In this chapter authors have given the examples of multi-agent approach usage in three different energy problems. This approach has shown good results in solving of these problems, despite its relative novelty. Efficiency of multi-agent approach to energy problems has been proved by numerical simulations. Plans of future investigations include development and improvement of described methods and realization of these methods in practical applications.

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A multi-agent system (MAS) is a system composed of multiple interacting intelligent agents. Multi-agent systems can be used to solve problems which are difficult or impossible for an individual agent or monolithic system to solve. Agent systems are open and extensible systems that allow for the deployment of autonomous and proactive software components. Multi-agent systems have been brought up and used in several application domains.

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