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A Multi-Agent Approach to Coordination of Different Emergency Control Devices Against Voltage Collapse

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***Abstract*—The paper presents a control system based on the multi-agent technique. The control system coordinates different discrete and continuous control devices during the post-disturbance period in order to prevent voltage collapse of the whole system. The model of the test power system was simulated by Matlab/PSAT software. Multi-agent system (MAS) has been implemented in Java language using JADE (Java Agent Development Framework) package. The efficiency of the proposed technique has been proved by numerical simulations. The proposed MAS software allows the use of complex Matlab/PSAT routines as well as the modeling of complex behavior of the agents.**

***Index Terms*—Cooperative systems, multi-agent systems, power system dynamic stability, reactive power control, voltage control.**

I. Introduction

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 [1].

These accidents highlighted the deficiency of the existing protection systems that cannot maintain the integrity of the transmission grid during multiple contingencies [2].

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 it 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.

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II. 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 [3].

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 some time 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 [2]. 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.

III. A Multi-Agent Approach Outlines

There is a number of definitions for what an agent is. This fact testifies to the difficulty in defining the notion of multi-agent systems (MAS). General definition says that MAS is a distributed and coupled network of intelligent hardware and software agents that work together to achieve the global goal. Agents are autonomous structures and they operate with each other through different mechanisms.

MAS could have different architectures. *Reactive architecture* is one of them. It is based on a simple stimulus-response mechanism triggered by sensor data. Its advantage is a faster but not reason better response in dynamic environments. Agents in reactive architecture are also simpler in design than agents that are more intelligent. Power systems are already using many reactive agents such as protective relays, automatic voltage regulators, etc. However, the fact that these simple reactive agents have extremely narrow knowledge about one another, results in some disadvantages, for instance, lack of coordination. Another type of the MAS architecture is *layered (hybrid) architecture* that allows both reactive and deliberative agent behavior.

Another key component of the MAS is a communication principle. If agents need to cooperate and be coordinated, they have to communicate with one another by using some communication language. Currently, the most used communication language is the FIPA (The Foundation for Intelligent, Physical Agents). FIPA standards can be found in [4]. Coordination among agents can be provided by using different approaches including *organizational structuring* and *distributed multi-agent planning*.

Organizational structuring provides coordination through the definition of roles, communication paths and authority relationship. Organizational structuring is the easiest way to resolve conflicts among agents and provide their coherent behavior. Power system control centralization is an example of organizational structuring: there is an agent (control center) which has some knowledge of the current and the prospective system states and establishes rules for other agents according to hierarchical structure of the MAS. However, such an approach sometimes is impractical, because it is hard to design such a central controller, especially when the latter has a little time for collecting a lot of information to provide control actions.

Another approach to agent coordination is a distributed multi-agent planning. In order to avoid inconsistent or conflicting actions, agents can build a multi-agent plan that details all the future agent actions and interactions required to achieve their global goal. In the process of working agents communicate in order to build and correct their individual plans until all conflicts are removed.

We believe that MAS that is likely to be used for protection against voltage collapse should have layered architecture and use distributed multi-agent planning approach as a perspective way to provide coordination between different control devices during the post-disturbance period. For better understanding of the multi-agent approach principles see [5]- [7].

IV. 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 [8]. 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 [1]. 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 [3]:

- 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 [9].

The proposed control system can be built by using distributed intelligence principles. The distributed intelligence is taken to mean the multi-agent system.

V. Multi-Agent Control System Structure

Current overload of the network elements in post-disturbance 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.5 is used to illustrate the main principles of the proposed multi-agent approach. 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.5). 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.1.

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.

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. Some time later, Generator Agent will receive Inform-Done message with *Stop Reactive Power Increase*

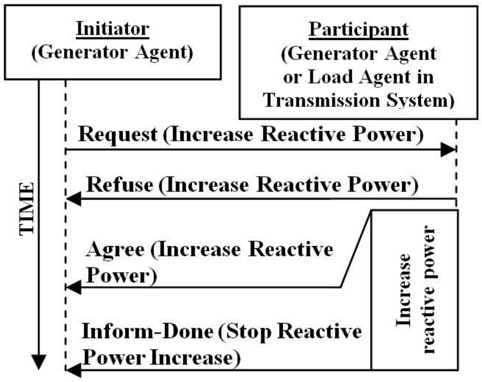

Fig. 1. Request Interaction protocol used by Generator Agent

action, which means that the participant stopped increasing reactive power (see Fig.1). 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.2). 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.

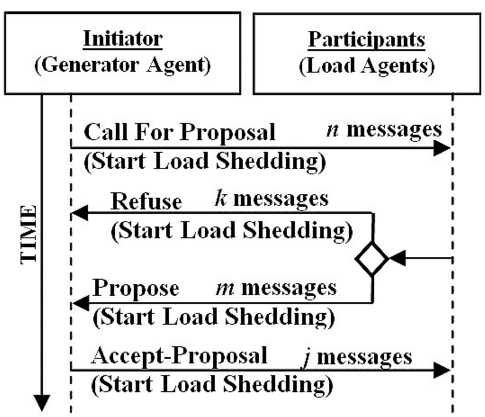

Fig. 2. Contract-Net Interaction protocol used by Generator Agent

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.3.

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.

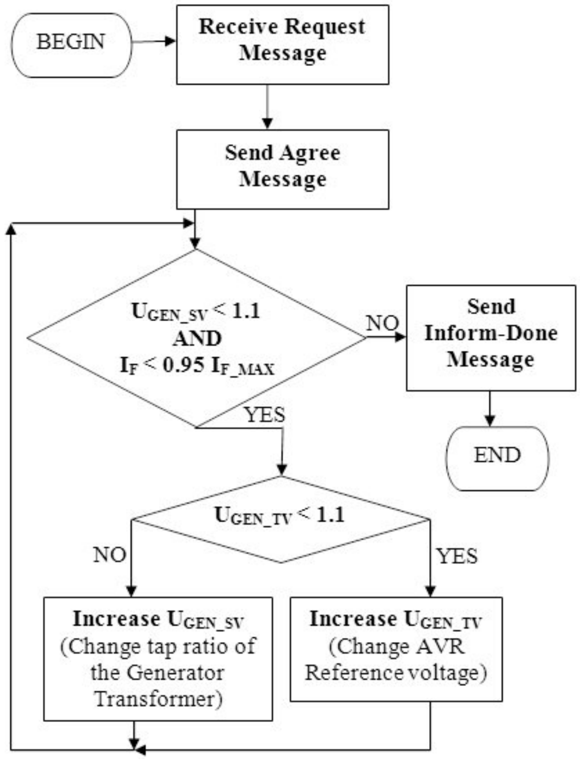

Fig. 3. Reactive power output increasing algorithm of Generator Agent

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.2). 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.1). 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.

VI. 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. 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. JADE provides programmers with the following ready-to-use functions: full compliance with the FIPA specifications; efficient transport of asynchronous messages; a simple agent life-cycle management; a library of interaction protocols, etc. For further information about JADE platform, see [5], [7], [10].

Necessary power flows and time domain simulations were carried out in Matlab/PSAT environment [11]. Java capabilities of the JADE environment were used to implement communication between Matlab/PSAT and JADE, Fig.4.

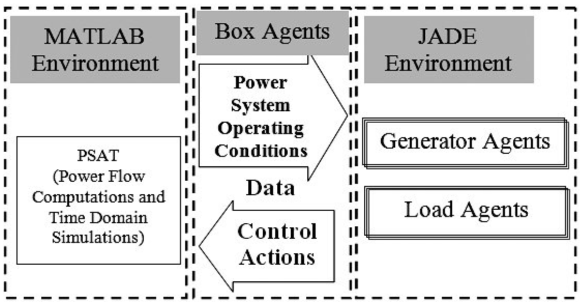

Fig. 4. MAS implementation

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. 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.

VII. 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) (see [12]).
- Three machines connected to Bus201 – Bus203 in subtransmission system (see Fig.5) were equipped with over excitation limiters (OXLs) (see [12]).

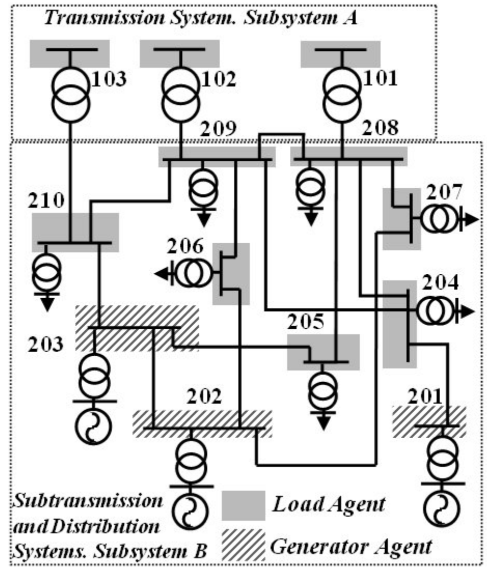

Fig. 5. A part of the modified IEEE One Area RTS-96 system

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 [11]. Parameters of the modified 42-bus test system can be found in [13]. For better understanding of the transient process, agents were installed only at the buses depicted in Fig.5.

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.2) 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.6.

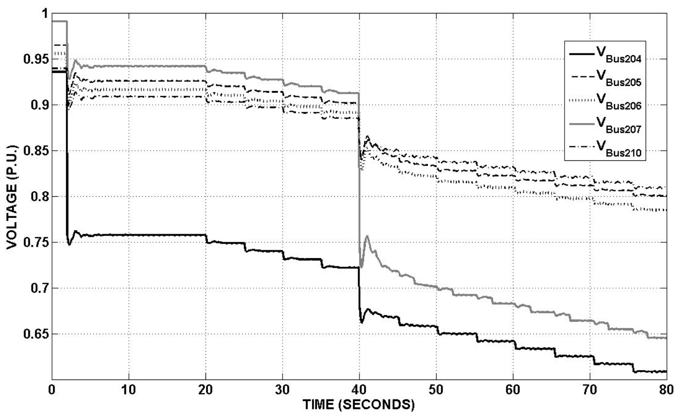

Fig. 6. Changes in HV substation voltage level

The change of rotor currents during simulation is represented in Fig.7.

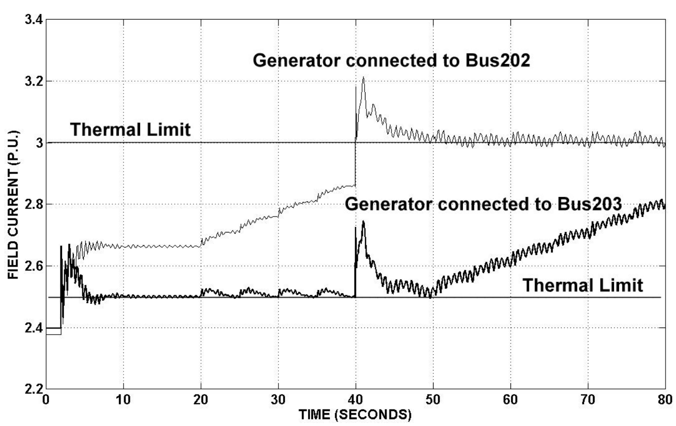

Fig. 7. Rotor current change

The change in AVR reference voltages during simulation is given in Fig.8.

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

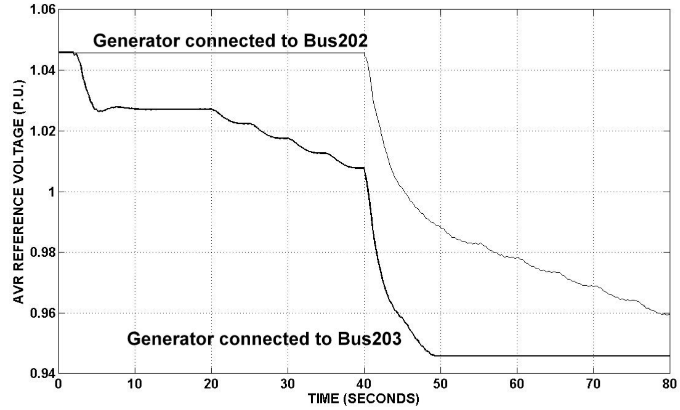

Fig. 8. AVR reference voltage change

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.

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.9.

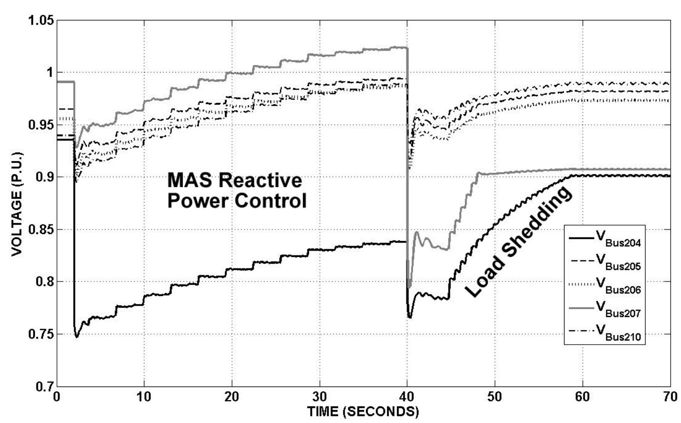

Fig. 9. Changes in HV substation voltage level

The change of rotor currents during simulation is presented in Fig.10.

The change in AVR reference voltages during simulation is given in Fig.11.

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.

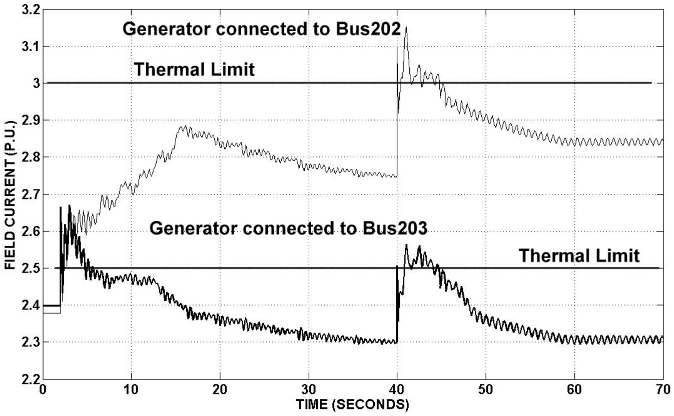

Fig. 10. Rotor current change

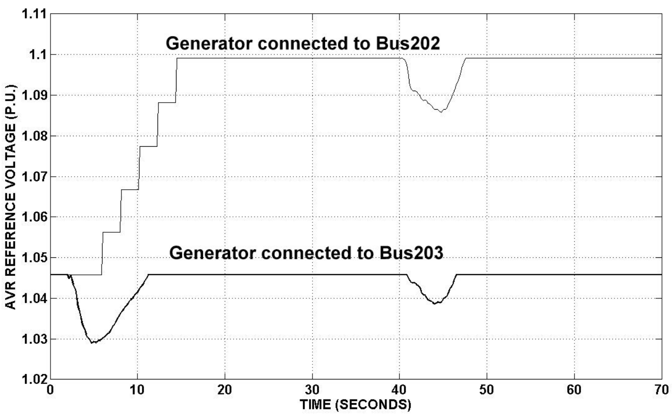

Fig. 11. AVR reference voltage change

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 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.

VIII. Conclusion

The absence of the control devices coordination during the post-disturbance period is one of the main causes of the voltage instability, which permanently occurs in power systems all over the world.

The proposed multi-agent control system provides reactive power control by coordinating the work of different discrete and continuous control devices in a post-disturbance period. The reactive power control in a post-disturbance period prevents generator tripping and maintains load bus voltages within the normal range. The efficiency of this approach has been proved by numerical simulations.

A. Further work

The proposed MAS do not solve completely the problem of current overload. Thus, the main purpose of further work is to develop agent behaviors, which could also solve the current and ohm relays coordination problem.

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