ON MULTI-AREA CONTROL IN ELECTRIC POWER SYSTEMS

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Abstract - In this paper we study the concept of electric power system control, when the responsibility for controlling the entire system is shared by agents controlling their assigned areas. Within this framework, we suggest to study the dynamics created by the interactions of agents. In particular, we discuss the relation that exists between the information available to the different agents and their optimisation objective, and the performance of the overall power system. Simulations results, carried out on a 39-node power system voltage control problem, are provided and analyzed. They highlight, among others, the sub-optimal performance level attained by the system when the different agents exchange information about their area dynamics without sharing a common control objective.

Keywords - multi-area control, power system security, secondary voltage control

1 INTRODUCTION

Large interconnected power systems are usually decomposed into areas or zones based on various criteria, such as legislative, historical, geographical (e.g. country borders), organizational, technical, etc. Therefore also the control of the whole interconnection is shared by agents (in today's context network operators) responsible for their respective areas. We refer to this type of control as multi-area control.

In many cases, each control agent has only a limited access to the data (system state, system dynamics, planned control actions and strategies etc.) from other areas. Interactions of various types are often present between different parts of power systems (e.g. contractual conditions for the energy delivery between energy traders, generation/consumption balance, inter-area power oscillations etc.).

Qualitatively, multi-area control aspects may be observed regardless of the dynamics of the problem. An example of slow dynamics control with time constants in order of magnitude of years is power system expansion - building of new transmission assets (such as lines etc.) and introduction of new generation. A representative of faster dynamics (time constants in the range of minutes to hours) is generators redispatch as a response of an operator to spontaneous load variation outside the limits of the day-ahead forecast, which could possibly cause some line overloads.

To keep security on the desired level, a higher degree of coordination among existing transmission system operators (TSOs) is probably required. Obstacles in this effort may be of technical (insufficient communication infrastructure, different data formats etc.) and nontechnical nature (conflicts in commercial and social interests or in regulatory frames).

In Europe, there are some ongoing intensive efforts towards the standardization of operation policies and practices, which are summarized in the UCTE Operation Handbook [1]. Most relevant policies are policies numbers 4, 6 and 7 (Coordinated Operational Planning, Communication Infrastructure and Data Exchange). One more example is an on-line exchange of data between two neighboring countries and execution of their common distributed state estimation has been investigated in the project EXaMINE [2].

On the other hand, in North America the approach consists of creating higher level operational entities (RTOs and Mega-RTOs) acting explicitly as the coordinator of the lower level TSOs over very large geographical areas. In this context, the multi-area control strategy may be seen as a way to handle the computational curse of dimensionality of the higher level control system. In this context reference [3] suggests criteria for evaluation of the performance of the area control (in this case California ISO) as a part of the system-wide control (Western Systems of United States).

The multi-area control of large scale power systems poses three main questions in terms of efficiency and reliability of system control, namely "When and how to decompose a large system into a number of areas?", "How to coordinate already existing independent agents controlling each one an area of a large interconnection?", and "When to merge several control areas into a single one?".

In this paper, we mainly investigate the second question. More precisely, starting with a control problem and a power system already decomposed into several areas, we analyze the behaviors of uncoordinated agents and highlight the fact that they may lead to different, sometimes counterintuitive, collective dynamics.

The rest of the paper is organized as follows. Section 2 discusses motivations and practical obstacles for stronger coordination among TSOs, mostly from the European perspective. Sections 3 and 4 respectively introduce centralized and multi-area control frameworks mostly from an intuitive (non formal) point of view. Section 5 illustrates some of these ideas on an academic test system for which we study the (secondary) voltage control problem.

2 INCENTIVES FOR MORE COORDINATION

We believe that that multi-area control is the key element in the concept of control of future power systems, especially considering recent trends in power industry such as unbundling, liberalization of electricity markets, system interconnections, energy trading etc. These result in:

Increase of number of agents. Number of involved parties has increased (traders, separate generation and transmission etc.).

Conflicting interests. Competition has been introduced even within a previously compact area (e.g., splitting of generation companies).

Stronger interactions. Interconnections between power systems have been established mainly for the mutual support under abnormal operation conditions, thus they were usually only lightly loaded. Now they are subjected to heavy power transfers, which result in stronger interactions on technical, organizational and contractual level.

On the other hand, to provide a solid justification for a request for an increased coordination, the following questions should be answered:

- Is it possible to establish an explicit link between the coordination and security of a power system?
- Is it possible to establish an explicit link between the coordination and economy of a power system?
- Is it possible to assign a value of worth to the improvement of security and economy of a power system due to an improvement in the coordination?
- How should this value of worth be distributed among the involved parties?
- What would be an incentive to participate in the efforts for a better coordination?
- How would such an increased coordination be implemented?
- Would all involved parties have to participate in the coordination efforts to make it worth?

To our knowledge, only reference [4] has addressed some of the above questions, particularly distributed optimal power flow yielding an improved economy of the operation of the entire ERCOT system.

3 CENTRALIZED CONTROL

Let us start by defining a globally optimal control configuration, that should provide the best achievable performance (thus the optimal configuration from this point of view), which can be used for reference purposes (at least from the conceptual point of view). Such a control configuration will consist of a single agent observing and supervising the whole system centrally (i.e., no hierarchical or distributed control structure) in order to capture all system-wide interactions. We will formulate this control problem in the optimal control framework.

In the optimal control framework, we would define the best control strategy as the strategy giving the least control effort yielding the best control performance. Then the task of the agent at the time t is to determine the optimal set of controls u_t^*, which will be applied between the time t and $t+T$, where T is the control and prediction horizon. Note, that u_t^* may be time dependent. This optimal set of controls u_t^* is chosen out of all available set of controls U_t in such a way, that the cost expressing the control objective is minimized and no system constraints are violated.

Notice that interconnected power systems are complex large-scale systems featuring:

- continuous dynamic states;
- discrete states;
- dynamics of various time scales (from milliseconds to years);
- nonlinearities;
- interactions between above four phenomena;
- interactions between various parts of the system.

Therefore it represents a big technical challenge to keep a power system in secure operation conditions, and even more to implement an optimal control strategy.

In addition, there are many other obstacles to the implementation of fully centralized power systems control, in particular:

1. legislation - interconnected power system may cover countries with different laws and operation rules
2. competition and conflict of commercial interests between the involved parties
3. reliability of all involved components
4. robustness - vulnerability of the centralized scheme to the outage of one of its components
5. willingness to share the information
6. cost
7. technology performance limitations:
    - computation power
    - communication infrastructure
    - different communication and computation standards

Except in some isolated systems, today there is no control scheme in power systems approaching the description of a single agent applying an optimal control strategy. In particular, it is very difficult to imagine a single agent supervising for example the entire European interconnection (including part of North Africa and Eastern Europe).

4 MULTI-AREA CONTROL

We describe the multi-area control framework, starting with an intuitive discussion and by describing the present control structure of interconnected power systems. We then focus on the type of information that can be exchanged among agents and discuss different kinds of dynamics induced by the mutli-area nature of the scheme.

4.1 Intuitive Motivation

Let us consider a boundary (interconnection) between two countries, say A and B. Each of them has its own Transmission System Operator (TSO), which is responsible for the country system operation. Both TSOs frequently face overloads in some parts of their system so they decide to install a FACTS device each, to relieve them. Thus their available control decision possibilities are type of the FACTS device, its rating and location. Since there is an interconnection between the countries, an action of the FACTS device installed in the system A will have an impact also on the system B and vice versa. This impact may be quite severe, for instance, engagement of the FACTS device located in the country A may cause overloads of some elements in the system B. If the TSO B receives the information about the planned location for the installation in the system A, it can compute the best location for the installation its own FACTS device accordingly. If it does not receive this information, it has to observe the changes in the interconnection flows introduced by the FACTS device in the system A and only after that to select the location for its own FACTS device. However, this will be only an estimate based on the observation of only some situations, which may lead to an inaccurate judgment. The final situation may lead to a state when power flows in both systems are not fully controlled by their TSOs and both system elements are overloaded based on the control of the other TSO. But if TSOs agree on a common control strategy (i.e., coordination in the process of the selection of the FACTS device installation), both of them may avoid overloads.

This practical simple example has outlined some principles/properties of multi-area control. In the subsequent subsections we try to generalize them.

4.2 Present Control in Power Systems

Perhaps the strongest distinguishing factor in categorization of the present power system control is the time scale (time constants, urgency of the situation etc.):

- long-term expansion planning (years)
- day-ahead planning (hours)
- preventive control (minutes, hours)
- emergency control (milliseconds, seconds)

Depending on the physical phenomena the last type is often addressed by the decentralized, local control. The first two types are usually the task of multi-area control.

We understand/define multi-area control as a control of a system by dividing it into N_A areas. To each of these areas (or zones) an agent i is assigned, who is responsible for the control within its area. For each agent i, during the time interval between t and $t+T$ there is a set of available controls U_t^i, so for the whole system there are sets of available controls $U_t^1, U_t^2 \dots U_t^{N_A}$. (Note, that $U_t^1 \cup U_t^2 \cup \dots \cup U_t^{N_A} = U_t$ and for any two agents $i \neq j$: $U_t^i \cap U_t^j = \{\}$) The goal of each agent at the time t is to find its corresponding optimal control set e.g., the agent i tries to determine $u_t^{i,*}$ yielding a minimum cost of its cost function.

The agents can obtain the information about the impacts of other areas on its own area either directly from other agents or by observing boundaries to neighboring areas. This topic is treated in the subsequent subsection.

4.3 Information Availability About the Effect of Other Areas

Since the agent i can execute actions only in its own area, the agent has to make some assumptions about the influence of other areas on its area based on the information available. This may result in a discrepancy between the predicted and actual effect of control actions on the system. We distinguish two types of situations to be discussed further.

4.3.1 The agent can observe the entire system

In this case, the agent i has at its disposal information about the whole system in the form of the actual system structure (e.g. system topology, line parameters etc.) and the actual system state (i.e., measurements).

However, the agent i lacks the information about control objectives of other agents, therefore also about the actions which can be expected from them. Thus the agent has to introduce a certain assumption about the actions of other agents when trying to compute its optimal control policy. This assumption is usually that the control actions of other agents remain constant during the entire horizon T, with the last observed values. But actions applied by other agents may (and generally they do) differ from assumed ones. Therefore these actions of other agents can be seen in terms of traditional control theory definitions as measured disturbances.

4.3.2 The agent can observe only its own area

In this situation (configuration) the agent i is aware of only its own area structure and the actual state. Therefore the agent sees other areas (i.e., the rest of the system) only via interfaces connecting it to them and thus it has to use observations from interfaces to model the influence of other areas on its own area. Again, a common assumption is that the state of interfaces remains constant during the whole horizon T. But even if control actions of other agents remain constant, interfaces are affected by control actions taken by the agent i and that in turn affects the area i itself. Thus, this modeling inaccuracy may be perceived as unmeasured disturbances in a traditional control theory.

We want to stress that this case is the closest one to the present power systems and therefore deserves a major attention.

4.4 Dynamics Created by Multi-Area Control

Multi-area control gives rise to a certain type of dynamics, which would not be present in the case of fully centralized control. There are several reasons for that, which we discuss in this subsection. As a consequence of this, the control actions computed by the agent i at the time t are not necessarily (actually almost never) the same ones in both types of control, i.e., centralized and multi-area control: $u_t^{i,*} \cap u_t^* \neq u_t^{i,*}$.

As mentioned before, the actual effect of the applied control differs from the one actually obtained in both cases in the subsection 4.3. In terms of the optimal control framework this may result in:

- suboptimality
- constraints violation

Up to now, we have not discussed the relation of control objectives (expressed by cost functions and constraints) of different agents. Game theory provides a framework for the description of situations, which may occur based on this relation:

Competition Game Each agent tries to improve its own cost, possibly at the expense of some other agents.

Cooperative/Coordination Game An agent can improve its cost by a coordination of its actions with other agents. By a coordination, in our context, we understand a degree in which control objectives and the time sequence of control actions applied by agents have been set with an interest common to all agents.

To demonstrate both above cases in our context, we consider two situations:

1. We assume the situation described in the subsection 4.3.1. If agents have conflicting interests (either in a direct or an indirect form), an agent may misuse the information it has about areas controlled by other agents. This yields a sequence of control actions in which each agent tries to minimize its cost by trying to obtain a benefit from other areas.

2. We assume the situation outlined in the subsection 4.3.2. Since an agent is not aware of other agents and an internal structure of the rest of the system, it has to rely on itself when computing optimal controls. This may actually lead to a search for a local controls approaching optimal controls, which would be determined if a centralized control would be employed.

Both above situations are shown in the example we provide in the next section.

5 ILLUSTRATION ON VOLTAGE CONTROL

5.1 Reactive Power Management Practice

Control of reactive power has essentially two goals: (i) a decrease of active power losses in the branches (i.e., lines and transformers); (ii) an increase of the power system robustness against voltage instability. The strategy used to obtain this robustness is typically to maximize reactive power reserves (i.e., minimization of the reactive power produced by generators and compensators) so that when the system is subjected to a contingency, there is enough fast reserve available to prevent voltage collapse.

Control resources for reactive power management in power systems can be capacitors, reactors, transformer taps, synchronous machines and static or synchronous Var compensators. Shunt capacitances of transmission lines and cables participate indirectly in the reactive power generation. In today's systems, a direct and smooth controllability is mainly provided by generators, but also in some cases by (static or synchronous) Var compensators.

In this paragraph we describe the main ideas of a hierarchical reactive power control structure implemented for example in Italy and France:

Tertiary Layer The country wide network is monitored with a SCADA/EMS system. Centrally collected data are used to determine an optimal system-wide voltage profile. The tight coupling between reactive power and voltage is a well established concept [5].

Secondary Layer The network is divided into areas, which should have negligible interactions. For each of these areas a reference voltage set-point for a so called pilot bus is computed. A pilot bus is the bus, which voltage represents the behavior of area voltages the best (sometimes chosen as the most sensitive voltage in the area). Generators in the area then try to track the reference voltage of the pilot buses by changing their reactive power output.

Primary Layer The primary layer is represented by local controllers of generators.

In our illustration, we want to study the dynamics of the secondary layer, i.e. mutual interactions between the areas. An interesting related work is reported in [6]. We assume a control inspired by (although less sophisticated than) the one introduced in the part of the French system and referred to in the literature as CSVC (Coordinated Secondary Voltage Control) [7]. In this control scheme, several pilot bus voltage deviations from their set-point are combined in the control objective with the (normalized) reactive power reserves of generators. In our example, we rather use the objective of minimizing total reactive power production by generators under voltage constraints.

In our simulations, the cost function represents the sum of reactive power produced by generators located in the area supervised by the agent. Inequality constraints express the goal of not exceeding a maximal or minimal voltage level as well as reactive power production limits of generators. The controls are reference voltage values of generators. We set the prediction horizon T equal to 0, so the response time of the system is neglected, thus the applied control action take an effect immediately. In addition, we assume a discrete time control, so the expression $t-1$ refers to the previous sample just before the time t.

5.2 *Test System*

We have chosen the New England 39-bus test system for our demonstration purposes. This test system has been already used by many authors dealing with voltage stability and control related topics. There are several slightly different versions of the data of this system, we have used the one available at [8]. We have divided the test system into three areas as shown in figure 1. Two areas are controlled by three generators each and one area by four generators.

We have chosen the reactive power limits of generators equal to 3 and -3 pu respectively. Voltage lower and upper limits are 0.95 pu and 1.05 pu respectively. In all cases, except one, we start from the same initial state, when voltages of all generators are equal to 1 pu. This initial state is not optimal so agents start to react. Agents use for their computation of control actions nonlinear optimization.

In the centralized control scheme, one agent controls all ten generators and observes the entire system. Therefore the effect of control actions is exactly the same one as computed by the agent.

The resulting generators voltage profile is close to the upper voltage limit, except the voltage of the generator 4, which higher voltage would probably cause an overvoltage in the bus 19. This high voltage profile charges line capacitances more significantly. Line capacitances then generate a considerable amount of the reactive power, thus the reactive power production of generators is not so high. The sum of reactive power production of all generators is then 12.1165 pu.

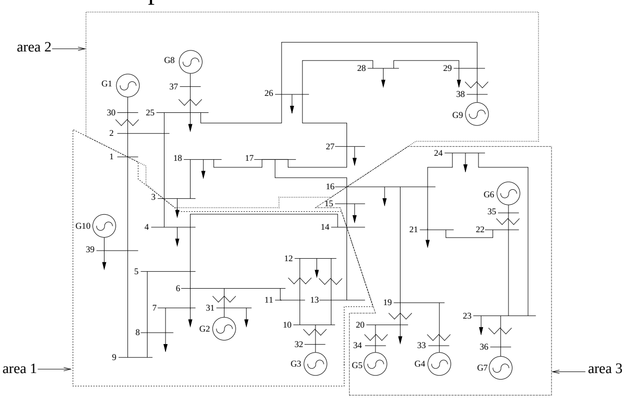

Figure 1: A single line diagram of the used test system.

5.3 *Observations*

We have conducted various simulations to reveal and stress important aspects of multi-area control dynamics discussed in the previous sections.

First we simulate the situation in which the generators of areas 2 and 3 remain with fixed voltage set-point whereas area 1 tries to minimize its reactive power production by adjusting the voltage set-points of its generators. In its computations at time step t, Area 1 represents the rest of the system (i.e. areas 2 and 3) as constant P-Q injections corresponding to the values of line flows outside of area 1 at the time $t-1$. The controls computed under this assumption have different effects from the expected one, as discussed in the subsection 4.3.2. This is shown in the top part of the figure 2, where the sum of the reactive power produced by generators G2, G3 and G10 differs from the one computed in the optimization as expected one. The bottom part of the figure 2 shows sum of reactive power produced by all ten generators in the system (including generators in the area 1). Moreover, although the goal of the area 1 agent is to minimize its area reactive power production, the production actually increases. This can be explained by the physics of the problem. Since the agent does not "see" the rest of the system, it tries to push voltages high in order to charge transmission lines more, so their shunt capacitances would produce more reactive power. But a significant part of this reactive power flows to the rest of the system, so the agent is not receiving the expected feedback, so it tries to continue in the described effort further. This results in a paradox situation, actions of the agent of area 1 are helping the system-wide objective, but noth the local objective of area 1 as one would expect.

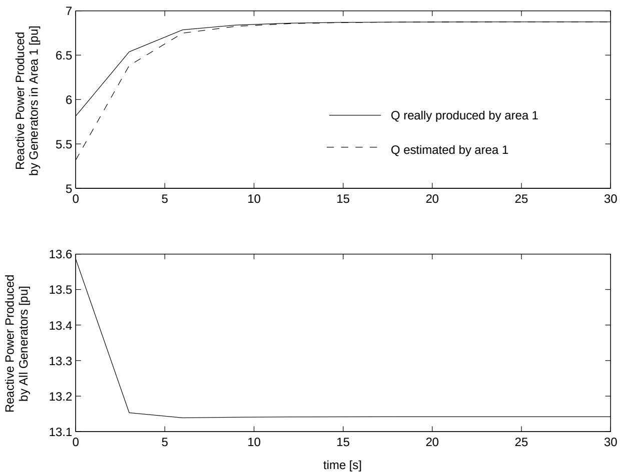

Figure 2: An impact of limited information availability on the accuracy of computation of controls.

To elaborate a bit further on the phenomenon described above, we consider a situation as follows. All three areas try to minimize their reactive power production in a sequential way, i.e. first area 1 executes a control, then area 2 observes the system response and then executes a control and so on. In the first case, area agents have only local observability as in the previous case with a single active area. In the second case, agents have information about the rest of the system at their disposal, so they can estimate the impact of their actions much better. The top part of figure 3, expressing the sum of reactive power production of all ten generators in the system, shows that system-wide performance gets actually much worse. The cause of this problem is that when agents have system-wide observability, they try to use it purely to their own benefit by trying to "pull" (import) the power from other areas by corresponding adjustments of their control strategy, see subsection 4.3.1. This can be observed in the bottom part of figure 3, where imported reactive power into each area is shown. The middle part of the figure 3 shows imported reactive powers of areas for the case of local observability of agents. So instead of the common effort to decrease the system-wide reactive power production, agents enter a competition and the control objective implicitly switches to the tendency to stabilize agents' conflicting interests. This might be perceived as a search for an equilibrium in which the import/export balance of each agent will approach zero.

One more important observation in this simulation is that (in case of the local observability) the final value of the generated power is 12.2833 pu. The minimum value obtained with a centralized agent is 12.1165 pu. This points out the first important consequence of multi-area control dynamics, i.e., a suboptimal value of the entire system cost function is obtained.

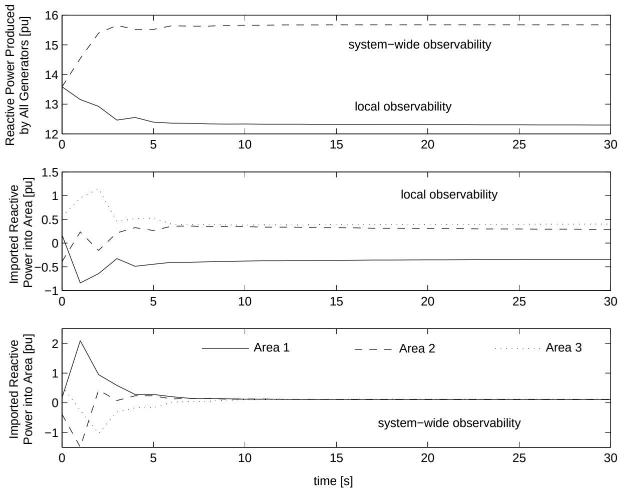

Figure 3: An impact of the information availability.

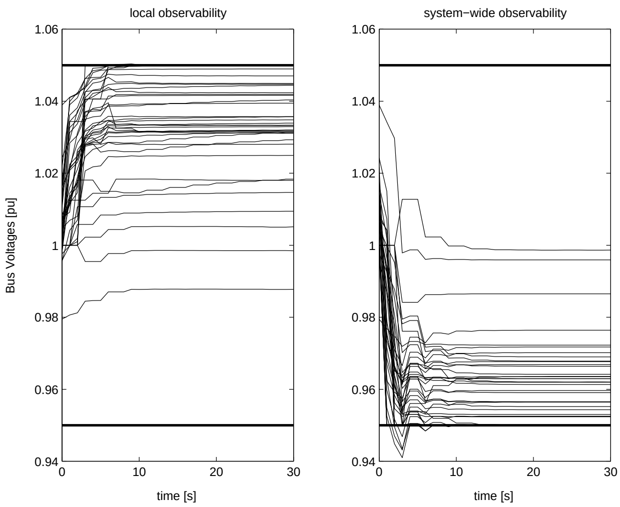

Figure 4: Violations of constraints. Thick solid lines represent borders of voltage operation range, i.e., $0.95pu$ and $1.05pu$.

As already discussed, the second important consequence of multi-area control dynamics is possible violation of the system limits. These are represented in our example by minimum and maximum operation voltages. Figure 4 shows that regardless of the information available to agents, this risk of violation is very probable. The voltage spectrum in the case of local observability is close to the top part of the operation range, therefore the violated limit is the maximal voltage. On the other hand, when agents have system-wide observability, they try to import the reactive power by decreasing their voltages towards the minimal allowed voltage. Thus the minimal voltage limit is violated.

To get a better insight into the motivation of an agent to apply a new set of controls, we can again study the case when agents act in the sequential way with the system-wide observability, what is shown in figure 5. The top part of the figure shows imported reactive power of all areas, several selected voltages of areas 1 and 3 (buses 4 7 8 12 15 20) are shown in the middle part of the figure and reference voltages (i.e., actions of agents) of all generators are displayed in the bottom part of the figure. In the beginning, in the time from 0 to 3, areas 1, 2 and 3 are trying to improve their cost function value by importing the reactive power by lowering their voltages. At the time 4, the agent controlling area 1, can not follow this strategy anymore, since four voltages of its area are already under the limit. Therefore the agent has to raise its voltages to correct the violation of the limit and sacrifice the amount of imported reactive power.

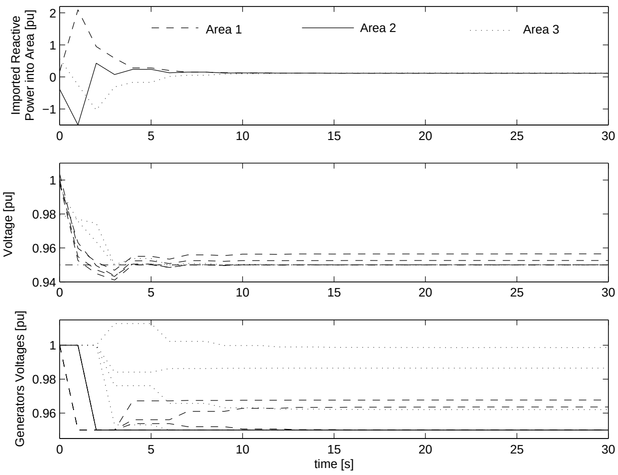

Figure 5: Actions driven by different motivations; removing constraints violations or reduction of the value of the cost function.

Up to this point, we demonstrated only cases of sequential control execution. Figure 6, showing the sum of reactive power produced by all generators, compares the convergence time and the final cost function value of sequential control with the control when all agents collect the information and execute the control at the same time. As it can be observed, the time synchronized control in case of the system-wide observability provides worse performance. This is due to the violation of the assumption mentioned in the subsection 4.3.1, i.e., the action of other agents do not remain constant.

Till now, we started all our simulation from the initial values of generators' voltages equal to 1 pu. If we started from other values, we would achieve the same result under the same control strategy, only the convergence process would slightly vary. Corresponding curves for the local observability time synchronized case are shown in figure 7 for different initial voltages. Shown quantities are sum of reactive power production of all ten generators in the system.

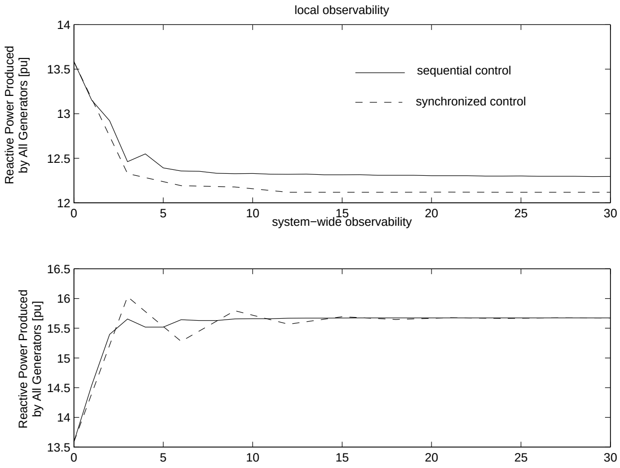

Figure 6: An impact of the time synchronization of actions.

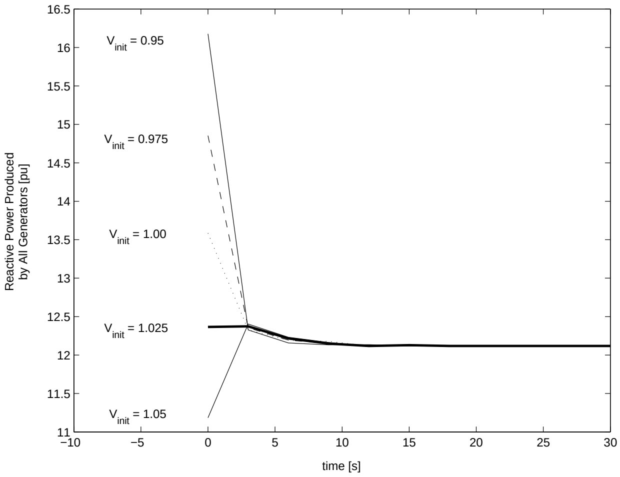

Figure 7: An impact of initial conditions on the convergence process.

In all previous examples we considered basically constant system conditions. However, the time variation is a very important property of power systems. Figure 8 shows the situation when the reactive power load varies and agents try to respond to it in a time synchronized manner with only local observability. It can be observed that the direction of the system conditions change plays a significant role. Agents push the voltages up in order to minimize the reactive power production, thus they operate closely to the upper voltage limit. Therefore when the system load decreases, there is an excess of reactive power generation, what results in the increase of voltages beyond the upper limit. The top part of the figure 8 shows the sum of reactive power production of all ten generators, the middle part of the figure shows the time evolution of the voltage in the bus 10, the bottom part of the figure presents the reference voltage of the generator 3, controlled by the agent supervising the area 1 or by the overall system agent in the centralized case.

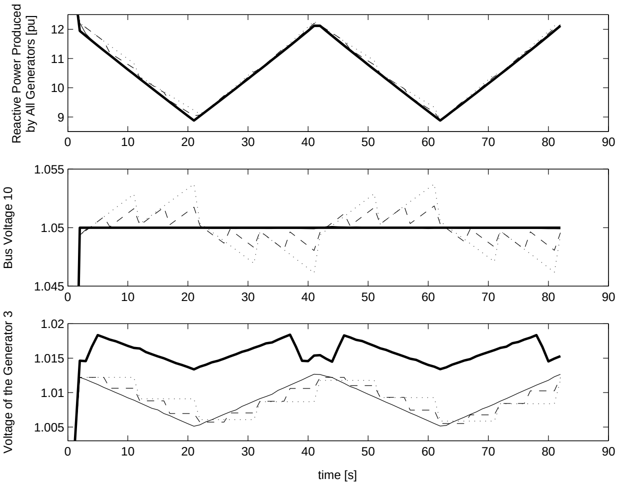

Figure 8: An impact of time varying system conditions and agent speed (i.e., sampling time). The thick solid line expresses a reference obtained with the centralized control. Remaining lines correspond to the time synchronized multi-area control with sampling times 1, 5 and 10 seconds.

We summarize the simulation results as follows. We discovered, that all multi-area control schemes in our example have led to a suboptimal result (sum of reactive power production of generators, both for the each area as well as entire system) when comparing with the centralized control. However, the degree of suboptimality and performance of schemes differ. We have observed that schemes in which agents have system-wide observability lead to worst overall result, i.e., highest sum of reactive power production of all generators (after stabilization, when the result converges due to disappearing of multi-area interactions dynamics) and most severe violation of voltage limits. This is caused by conflicting interests of agents, thus all agents try to select actions, which would result in import of reactive power from remaining areas. This drives the entire system into the equilibrium far from the optimal one (both from the system-wide as well as area view).

Control type	$G_1(2)$	$G_2(1)$	$G_3(1)$	$G_4(3)$	$G_5(3)$	$G_6(3)$	$G_7(3)$	$G_8(2)$	$G_9(2)$	$G_{10}(1)$
Centralized control	1.0136	1.0330	1.0154	0.9975	1.0042	1.0500	1.0500	1.0207	1.0395	1.0394
Loc. obs., synchr.	1.0134	1.0387	1.0127	0.9975	1.0041	1.0500	1.0500	1.0199	1.0394	1.0395
Loc. obs., seq.	1.0096	1.0311	1.0178	0.9984	1.0051	1.0500	1.0500	1.0149	1.0197	1.0419
Sys. obs., seq.	0.9500	0.9677	0.9636	0.9500	0.9865	0.9620	0.9986	0.9500	0.9500	0.9501
Sys. obs., synchr.	0.9500	0.9677	0.9636	0.9500	0.9865	0.9620	0.9986	0.9500	0.9500	0.9501

Table 1: Control actions of agents - reference voltage set points of generators. Number in the brackets behind the generator number indicates the area to which the generator belongs in multi-area control scheme. The numbers correspond to the final state of the simulation with converged results, i.e., 50 seconds. Abbreviations meanings: Loc. = local, obs. = observability, seq. = sequential, synchr. = synchronized, sys. = system-wide.

When area agents in our example have only local observability, their actions approach the ones chosen by the centralized agent, see table 1 , since their control objectives can be seen as a decomposition of the system-wide objective. Therefore based on the observations of simulation results we suggest that local observability yields much better performance, especially in the case when actions of agents are synchronized in time. For more detailed comparison of control schemes, please see table 2.

Control type	Q_{system}	T_c	a	b
Centralized control	12.1165	1	0	0
Loc. obs., synchr.	12.1194	< 15	4	0.0039
Loc. obs., seq.	12.2833	< 15	2	0.0017
Sys. obs., seq.	15.6742	< 10	5	0.0380
Sys. obs., synchr.	15.6742	< 20	9	0.0925

Table 2: Comparison of performance of control schemes. Q_{system} represents the sum of reactive power production of all generators after an obtained convergence (i.e., when the interactions dynamics disappears) expressed by the time T_c. Coefficient a indicates how many bus voltages have violated operation limits during the convergence process. Coefficient b is sum of all limits violations during the convergence process, so it describes also the severity of violations (since it considers magnitude, duration and number of violations).

6 CONCLUSIONS AND FUTURE WORK

Multi-area control is a natural control concept in power systems. Although it is today's practice, requirements and demands on its quality are significantly increasing by a number of reasons. This calls for that different aspects related to it need to be studied thoroughly, particularly the coordination and information exchange issues are of significant importance in interconnected power systems.

In this paper, we provided insights into the dynamics created by interactions between control actions performed by agents responsible for the control of the individual areas. First we discussed these issues on a principal level and later we demonstrated them with an example of reactive power generation minimization. It was shown that dependent on the information available for the agents, the system performances were different.

Many of the problems introduced and briefly discussed in this paper need to be researched in a more systematic way. A more formal and stringent formulation of the multi-area control problem in power systems needs to be developed. The description of interactions between agents should be refined and innovative control schemes need to be designed. Important aspects to consider in this design process are system security, system efficiency, information exchange, communication, and market requirements.

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REFERENCES

[1] http://www.ucte.org/ohb

[2] A. Diu and L. Wehenkel, "EXaMINE - Experimentation of a Monitoring and Control System for Managing Vulnerabilities of the European Infrastructure for Electrical Power Exchange," http://www.examine.ree.es/free/papers/paper1.pdf, 2001.

[3] Y. V. Makarov, D. L. Hawkins and P. Zhang, "New Performance Indicator for Quality of Area Control," *CIGRE/IEEE PES International Symposium on Quality and Security of Electric Power Delivery Systems*, Montreal, Canada, 7-10 October, 2003.

[4] B. H. Kim and R. Baldick, "Coarse-grained Distributed Optimal Power Flow," *IEEE Transactions on Power Systems*, Vol. 12, No. 2, pp. 932-939, May 1997.

[5] P. Kundur, "Power System Stability and Control," *McGraw-Hill Professional Publishing*, ISBN 007035958X, 1994.

[6] M. Ilic, X. Liu, B. Eidson, C. Vialas and M. Athanas, "A Structure-based Modeling and Control of Electric Power Systems," *Automatica*, Vol. 33, No. 4, pp. 515-531, 1997.

[7] H. Vu, P. Pruvot, C. Launay and Y. Harmand, "An Improved Voltage Control on Large-Scale Power System," *IEEE Transactions on Power Systems*, Vol. 11, No. 3, pp. 1295-1303, August 1996.

[8] http://www.pserc.cornell.edu/tcc/tcc.md