Multi-Agent Model Predictive Control

with Applications to Power Networks

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Multi-Agent Model Predictive Control
with Applications to Power Networks

Proefschrift

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Contents

Chapter 5

Overlapping subnetworks

In Chapter 4 we have considered the control of several control agents in a lower control layer by a single control agent in a medium control layer. The control agent in the medium control layer has used a prediction model including both the behavior of the lower control layer and the physical network. In this chapter we consider control by multiple control agents in a higher control layer. The control agents assume that the dynamics of the lower control layers and the physical network are instantaneous. We focus on the question of how nodes of a network should be assigned to subnetworks. In Chapters 2 and 3 the subnetworks into which the transportation networks were divided were not overlapping. In this chapter we will discuss how subnetworks can be defined that are overlapping.

We first formalize the way in which we model general transportation networks in this chapter in Section 5.1. We then discuss several approaches for defining subnetworks and the properties of the resulting subnetworks in Section 5.2. In Section 5.3 we focus on a particular approach for defining subnetworks based on the influence that actuators in these subnetworks have. Currently existing approaches for multi-agent control assume that the subnetworks that control agents control are not overlapping. However, as we will see, the influence-based approach might result in subnetworks that are overlapping. To deal with this, in Section 5.4 we first discuss a recently proposed approach that can be used for the higher-layer multi-agent control of subnetworks that are not overlapping, but that do have links among them. We then propose an extension of this approach for application to higher-layer multi-agent control of subnetworks that are overlapping in Section 5.5.

In this chapter we consider as application optimal power flow control of large power networks. In particular, in Section 5.6 we apply the approach for overlapping subnetworks to an optimal power flow control problem using FACTS devices, in which each FACTS device is controlled by a different control agent. Experiments are carried out on an adjusted IEEE 57-bus power network.

Parts of this chapter have been published in [69].

5.1 Steady-state models of transportation networks

As explained in Chapter 1, in a transportation network there is some commodity flowing through the network over links between nodes inside the network. The nodes can be arranged in a topology to reflect how the elements inside the network are connected to each other. Depending on the flows of the commodity in the network, the values of the variables associated with the nodes, e.g., pressures, speeds, etc., take on different values. By changing the values of actuators that are located in the network, the flows and, hence, the values of the variables can be changed. Control agents are used to determine how the values of the actuators should be changed in order to achieve desired behavior, which is directly related to desired values for the variables associated with the nodes inside the network.

In Chapter 4, we have discussed multi-layer control, and made a distinction between lower, medium, and higher control layers, as depicted in Figure 4.1. In that chapter, we have in particular considered control of an individual medium-layer control agent, that uses a model of the dynamics of the lower control layer and physical network. Here we consider the control of multiple control agents in a higher control layer. The control agents in this higher control layer are interested in controlling the very slow dynamics or the long term behavior, and therefore assume that dynamics of the lower control layers and physical network can be represented by instantaneous dynamics. Therefore, the control agents in the higher control layer consider only steady-state characteristics, i.e., the characteristics of the lower control layers and the network when transients have faded out and the network has settled in a steady state, e.g., after a change in the settings of an actuator.

To model the steady-state characteristics, each of the nodes in the network has associated with it variables and constraints used to compute the steady-state values for these variables, given values for actuator settings and exogenous inputs. Let the network consist of ν nodes, and let ι, for $\iota \in \{1,\ldots,\nu\}$ denote a particular node. The constraints of a particular node ι involve variables of that particular node ι and possibly variables of the nodes of neighboring nodes $\omega \in \mathcal{N}^\iota$, where $\mathcal{N}^\iota = \{\omega_{\iota,1},\ldots,\omega_{\iota,n_{\mathcal{N}^\iota}}\}$ is the set of neighboring nodes of node ι. The set of neighboring nodes $\mathcal{N}^\iota$ of node ι contains those nodes that can be reached from node ι by going over one link in the topology.

Let for node $\iota \in \{1,\ldots,\nu\}$, the variables $\mathbf{z}^\iota \in \mathbb{R}^{n_{\mathbf{z}^\iota}}$, $\mathbf{u}^\iota \in \mathbb{R}^{n_{\mathbf{u}^\iota}}$, and $\mathbf{d}^\iota \in \mathbb{R}^{n_{\mathbf{d}^\iota}}$, denote the algebraic[1], the input, and the exogenous input variables associated with node ι, respectively, and let the constraints of node ι be given by:

$$0 = \mathbf{g}^\iota(\mathbf{z}^\iota,\mathbf{u}^\iota,\mathbf{d}^\iota,\mathbf{z}^{\omega_{\iota,1}},\ldots,\mathbf{z}^{\omega_{\iota,n_{\mathcal{N}^\iota}}}) \tag{5.1}$$

where $\mathbf{z}^\omega$ are the variables of neighboring node $\omega \in \mathcal{N}^\iota$, and $\mathbf{g}^\iota$ are smooth constraint functions of node ι. A steady-state model for the overall network is obtained by aggregating the constraints (5.1) for all nodes $\iota \in \{1,\ldots,\nu\}$, and is compactly represented as:

$$0 = \mathbf{g}(\mathbf{z},\mathbf{u},\mathbf{d}), \tag{5.2}$$

where $\mathbf{z}$, $\mathbf{u}$, and $\mathbf{d}$ are the algebraic, input, and exogenous input variables of the overall network, and $\mathbf{g}$ defines the steady-state characteristics of the network. Given the inputs $\mathbf{u}$ and the exogenous inputs $\mathbf{d}$, the steady state in which the network settles is determined by solving the system of equations (5.2).

Assume that there are multiple control agents, with the objective to reach overall network objectives, like safety and security. With each node a number of objective terms can be associated. These objective terms are used to indicate which behavior is desired for the

[1] Sometimes the algebraic variables are also referred to as static states.

variables $\mathbf{z}^\iota$ and $\mathbf{u}^\iota$ of that node. The terms involve the variables of node ι and possibly the variables of the neighboring nodes $\omega \in \mathcal{N}^\iota$. The aggregation of the objectives terms of each node gives the objective for the control of the overall network.

The nodes that a control agent considers in its decision making form the subnetwork of that control agent. Given that each control agent has access to a particular actuator, the issue that we address below is how to determine which nodes of the overall network a control agent should consider, i.e., how should the subnetwork of a control agent be determined.

5.2 Subnetworks and their properties

We first introduce some properties of subnetworks, and then we discuss different approaches for defining subnetworks and the properties of the resulting subnetworks.

5.2.1 Properties of subnetworks

We make distinctions among *non-overlapping*, *touching*, and *overlapping* subnetworks. If for each subnetwork, the nodes belonging to that subnetwork do not coincide with the nodes belonging to any other subnetwork, and if there are no links going from nodes in one subnetwork into nodes of another subnetwork, then the subnetworks are non-overlapping. If for each subnetwork, the nodes belonging to that subnetwork do not coincide with the nodes of any other subnetwork, but if there are links between nodes of one subnetwork and nodes of another subnetwork, then the subnetworks are touching. If the nodes belonging to some subnetworks partially coincide with the nodes belonging to other subnetworks, then the subnetworks are overlapping. In that case, *common* subnetworks of particular subnetworks are defined as the subnetworks consisting of those nodes that belong to each of these particular subnetworks. Figure 5.1 illustrates the different types of subnetwork divisions. Note that it is not strictly necessary that each node is part of a subnetwork.

In addition to non-overlapping, touching, and overlapping subnetworks, we make a distinction between *time-invariant* and *time-varying* subnetworks. With a time-invariant subnetwork we refer to a subnetwork of which the assignment of nodes does not change over time. With a time-varying subnetwork we refer to a subnetwork of which the assignment of nodes does change over time.

5.2.2 Defining subnetworks

Given an overall transportation network, there are several approaches that can be taken to define subnetworks inside that transportation network, i.e., how to determine which nodes belong to which subnetwork. Some examples of approaches to define subnetworks are the following:

1. Subnetworks can be defined through geographical borders, e.g., of cities, provinces, countries, etc., i.e., based on an existing grouping of nodes.

2. Subnetworks can be defined through clustering of nodes into a predefined number of groups, in such a way that the number of interconnections among the resulting subnetworks is minimized.

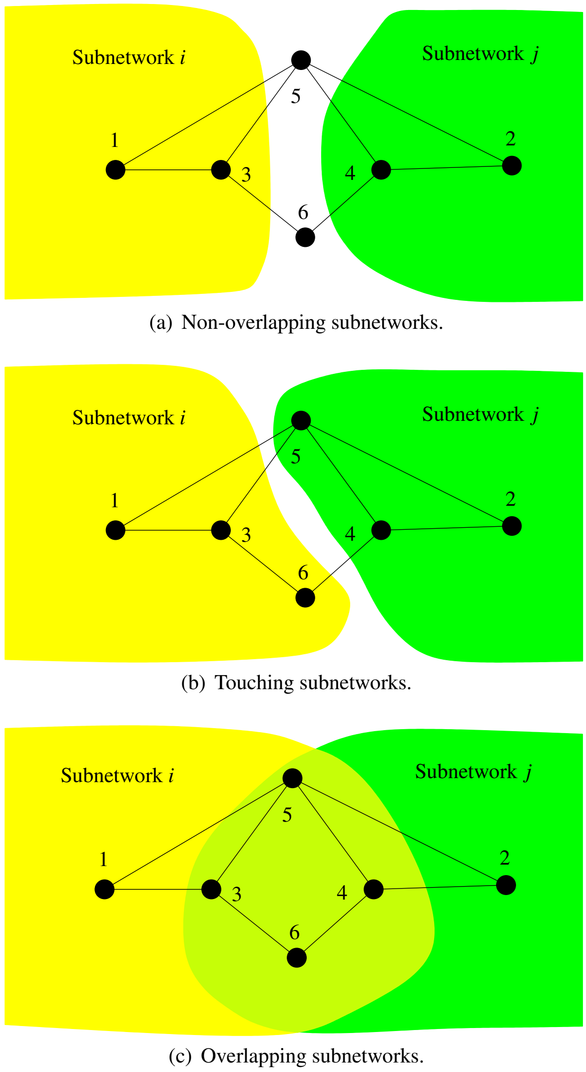


Figure 5.1: Illustration of different types of subnetworks.

3. Subnetworks can be defined based on a radius around nodes, i.e., nodes reachable within a certain number of links from a particular main node (e.g., the node with an actuator) are included in a particular subnetwork.

4. Subnetworks can be defined by including in the subnetwork of a control agent only nodes that can be influenced by the actuators of that control agent.

The first approach can lead to subnetworks that are non-overlapping, touching, or overlapping. E.g., if the subnetworks are defined based on city borders, then the subnetworks can be non-overlapping; if the subnetworks are defined based on country borders, then the subnetworks can be touching; and, if the subnetworks are defined based on country and city borders, the subnetworks can be overlapping. In the case that subnetworks are defined in this way, each subnetwork is typically already controlled by a control authority. The subnetworks resulting from this approach are typically time-invariant, unless wars, city restructuring, breakdowns, etc., are taken into account.

The second approach can lead to non-overlapping or touching subnetworks. If not all nodes of the network are assigned to a subnetwork, then the subnetworks can be non-overlapping. However, if all nodes of the network are assigned to a subnetwork, the subnetworks are touching. Note that using this approach, it may be the case that actuators owned by different control authorities are placed in one subnetwork. The subnetworks resulting from this approach are typically time invariant.

The third approach can lead to non-overlapping, touching, and overlapping subnetworks, depending on the number of nodes that is taken to belong to a particular subnetwork. The underlying idea of considering a radius is that the dynamics topologically far from an actuator are not relevant, since these far away dynamics do not have a significant influence on the dynamics around the actuator. The resulting subnetwork is typically time invariant.

The fourth approach can also lead to non-overlapping, touching, and overlapping subnetworks. In this approach, first it is determined how much the variables of each node can be influenced by actuators, and then depending on the influence on the nodes it is determined which nodes should be included in a subnetwork. If the influence varies over time, then the resulting subnetwork is time-varying. Otherwise it is not.

In the following sections we consider the fourth approach for defining subnetworks, and discuss how coordination among control agents that control subnetworks defined in that way can be achieved, in particular when the resulting subnetworks are overlapping.

5.3 Influence-based subnetworks

The idea of influence-based subnetworks is that the subnetworks are defined based on the nodes that a certain actuator and, hence, a control agent controlling that actuator, can influence. When the nodes that can be influenced have been computed for each actuator, the influence-based subnetwork is defined as the union of these nodes over all actuators of a control agent.

5.3.1 Using sensitivities to determine subnetworks

To determine which dynamics an actuator can influence, sensitivities can be used [51]. The sensitivity of a variable z^{ω} associated with a node $\omega \in \{1, \ldots, \nu\}$ in the network with respect to an input u^{ι} indicates how much the value of variable z^{ω} changes when the input u^{ι} changes. Therefore, an input u^{ι} with respect to which variable z^{ω} has a high sensitivity, i.e., a sensitivity with an absolute value relatively far from zero, has a large influence on the value of variable z^{ω}, whereas an input u^{ι} with respect to which the variable z^{ω} has a low sensitivity, i.e., a sensitivity with an absolute value close to zero, has a low influence on the value of the variable z^{ω}. Knowledge of those variables that have a relatively high sensitivity to the inputs is more important than accurate knowledge of variables that have a relatively low sensitivity. Given the sensitivities, sensitivity thresholding can be used to determine which variables have to be known and which may be neglected. In general, it is to be expected that variables representing dynamics appearing geographically far from a particular input, will have relatively low sensitivity with respect to that input, when compared to variables representing dynamics in the geographical vicinity of that input.

5.3.2 Computing the sensitivities

To determine the sensitivity of the steady-state characteristics of the network, i.e., the sensitivity of the algebraic variables $\mathbf{z}$ with respect to a particular input u^{ι} at node ι, consider the constraint functions $\mathbf{g}_{u^{\iota}}(\mathbf{z}, u^{\iota})$, where $\mathbf{g}_{u^{\iota}}$ are the constraint functions in $\mathbf{g}$ in which all elements of $\mathbf{u}$, except for the element corresponding to u^{ι}, and all elements of $\mathbf{d}$ have been set to fixed values. Since $0 = \mathbf{g}(\mathbf{z}, \mathbf{u}, \mathbf{d})$, also $0 = \mathbf{g}_{u^{\iota}}(\mathbf{z}, u^{\iota})$. In addition, since $\mathbf{z}$ depends on u^{ι}, it follows by the chain rule that:

$$0 = \frac{\partial \mathbf{g}_{u^{\iota}}}{\partial \mathbf{z}}(\mathbf{z}, u^{\iota}) \frac{\partial \mathbf{z}}{\partial u^{\iota}}(\mathbf{z}, u^{\iota}) + \frac{\partial \mathbf{g}_{u^{\iota}}}{\partial u^{\iota}}(\mathbf{z}, u^{\iota}),$$

and therefore:

$$\frac{\partial \mathbf{z}}{\partial u^{\iota}}(\mathbf{z}, u^{\iota}) = \left(-\frac{\partial \mathbf{g}_{u^{\iota}}}{\partial \mathbf{z}}(\mathbf{z}, u^{\iota})\right)^{-1} \frac{\partial \mathbf{g}_{u^{\iota}}}{\partial u^{\iota}}(\mathbf{z}, u^{\iota}), \tag{5.3}$$

under the assumption that the inverse term exists. The term $\frac{\partial \mathbf{z}}{\partial u^{\iota}}(\mathbf{z}, u^{\iota})$ is the sensitivity of $\mathbf{z}$ with respect to u^{ι}. From this sensitivity we can determine which terms of the algebraic variables $\mathbf{z}$ are significantly influenced by input u^{ι}. If the absolute value of the sensitivity of a particular element of $\mathbf{z}$ with respect to input u^{ι} is larger than a sensitivity threshold γ_{s}, then that element of $\mathbf{z}$ cannot be neglected. The elements of $\mathbf{z}$ that cannot be neglected can be linked to their corresponding nodes, giving a set of nodes that can be significantly influenced by input u^{ι}.

The set of nodes that can be influenced by an actuator depends on the sensitivity threshold γ_{s} used. On the one hand, if a sensitivity threshold γ_{s} of 0 is used, all nodes will be selected. Hence, the subnetwork resulting from this approach will correspond to the full network. On the other hand, if a very large sensitivity threshold γ_{s} is used, no nodes will be selected, and the subnetwork resulting from this approach will be empty. In Section 5.6.2 we give an illustration of this.

5.3.3 Control of influence-based subnetworks

The settings of the actuators in the network should be adjusted in such a way that the objectives associated with the nodes are achieved as well as possible. Let each actuator be controlled by a control agent, and let the task of each control agent be to determine new set points for its actuators. Control agent i considers as its subnetwork the union of the nodes that can be influenced by the actuators that control agent i can control. The prediction model M_i that control agent i considers therefore also consists of the union of the constraints in the influence-based models for each actuator that it controls.

Remark 5.1 Since in this chapter we consider only steady-state characteristics, it is not beneficial to formulate the control problem of each control agent in an MPC setting. If we would formulate the control problem as an MPC problem, then the MPC problem would consist of the combination of static problems for each prediction step, without having coupling between the static problems. Hence, this would effectively mean solving N independent static optimization problems without any coupling between them each time a control agent has to determine actions. However, note that if dynamics depending on time, or if objective terms depending on inputs implemented earlier are included, that then it does make sense to formulate an MPC control problem. □

When the influence-based approach is used to determine for each control agent which subnetwork it should consider, the resulting subnetworks can be non-overlapping, touching, or overlapping. In addition, the influence-based approach uses the sensitivity (5.3), which is a function of the operating point, to select which nodes should belong to a subnetwork. Since the operating point can change over time, the nodes that would be assigned to a subnetwork can differ as well. Hence, the subnetworks can be time-varying.

If the subnetworks are non-overlapping, then the values of the variables of the nodes that control agents can influence significantly do not overlap, so no coordination among control agents is necessary. Adequate control performance can then be obtained, as illustrated in [51]. If the subnetworks are touching, then techniques based, e.g., on the ideas of Chapter 2 can be used to obtain coordination. For subnetworks that are overlapping, no techniques have been proposed so far for obtaining coordination. For overlapping subnetworks, the control agents will have to find agreement on how the variables involved in the dynamics of the common subnetworks will evolve over time. In the following we first discuss an approach that can be used for controlling time-invariant touching subnetworks. Then we extend this approach to be able to deal with time-invariant overlapping subnetworks. For sake of simplicity we assume below that all nodes in the network are assigned to a subnetwork.

5.4 Multi-agent control of touching subnetworks

In Chapters 2 and 3 we have discussed two approaches for coordinating multiple control agents when subnetworks are touching, based on a decomposition of an augmented Lagrange function. Below we discuss a technique for coordinating such control agents based on the ideas of the modified Lagrange technique proposed in [31]. The underlying idea is to determine subproblems in such a way that the first-order optimality conditions for the subproblems of all control agents together are equivalent to the first-order optimality conditions of a hypothetical overall control problem [31].

5.4.1 Internal and external nodes

Before explaining how the approach for multi-agent control of touching subnetworks works, we first define some concepts that will be frequently used in the following:

- We categorize the nodes that control agent i considers based on their location. For touching subnetworks, the nodes that control agent i considers can be *internal* nodes or *external* nodes. The internal nodes of control agent i are those nodes that belong exclusively to its subnetwork. The external nodes of control agent i are those nodes that do not belong to its subnetwork.

type	location	variables involved in constraint
$\mathcal{C}_{i,\text{int}}^{\text{int}}$	internal	internal
$\mathcal{C}_{i,\text{int}}^{\text{int+ext}}$	internal	internal+external
$\mathcal{C}_{i,\text{ext}}^{\text{ext}}$	external	external
$\mathcal{C}_{i,\text{ext}}^{\text{int+ext}}$	external	internal+external

Table 5.1: Localized constraint types of constraints associated with nodes in a subnetwork that touches other subnetworks. The location indicates the location of the node from the point of view of control agent i. The variables involved in the constraint indicate which variables are involved in the constraint, from the point of view of control agent i.

- Based on the distinction between internal and external nodes of control agent i, we make a distinction between internal and external variables of control agent i. The internal variables are those variables associated with the internal nodes of control agent i. The external variables are those variables associated with the external nodes of control agent i.

- For control agent i, the *localized constraint type* of a particular constraint associated with a node ι that control agent i considers is formed by the combination of the location and the types of variables involved in that constraint. The localized constraint type of a constraint associated with a node ι considered by control agent i is denoted by $\mathcal{C}_{i,\text{Loc}}^{\text{Vars}}$, where $Loc \in \{\text{int}, \text{ext}\}$ indicates the location of the node to which the constraint is associated, and $Vars \in \{\text{int}, \text{int+ext}\}$ indicates the variables involved in the constraint. Recall that a constraint associated with a particular node ι involves variables of that particular node and possibly variables of neighboring nodes. The constraints associated with the nodes considered by control agent i can therefore have the localized constraint types as depicted in Table 5.1. Figure 5.2 illustrates for some nodes the localized constraint types that can be found at these nodes.

- In a similar way as we defined localized constraint types $\mathcal{C}_{i,\text{Loc}}^{\text{Vars}}$, we also define localized objective term types $\mathcal{J}_{i,\text{Loc}}^{\text{Vars}}$, referring to the location of the node to which an objective term is associated and the variables that are involved in the objective function term.

5.4.2 Control problem formulation for one agent

The optimization problem of control agent i at time step k consists of minimizing the objective function J_i, subject to the steady-state characteristics of subnetwork i and additional constraints on inputs and outputs. Below we focus on the difficulties that arise with respect to the prediction model and the objective function due to the existence of other control agents that control subnetworks that are touching the subnetwork of control agent i.

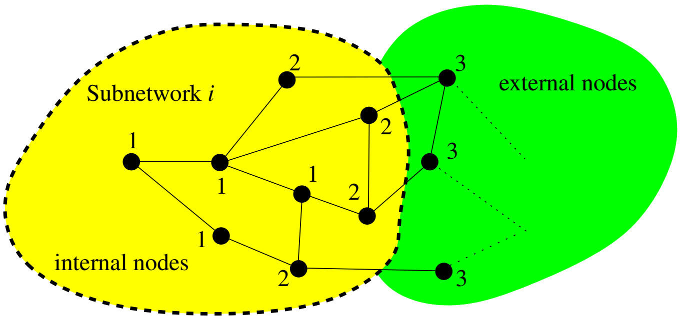


Figure 5.2: Illustration of different localized constraint types that can be found at nodes considered by control agent i. The number next to a node in the figure corresponds as follows to the localized constraint types of the constraints that can be associated to that node: (1) $\mathcal{C}_{i,int}^{int}$*; (2)* $\mathcal{C}_{i,int}^{int}, \mathcal{C}_{i,int}^{int+ext}$*; (3)* $\mathcal{C}_{i,ext}^{int+ext}, \mathcal{C}_{i,ext}^{ext}$*.*

Prediction model

The prediction model of control agent i consists of the constraints associated with all its internal nodes. The internal nodes that do not have external neighboring nodes do not require special attention, since the variables involved in the constraints of these internal nodes are of localized constraint type $\mathcal{C}_{i,\text{int}}^{\text{int}}$ and therefore only involve variables that are influenced by control agent i. However, the internal nodes that are connected to external nodes do require special attention, since the constraints associated with these internal nodes can be of localized constraint type $\mathcal{C}_{i,\text{int}}^{\text{int+ext}}$, and therefore involve not only variables of the subnetwork of control agent i, but also variables of the subnetwork of a neighboring agent $j \in \mathcal{N}_i$. In order to make predictions over its prediction horizon, control agent i has to know accurate values for the external variables involved in the constraints of these nodes. Therefore, control agent i has to coordinate with the neighboring agents which values external variables should have. To obtain coordination on the values of the external variables, we apply an idea that was first proposed in [31] as follows.

Control agent i considers the constraints that are associated with its internal nodes and that are of localized constraint type $\mathcal{C}_{i,\text{int}}^{\text{int+ext}}$, using fixed values for the external variables. The values for these external variables have been obtained from the neighboring agent j that has the node of these external variables as an internal node. Control agent i solves its local optimization problem using these values for the external variables. The optimization yields values for the internal variables of control agent i, and for the Lagrange multipliers that are associated with the constraints of localized constraint type $\mathcal{C}_{i,\text{int}}^{\text{int+ext}}$. The Lagrange multipliers of these constraints and the values of the internal variables involved in these constraints are sent to each neighboring agent j that has a node to which the external variables of these constraints correspond as an internal node.

Each neighboring agent j considers the constraints of the internal nodes of control agent i that involve external variables of control agent i in its decision making by including these associated constraints as soft constraints in its objective function. Note that internal and external nodes of control agent i correspond to external and internal nodes, respectively, of a control agent j. In the soft constraints of such a control agent j, the external variables, which

localized constraint type	constraint
$C^{\text{int}}_{i,\text{int}}$	hard
$C^{\text{int+ext}}_{i,\text{int}}$	hard
$C^{\text{int+ext}}_{i,\text{ext}}$	soft

Table 5.2: The constraints that control agent i can have and how it deals with these constraints. For the hard and soft constraints, the external variables are fixed to values obtained from neighboring agents. For the hard constraints with external variables Lagrange multipliers are determined. The soft constraints are weighted using the Lagrange multipliers received from neighboring agents.

localized objective term type	how deal with the objective term
$\mathcal{J}^{\text{int}}_{i,\text{int}}$	include as is
$\mathcal{J}^{\text{int+ext}}_{i,\text{int}}$	include as is

Table 5.3: The localized objective term types that control agent i considers and how it deals with these terms. External variables are fixed to values obtained from neighboring agents.

correspond to internal variables of control agent i, are fixed to the values that control agent i has sent to control agent j. In addition, the soft constraints are weighted by the Lagrange multipliers as given by control agent i. Neighboring agent j solves its optimization problem, yielding values for its internal variables. It sends the values of the internal variables that appear in the soft constraints to control agent i, such that control agent i can update its information about the corresponding external variables.

Based on this idea, Table 5.2 shows how control agent i deals with the different constraints, when formulating its optimization problem.

Objectives

The objective function for control agent i consists of objective function terms that are associated with the nodes in its subnetwork. Objective terms associated with internal nodes that are only connected to internal nodes do not give rise to issues, since no other control agents consider these objective terms. However, objective terms associated with internal nodes that are also connected to external nodes cause problems for the same reason as with the constraints associated with such nodes. Coordination on the values of these variables is obtained by obtaining the desired values for the external variables from neighboring agents.

Table 5.3 shows the different localized objective term types that control agent i considers, and how it deals with these, when formulating its optimization problem.

5.4.3 Control scheme for multiple agents

The multi-agent control scheme taking into account the prediction model and objective function discussed above operates in an iterative way. When the control agents have to determine actions, they perform a series of iterations, in each of which the control agents perform a local optimization step and communicate information. The outline of the scheme is as follows:

1. Each control agent i measures the current values for the algebraic variables $\mathbf{z}_i$ and the input variables $\mathbf{u}_i$ that are associated with the nodes in its subnetwork. In addition, it obtains predictions of known exogenous inputs $\mathbf{d}_i$. Furthermore, it obtains through communication from its neighbors values for the external variables and Lagrange multipliers associated with the external nodes that control agent i considers.

2. The iteration counter s is set to 1.

3. Let $\mathbf{w}_{\text{in},i}^{(s-1)}$ and $\tilde{\boldsymbol{\lambda}}_{\text{soft},i}^{(s-1)}$ denote the external variables and Lagrange multipliers, respectively, of which control agent i has received the values from neighboring agents. Given $\mathbf{w}_{\text{in},i}^{(s-1)}$ and $\tilde{\boldsymbol{\lambda}}_{\text{soft},i}^{(s-1)}$, each control agent $i \in \{1,\dots,n\}$ performs the following steps in parallel:

   (a) Control agent i solves the optimization problem:

$$\min_{\mathbf{z}_i,\mathbf{u}_i,\mathbf{w}_{\text{out},i}} J_i\left(\mathbf{z}_i,\mathbf{u}_i,\mathbf{w}_{\text{in},i}^{(s-1)}\right) + \left(\tilde{\boldsymbol{\lambda}}_{\text{soft},i}^{(s-1)}\right)^{\mathrm{T}} \tilde{\mathbf{g}}_{\text{soft},i}\left(\mathbf{z}_i,\mathbf{u}_i,\mathbf{w}_{\text{in},i}^{(s-1)}\right)$$

   subject to

$$\tilde{\mathbf{g}}_{\text{hard},i}(\mathbf{z}_i,\mathbf{u}_i,\mathbf{d}_i) = 0$$

$$\tilde{\mathbf{g}}_{\text{hard,ext},i}\left(\mathbf{z}_i,\mathbf{u}_i,\mathbf{d}_i,\mathbf{w}_{\text{in},i}^{(s-1)}\right) = 0 \quad (5.4)$$

$$\mathbf{w}_{\text{out},i} = \tilde{\mathbf{K}}_i \begin{bmatrix}\mathbf{z}_i^{\mathrm{T}} & \mathbf{u}_i^{\mathrm{T}} & \mathbf{d}_i^{\mathrm{T}}\end{bmatrix}^{\mathrm{T}} \quad (5.5)$$

$$\mathbf{z}_{i,\min} \le \mathbf{z}_i \le \mathbf{z}_{i,\max}$$

$$\mathbf{u}_{i,\min} \le \mathbf{u}_i \le \mathbf{u}_{i,\max},$$

   where $\mathbf{z}_{i,\min}$ and $\mathbf{z}_{i,\max}$ are upper and lower bounds on $\mathbf{z}_i$, $\mathbf{u}_{i,\min}$ and $\mathbf{u}_{i,\max}$ are upper and lower bounds on $\mathbf{u}_i$, $\tilde{\mathbf{g}}_{\text{soft},i}$ are the constraints of localized constraint type $\mathcal{C}_{i,\text{ext}}^{\text{int+ext}}$, $\tilde{\mathbf{g}}_{\text{hard},i}$ are the constraints of localized constraint type $\mathcal{C}_{i,\text{int}}^{\text{int}}$, $\tilde{\mathbf{g}}_{\text{hard,ext},i}$ are the constraints of localized constraint type $\mathcal{C}_{i,\text{int}}^{\text{int+ext}}$, and $\mathbf{w}_{\text{out},i}$ are the variables that control agent i uses in communication to neighboring agents, selected using selection matrix $\tilde{\mathbf{K}}_i$. The optimization results in values for the variables $\mathbf{z}_i^{(s)}$ and $\mathbf{u}_i^{(s)}$, Lagrange multipliers $\tilde{\boldsymbol{\lambda}}_{\text{hard,ext},i}^{(s)}$ associated with the constraints (5.4) for current iteration s, and values for $\mathbf{w}_{\text{out},i}^{(s)}$.

   (b) Control agent i sends the values of the Lagrange multipliers $\tilde{\boldsymbol{\lambda}}_{\text{hard,ext},i}^{(s)}$ of the hard constraints of localized constraint type $\mathcal{C}_{i,\text{int}}^{\text{int+ext}}$ and the values of $\mathbf{w}_{\text{out},i}$ corresponding to internal variables of these nodes to the neighboring agents that consider the involved external variables.

   (c) Control agent i receives from the neighboring agents $j \in \mathcal{N}_i$ those Lagrange multipliers related to the localized constraint type $\mathcal{C}_{i,\text{ext}}^{\text{int+ext}}$ and those values of the internal variables of the neighboring agents that control agent i requires to fix its external variables. Control agent i uses this received information at the next iteration as $\tilde{\boldsymbol{\lambda}}^{(s)}_{\text{soft},i}$ and $\mathbf{w}^{(s)}_{\text{in},i}$.

4. The next iteration is started by increasing s and going back to step 3, unless a stopping condition is satisfied. The stopping condition is defined as the condition that the absolute changes in the Lagrange multipliers from iteration $s-1$ to s are smaller than a pre-defined small positive constant $\gamma_{\epsilon,\text{term}}$.

Although the approach discussed above can coordinate control agents that control touching subnetworks, a shortcoming of this method is that it requires that the subnetworks are touching, since it assumes that each node in the network is assigned to only one of the subnetworks. However, in the case of control of overlapping subnetworks, some of the nodes are included in more than one subnetwork and the identification of internal and external nodes of a control agent is not straightforward any more. Therefore, the method is not directly applicable to overlapping subnetworks. In the following, we consider an extension of the method discussed above to control of overlapping subnetworks.

5.5 Multi-agent control for overlapping subnetworks

Now, we extend the approach for control of touching subnetworks to control of overlapping subnetworks. We first propose some new definitions, then consider the issues appearing due to the overlap, and then propose a way to deal with these issues.

5.5.1 Common nodes

In addition to internal and external nodes as defined before, for control of overlapping subnetworks we make the following definitions:

- *Common* nodes are nodes that belong to the subnetwork of control agent i and that also belong to the subnetwork of another control agent j. A subnetwork defined by the nodes common to several subnetworks is referred to as a common subnetwork.

- The variables associated with the common nodes are referred to as the common variables.

- Given the definition of a common node, the number of possibilities for localized constraint types increases. Table 5.4 lists the localized constraint types that can be considered by a control agent when subnetworks can be overlapping. In total there are 12 different localized constraint types. Figure 5.3 illustrates some of the possible localized constraint types.

- In addition to the extension of the localized constraint types, the localized objective term types are extended also accordingly.

type	location	variables involved in constraint
$C_{i,\text{int}}^{\text{int}}$	internal	internal
$C_{i,\text{int}}^{\text{int+com}}$	internal	internal+common
$C_{i,\text{int}}^{\text{int+ext}}$	internal	internal+external
$C_{i,\text{int}}^{\text{int+com+ext}}$	internal	internal+common+external
$C_{i,\text{com}}^{\text{int+com}}$	common	internal+common
$C_{i,\text{com}}^{\text{int+com+ext}}$	common	internal+common+external
$C_{i,\text{com}}^{\text{com}}$	common	common
$C_{i,\text{com}}^{\text{com+ext}}$	common	common+external
$C_{i,\text{ext}}^{\text{ext}}$	external	external
$C_{i,\text{ext}}^{\text{int+ext}}$	external	internal+external
$C_{i,\text{ext}}^{\text{com+ext}}$	external	common+external
$C_{i,\text{ext}}^{\text{int+com+ext}}$	external	internal+common+external

Table 5.4: Localized constraint types for overlapping subnetworks.

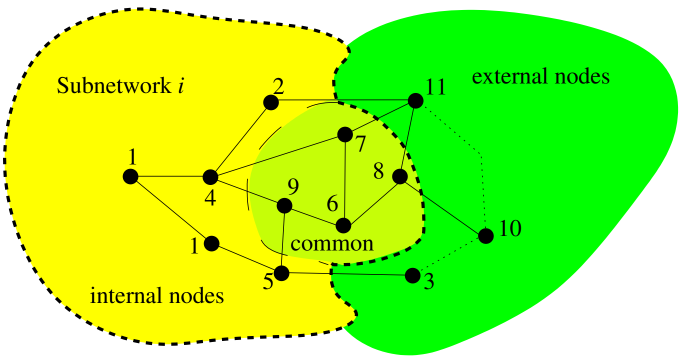


Figure 5.3: Illustration of different localized constraint types that can be found at particular nodes. The number next to a node in the figure corresponds as follows to the localized constraint types of the constraints that can be associated to that node: (1) $C_{i,int}^{int}$; (2) $C_{i,int}^{int}$, $C_{i,int}^{int+ext}$; (3) $C_{i,ext}^{int+ext}$, $C_{i,ext}^{ext}$; (4) $C_{i,int}^{int}$, $C_{i,int}^{int+com}$; (5) $C_{i,int}^{int}$, $C_{i,int}^{int+com}$, $C_{i,int}^{int+ext}$, $C_{i,int}^{int+com+ext}$; (6) $C_{i,com}^{com}$; (7) $C_{i,com}^{int+com}$, $C_{i,com}^{com+ext}$, $C_{i,com}^{com}$, $C_{i,com}^{int+com+ext}$; (8) $C_{i,com}^{com}$, $C_{i,com}^{com+ext}$; (9) $C_{i,com}^{com}$, $C_{i,com}^{int+com}$; (10) $C_{i,ext}^{ext}$, $C_{i,ext}^{ext+com}$; (11) $C_{i,ext}^{int+ext}$, $C_{i,ext}^{com+ext}$, $C_{i,ext}^{ext}$, $C_{i,ext}^{int+com+ext}$.

5.5.2 Control problem formulation for one agent

For multi-agent control of overlapping subnetworks an approach has to be found to deal with the common nodes. Since the common nodes are considered by several control agents, also the constraints associated with these common nodes appear in the subnetwork models of multiple control agents. Even though we assume that the control agents have the same objective with respect to these nodes, combined with the objective for their internal nodes, conflicting intentions for the common nodes can be the result. Below we discuss how to extend the scheme of the previous section for control of overlapping subnetworks.

Prediction model

Similar as for control of touching subnetworks, for control of overlapping subnetworks, internal nodes of control agent *i* that are connected to external nodes require special attention, since the constraints associated to these nodes may involve external variables. In addition to this, also common nodes of control agent *i* that are connected to external nodes require special attention. The extension of the approach for control of touching subnetworks to the control of overlapping subnetworks consists of the following with respect to the prediction model.

Control agent *i* considers as prediction model the constraints of all internal *and* common nodes. For the constraints of localized constraint types $\mathcal{C}_{i,\text{int}}^{\text{int+ext}}$, $\mathcal{C}_{i,\text{int}}^{\text{int+ext+com}}$, $\mathcal{C}_{i,\text{com}}^{\text{com+ext}}$, and $\mathcal{C}_{i,\text{com}}^{\text{int+com+ext}}$ the control agent takes for the external variables values that it has received from neighboring agents. When control agent *i* has solved its optimization problem, it sends the values of the internal *and* the common variables of the constraints of these specialized constraint types to neighboring agents.

Each neighboring agent *j* considers the constraints of the internal and common nodes of control agent *i* that involve external variables of control agent *i* in its optimization problem as soft constraints by including them in the objective function, weighted by the Lagrange multipliers provided by control agent *i*, and with fixed values for the external *and* common values in the soft constraints as received from control agent *i*. The result of solving the optimization problem of neighboring agent *j* yields values for the internal, common, and external variables of control agent *j*. The internal variables of control agent *j* related to the soft constraints are sent to control agent *i*.

Table 5.5 summarizes how control agent *i* deals with the different localized constraint types.

Objectives

With the nodes that control agent *i* has in its subnetwork objective terms are associated. The objective function terms associated with each node can depend on the variables associated with that node and its neighboring nodes. As before, the objective terms involving only internal variables require no special attention. The objective terms involving both internal and external variables can be dealt with by fixing the external variables, as is also done for control of touching subnetworks. However, the common variables appearing in control of overlapping subnetworks do require special attention.

For control of overlapping subnetworks, multiple control agents will try to control the values of the common variables. To allow control agents to jointly achieve performance

localized constraint type	constraint
$\mathcal{C}_{i,\text{int}}^{\text{int}}$	hard
$\mathcal{C}_{i,\text{int}}^{\text{int+ext}}$, $\mathcal{C}_{i,\text{int}}^{\text{int+com}}$	hard
$\mathcal{C}_{i,\text{int}}^{\text{int+com+ext}}$	hard
$\mathcal{C}_{i,\text{com}}^{\text{int+com}}$	hard and soft
$\mathcal{C}_{i,\text{com}}^{\text{int+com+ext}}$	hard and soft
$\mathcal{C}_{i,\text{com}}^{\text{com}}$	hard
$\mathcal{C}_{i,\text{com}}^{\text{com+ext}}$	hard
$\mathcal{C}_{i,\text{ext}}^{\text{int+ext}}$	soft
$\mathcal{C}_{i,\text{ext}}^{\text{int+ext+com}}$	soft

Table 5.5: The way in which control agent i considers the constraints of particular localized constraint types in its optimization problem. For the hard constraints all common variables are fixed to values obtained from neighboring agents. For the soft constraints all external and common variables are fixed. For the hard constraints with external variables Lagange multipliers are determined. The soft constraints are weighted with Lagrange multipliers obtained from neighboring agents.

localized objective term type	how deal with the objective term
$\mathcal{J}_{i,\text{int}}^{\text{int}}$	include as is
$\mathcal{J}_{i,\text{int}}^{\text{int+ext}}$	include as is
$\mathcal{J}_{i,\text{int}}^{\text{int+com}}$	include as is
$\mathcal{J}_{i,\text{com}}^{\text{com}}$	include partially: $1/N_\iota$
$\mathcal{J}_{i,\text{com}}^{\text{int+com}}$	include partially: $1/N_\iota$

Table 5.6: The localized objective term types that control agent i considers and how it deals with the associated objective terms. External variables are fixed. Variable N_ι is the number of control agents considering node N_ι as common node.

comparable to the performance that an overall centralized control agent can achieve, the responsibility for the objective terms involving only common variables, i.e., of localized objective term type $\mathcal{C}_{i,\text{com}}^{\text{com}}$, is shared equally by the control agents. Hence, each control agent i that considers a particular common node ι, takes in its objective function $1/N_\iota$ times the objective function terms of that common node that involve only common variables, where N_ι is the number of control agents considering node N_ι as common node. Control agent i in addition includes the objective terms of internal and common nodes that involve only internal and common variables, i.e., of localized objective term types $\mathcal{C}_{i,\text{int}}^{\text{int}}$, $\mathcal{C}_{i,\text{int}}^{\text{int+com}}$, $\mathcal{C}_{i,\text{com}}^{\text{com}}$, and $\mathcal{C}_{i,\text{com}}^{\text{int+com}}$.

Table 5.6 summarizes how control agent i deals with the different localized objective term types.

5.5.3 Control scheme for multiple agents

We have discussed how each control agent formulates its prediction model and objective function. The scheme that we propose for multi-agent control for overlapping subnetworks consists of the scheme proposed in Section 5.4 for touching subnetworks, with the following changes:

- Control agent i receives from the neighboring agents the following information at initialization and after each iteration:
  - Lagrange multipliers with respect to the constraints of localized constraint type $\mathcal{C}_{i,\text{ext}}^{\text{ext+int}}$, $\mathcal{C}_{i,\text{ext}}^{\text{ext+com}}$, $\mathcal{C}_{i,\text{ext}}^{\text{ext+com+int}}$.
  - Values for the external variables *and* the common variables involved in these constraints.
- The optimization problem that each agent solves is changed accordingly to reflect the extensions discussed in this section, i.e., to take into account the constraints as given in Table 5.5 and the objective terms as given in Table 5.6.

The result is a control scheme that can be used by higher-layer control agents that control subnetworks that are overlapping. In the next section we apply this scheme on an optimal flow control problem in power networks.

5.6 Application: Optimal flow control in power networks

In this section we propose to use the scheme discussed in Section 5.5 for multi-agent control of overlapping subnetworks to the problem of optimal power flow control in power networks. Optimal power flow control is a well known-method to control and optimize the operation of a power network [82]. Optimal power flow control is typically used to improve steady-state network security by improving the voltage profile, preventing lines from overloading, and minimizing active power losses. Usually settings for generators are determined by solving an optimization problem that minimizes an objective function encoding the system security objectives, subject to the steady-state characteristics of the network.

Typically only steady-state characteristics at on time step are considered, not taking into account future known exogenous inputs. The conventional optimal power flow control can be easily generalized to an optimal power flow control taking into account future known exogenous inputs. In this way, indeed, the optimal power flow control can be seen as an application of model predictive control, in which the prediction model consists of the steady-state characteristics defined over a particular prediction horizon.

Flexible alternating current transmission systems (FACTS) are devices that can improve power network operation. They can be used for dynamic control of voltage, impedance, and phase angle. The usage of FACTS devices has the potential to improve the security of the network, to increase the dynamic and transient stability, to increase the quality of supply for sensitive industries, and to enable environmental benefits, all without changing the topology of the existing network [62]. Some frequently used types of FACTS devices, and the types of FACTS devices that we consider below, are Static Var Compensators (SVCs) and Thyristor Controlled Series Compensators (TCSCs) [40].

Traditional approaches for multi-agent optimal power flow control assume that a decomposition of the overall network and control objectives into touching subnetworks is possible [80, 116], as shown in Figure 5.1(b). When the optimal power flow control problem involves multiple subnetworks and each bus in these subnetworks is assigned to exactly one subnetwork, then the assumption of touching subnetworks is appropriate to make. However, when a bus in a subnetwork is assigned to multiple subnetworks, then this assumption no longer holds. In our case, we are interested in control using FACTS devices of subnetworks that have been determined by sensitivity analysis, as discussed in Section 5.3. As we discussed in that section, the resulting subnetworks can be non-overlapping, touching, or overlapping. Indeed, if FACTS devices are positioned topologically far from each other, their influence-based subnetworks will typically not overlap, whereas if they are positioned topologically close to each other, their influence-based subnetworks will typically overlap. Hence, an approach that can be used by the control agents controlling the FACTS devices in such overlapping subnetworks is required. The approach proposed in Section 5.5 is suitable for this.

Simulations are carried out on the IEEE 57-bus power network with additional FACTS devices installed at various locations [5]. The base parameters of the IEEE 57-bus network can be obtained from the Power Systems Test Case Archive[2]. Line limits have been assigned to the lines in such a way that no lines are overloaded. In order to find an interesting and meaningful situation for FACTS control, the grid was adapted by placing an additional generator at bus 30 leading to increased power flows in the center of the grid. The values of all parameters of the used power network are available from the author on request.

Below we formulate the steady-state models used to describe the network behavior, we assign the constraints to buses, we set up the objective terms associated with the buses, we discuss the way in which the subnetworks can be determined using the influence-based approach, and we show the workings of the proposed approach.

5.6.1 Steady-state characteristics of power networks

As the focus lies on improving the steady-state network security, the power network is modeled using equations describing the steady-state characteristics of the power network. As we will see, the aspects of the steady-state security that we are interested in can be determined from the voltage magnitude $z_{V,\iota}$ per unit (p.u.) and voltage angle $z_{\theta,\iota}$ (degrees) associated with each bus ι in the network. In order to determine the values for these variables under different exogenous inputs and actuator values, models for the components and their influence on the voltage magnitude and angle are defined. We model the transmission lines, the generators, the loads, and the FACTS devices.

Transmission lines

For the transmission lines the well known π-model is used [82]. The active power $z_{P,\iota\omega}$ (p.u.) and the reactive power $z_{Q,\iota\omega}$ (p.u.) flowing from bus ι over the transmission line to

[2] http://www.ee.washington.edu/research/pstca/pf57/pg_tca57bus.htm

bus ω are then given by, respectively:

$$z_{P,\iota\omega} = (z_{V,\iota})^2 \left(\frac{\eta_{\mathrm{R},\iota\omega}}{(\eta_{\mathrm{R},\iota\omega})^2 + (\eta_{\mathrm{X},\iota\omega})^2} \right) - z_{V,\iota} z_{V,\omega} \left(\frac{\eta_{\mathrm{R},\iota\omega}}{(\eta_{\mathrm{R},\iota\omega})^2 + (\eta_{\mathrm{X},\iota\omega})^2} \cos(z_{\theta,\iota} - z_{\theta,\omega}) \right)$$
$$+ z_{V,\iota} z_{V,\omega} \left(\frac{\eta_{\mathrm{X},\iota\omega}}{(\eta_{\mathrm{R},\iota\omega})^2 + (\eta_{\mathrm{X},\iota\omega})^2} \sin(z_{\theta,\iota} - z_{\theta,\omega}) \right) \tag{5.6}$$

$$z_{Q,\iota\omega} = (z_{V,\iota})^2 \left(\frac{\eta_{\mathrm{X},\iota\omega}}{(\eta_{\mathrm{R},\iota\omega})^2 + (\eta_{\mathrm{X},\iota\omega})^2} - \frac{\eta_{\mathrm{B},\iota\omega}}{2} \right)$$
$$+ z_{V,\iota} z_{V,\omega} \left(\frac{\eta_{\mathrm{R},\iota\omega}}{(\eta_{\mathrm{R},\iota\omega})^2 + (\eta_{\mathrm{X},\iota\omega})^2} \sin(z_{\theta,\iota} - z_{\theta,\omega}) \right)$$
$$- z_{V,\iota} z_{V,\omega} \left(\frac{\eta_{\mathrm{X},\iota\omega}}{(\eta_{\mathrm{R},\iota\omega})^2 + (\eta_{\mathrm{X},\iota\omega})^2} \cos(z_{\theta,\iota} - z_{\theta,\omega}) \right), \tag{5.7}$$

where $\eta_{\mathrm{B},\iota\omega}$ (p.u.) is the shunt susceptance, $\eta_{\mathrm{R},\iota\omega}$ (p.u.) is the resistance, and $\eta_{\mathrm{X},\iota\omega}$ (p.u.) is the reactance of the line between buses ι and ω.

The constraints for each transmission line going from bus ι to bus ω, for $\omega \in \mathcal{N}^\iota$, are assigned to bus ι.

Generators

Generators are modeled with constant active power injection and constant voltage magnitude. Hence, if a generator is connected to bus ι, then the following constraints are assigned to that bus:

$$z_{P,\mathrm{gen},\iota} = d_{P,\mathrm{gen},\iota}$$
$$z_{V,\iota} = d_{V,\mathrm{gen},\iota},$$

where $d_{P,\mathrm{gen},\iota}$ is the given active power that the generator produces, and $d_{V,\mathrm{gen},\iota}$ is the given voltage magnitude that the generator maintains. At most one generator can be connected to a bus, since a generator directly controls the voltage magnitude of that bus.

A single generator is used as slack generator, i.e., a generator with infinite active and reactive power capacity, with fixed voltage magnitude and angle [82]. Hence, if the slack generator is connected to bus ι, the following constraints are assigned to that bus:

$$z_{V,\iota} = d_{V,\mathrm{gen},\iota}$$
$$z_{\theta,\iota} = d_{\theta,\mathrm{gen},\iota},$$

where $d_{\theta,\mathrm{gen},\iota}$ is the given voltage angle ensured by the generator.

Loads

The loads are modeled with constant active and constant reactive power injections. Hence, if a load is connected to bus ι, then the following constraints are associated to that bus:

$$z_{P,\mathrm{load},\iota} = d_{P,\mathrm{load},\iota}$$
$$z_{Q,\mathrm{load},\iota} = d_{Q,\mathrm{load},\iota},$$

where $d_{P,\text{load},\iota}$ and $d_{Q,\text{load},\iota}$ are the given active and reactive power consumption, respectively, of the load connected to bus ι. For simplicity, one load can be connected to a node. Multiple loads can easily be aggregated to obtain a single load.

FACTS devices

SVC An SVC is a FACTS device that is shunt-connected to a bus ι and that injects or absorbs reactive power $z_{Q,\text{SVC},\iota}$ to control the voltage $z_{V,\iota}$ at that bus [62]. The SVC connected to bus ι is modeled as a shunt-connected variable susceptance, which accepts as control input the effective susceptance $u_{B,\text{SVC},\iota}$, as shown in Figure 5.4(a). The injected reactive power $z_{Q,\text{SVC},\iota}$ of the SVC is:

$$z_{Q,\text{SVC},\iota} = -(z_{V,\iota})^2 u_{B,\text{SVC},\iota}.$$

The control input $u_{B,\text{SVC},\iota}$ is limited to the domain:

$$u_{B,\text{SVC},\text{min},\iota} \leq u_{B,\text{SVC},\iota} \leq u_{B,\text{SVC},\text{max},\iota},$$

where the values of $u_{B,\text{SVC},\text{min},\iota}$ and $u_{B,\text{SVC},\text{max},\iota}$ are determined by the size of the device [52].

The constraints of an SVC are assigned to the bus to which the SVC is connected.

TCSC A TCSC is a FACTS device that can control the active power flowing over a line [62]. It can change the line reactance $z_{X,\text{line},\iota\omega}$, and hence the conductance $\eta_{\text{G},\iota\omega}$ and susceptance $\eta_{\text{B},\iota\omega}$ involved in (5.6)–(5.7). The TCSC is therefore modeled as a variable reactance $u_{X,\text{TCSC},\iota\omega}$ connected in series with the line, as shown in Figure 5.4(b). If a TCSC is connected in series with a transmission line between buses ι and ω, the total reactance $z_{X,\text{line},\iota\omega}$ of the line including the TCSC is given by:

$$z_{X,\text{line},\iota\omega} = \eta_{\text{X},\iota\omega} + u_{X,\text{TCSC},\iota\omega},$$

where $\eta_{\text{X},\iota\omega}$ is the reactance of the line without the TCSC installed. The reactance $u_{X,\text{TCSC},\iota\omega}$ is limited to the domain:

$$u_{X,\text{TCSC},\text{min},\iota\omega} \leq u_{X,\text{TCSC},\iota\omega} \leq u_{X,\text{TCSC},\text{max},\iota\omega},$$

where the values of $u_{X,\text{TCSC},\text{min},\iota\omega}$ and $u_{X,\text{TCSC},\text{max},\iota\omega}$ are determined by the size of the TCSC device and the characteristics of the line in which it is placed, since due to the physics the allowed compensation rate of the line $u_{X,\text{TCSC},\iota\omega}/\eta_{\text{X},\iota\omega}$ is limited [52].

The constraints of the TCSC at the line between bus ι and ω are assigned to bus ι.

Power balance

By Kirchhoff's laws, at each bus the total incoming power and the total outgoing power has to be equal. This yields for bus ι the following additional constraints:

$$0 = \sum_{\omega \in \mathcal{N}^\iota} (z_{P,\iota\omega}) + z_{P,\text{load},\iota} - z_{P,\text{gen},\iota}$$
$$0 = \sum_{\omega \in \mathcal{N}^\iota} (z_{Q,\iota\omega}) + z_{Q,\text{load},\iota} + z_{Q,\text{SVC},\iota}.$$

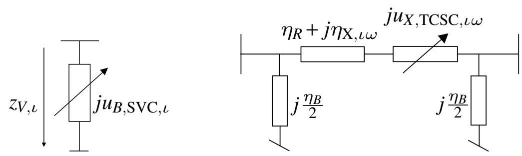


Figure 5.4: (a) Model of an SVC and (b) of a TCSC.

If no generator is connected to bus ι, then $d_{P,\mathrm{gen},\iota}$ and $z_{Q,\mathrm{gen},\iota}$ are zero. If no load is connected to bus ι, then $z_{P,\mathrm{load},\iota}$ and $z_{Q,\mathrm{load},\iota}$ are zero. If no SVC is connected to bus ι, then $z_{Q,\mathrm{SVC},\iota}$ is zero.

5.6.2 Control objectives

The objectives of the control are to improve the system security through minimization of deviations of bus voltages from given references to improve the voltage profile, minimization of active power losses, and preventing lines from overloading, by choosing appropriate settings for the FACTS devices. These objectives are translated into objective terms associated with the buses as follows:

- To minimize the deviations of the bus voltage magnitude $z_{V,\iota}$ of bus ι from a given reference $d_{V,\mathrm{ref},\iota}$, an objective term $p_V\,(z_{V,\iota} - d_{V,\mathrm{ref},\iota})^2$ is associated with bus ι, where p_V is a weighting coefficient.
- To minimize the active power losses over a line between bus ι and bus ω, an objective term $p_{\mathrm{loss}} z_{P,\mathrm{loss},\iota\omega}$ is associated to bus ι, where p_{loss} is a weighting coefficient, and where $z_{P,\mathrm{loss},\iota\omega} = z_{P,\iota\omega} + z_{P,\omega\iota}$.
- To minimize the loading of the line between buses ι and ω, an objective term is associated to bus ι as $p_{\mathrm{load}}\left(\frac{z_{S,\iota\omega}}{z_{S,\max,\iota\omega}}\right)^2$, where p_{load} is a weighting coefficient, and where $z_{S,\iota\omega} = \sqrt{(z_{P,\iota\omega})^2 + (z_{Q,\iota\omega})^2}$ is the apparent power flowing over the line from bus ι to bus ω. The relative line loading is penalized in a quadratic way such that an overloaded line is penalized more severely than a line that is not overloaded.

The weighting coefficients p_V, p_{loss}, and p_{load} allow to put change the weight given to each objective. In the following we take $p_V = 1000$, $p_{\mathrm{loss}} = 100$, and $p_{\mathrm{load}} = 1$.

5.6.3 Setting up the control problems

Each FACTS device is controlled by a different control agent. The influence-based subnetworks of the control agents controlling the FACTS devices can be overlapping, and therefore the control problems of the control agents are set up using the approach discussed in Section 5.5. To solve their subproblems at each iteration the control agents use the nonlinear problem solver SNOPT v5.8 [50], as implemented in Tomlab v5.7 [65], and accessed from Matlab v7.3 [98].

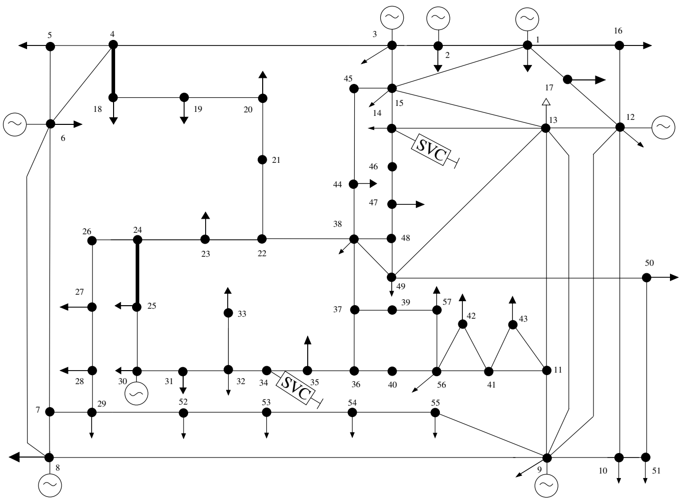


Figure 5.5: IEEE 57-bus network with SVCs installed at buses 14 and 34.

In the following we illustrate how the subnetwork of a control agent changes depending on the sensitivity threshold γ_{s}, and how the approach works for a particular assignment of buses to subnetworks in two representative scenarios.

5.6.4 Illustration of determination of subnetworks

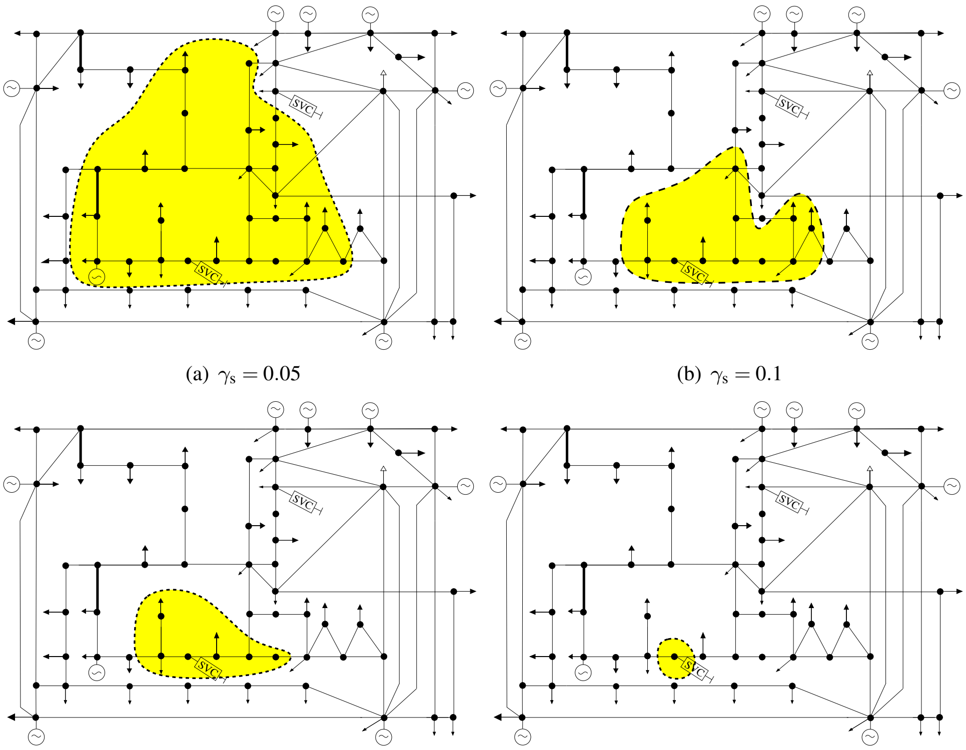
To illustrate the way in which influence-based subnetworks can be defined for a power network, consider the adjusted IEEE 57-bus power network depicted in Figure 5.5 with SVCs installed at buses 14 and 34. We illustrate how the influence of the SVC at bus 34 on the buses in the network changes depending on the sensitivity threshold γ_{s}.

Remark 5.2 Instead of computing the gradients of the constraint functions of the network with respect to the SVC input analytically, we have numerically approximated them. The approximation is made by initializing the network in a particular operating point $\bar{\mathbf{z}}, \bar{\mathbf{u}}$, increasing the value of the SVC input by $\gamma_{\Delta u_{B,\mathrm{SVC}}}$, determining the values of $\mathbf{z}$, and computing the sensitivity of $\mathbf{z}$ with respect to the SVC input as: $\frac{1}{\gamma_{\Delta u_{B,\mathrm{SVC}}}}(\mathbf{z}-\bar{\mathbf{z}})$, where $\gamma_{\Delta u_{B,\mathrm{SVC}}} = 10^{-6}$. Since we are interested in the sensitivity of the SVC input with respect to the voltage magnitudes, the sensitivity criterion is checked only for the elements of $\mathbf{z}$ corresponding to the voltage magnitudes. $\square$

Figure 5.6 shows the subnetworks and Figure 5.7 shows the number of nodes in the subnetworks, as the sensitivity threshold γ_{s} is increased. We observe that, indeed, with a lower threshold, more buses are included in the subnetwork, and with a higher threshold, fewer buses are included.

5.6.5 Simulations

Various test scenarios with different FACTS devices and subnetworks have been examined. Here we present two representative scenarios. The subnetworks used in these scenarios are



(a) $\gamma_s = 0.05$ (b) $\gamma_s = 0.1$

(c) $\gamma_s = 0.25$ (d) $\gamma_s = 0.45$

Figure 5.6: Subnetworks constructed with different sensitivity threshold settings.

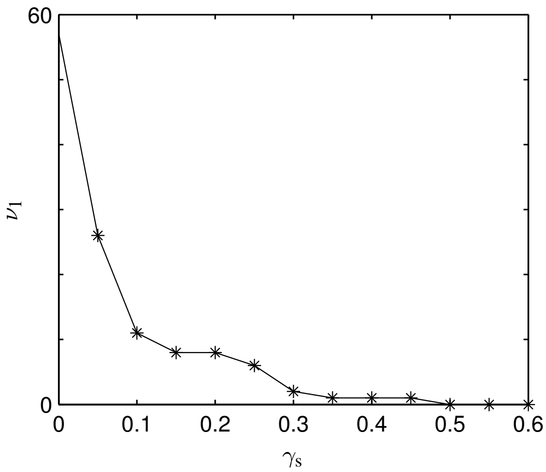


Figure 5.7: Number of nodes ν_1 selected for subnetwork 1 for different values of the ensitivity threshold γ_s.

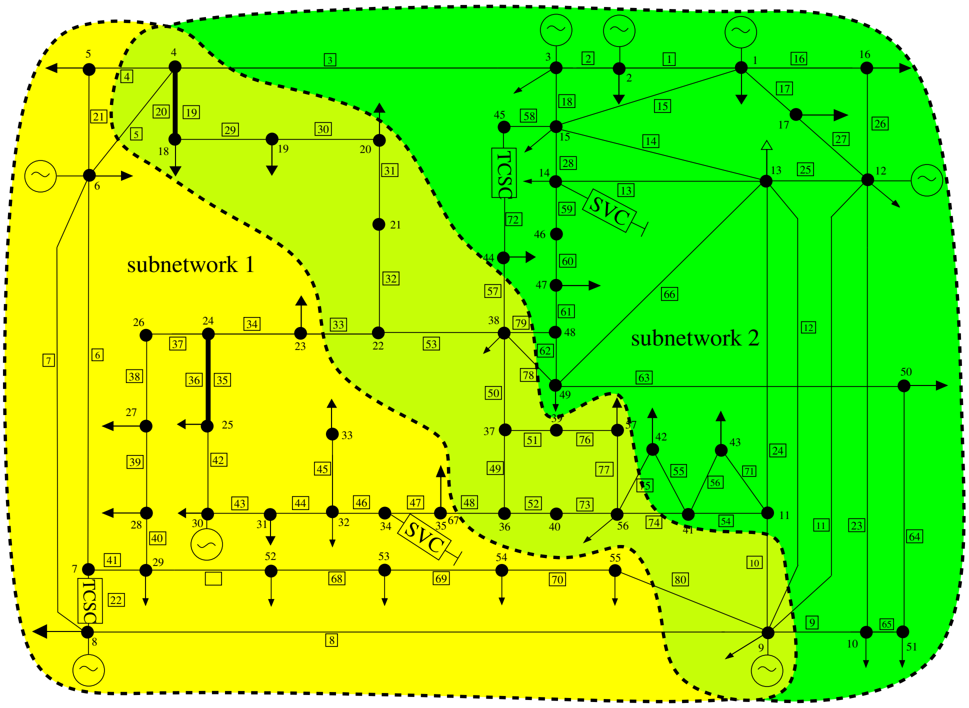


Figure 5.8: IEEE 57-bus system with decomposition into 2 subnetworks. Scenario 1: SVCs at buses 14 and 34, scenario 2: TCSCs in lines 22 and 72.

shown in Figure 5.8. It can be seen that these subnetworks are overlapping, since there are several buses that are included in both subnetworks.

Scenario 1: Control of SVCs

In the first scenario, SVCs are placed at buses 14 and 34. As the SVCs are mainly used to influence the voltage profile, the line limits are chosen such that no line is at the risk of being overloaded.

Figure 5.9 shows the convergence of the SVC device settings over the iterations. As can be seen, the settings of the SVC devices converge within only a few iterations to the final values, which in this case are equal to the values obtained from an overall optimization. Figure 5.10 shows the evolution of the deviations between the values determined by both subnetworks for the voltage magnitudes and angles at some common buses. In the figure the error $z_{V,\mathrm{err},\iota}$ is defined as the absolute difference between the values that control agents 1 and 2 want to give to the voltage magnitude $z_{V,\iota}$. Similarly, the error $z_{\theta,\mathrm{err},\iota}$ is defined as the absolute difference between the values that control agents 1 and 2 want to give to the voltage angles. As can be seen fast convergence is observed.

Scenario 2: Control of TCSCs

In the second scenario, TCSCs are installed in lines 72 and 22. Since TCSCs are mainly used to influence active power flows and to resolve congestion, the line limits are chosen

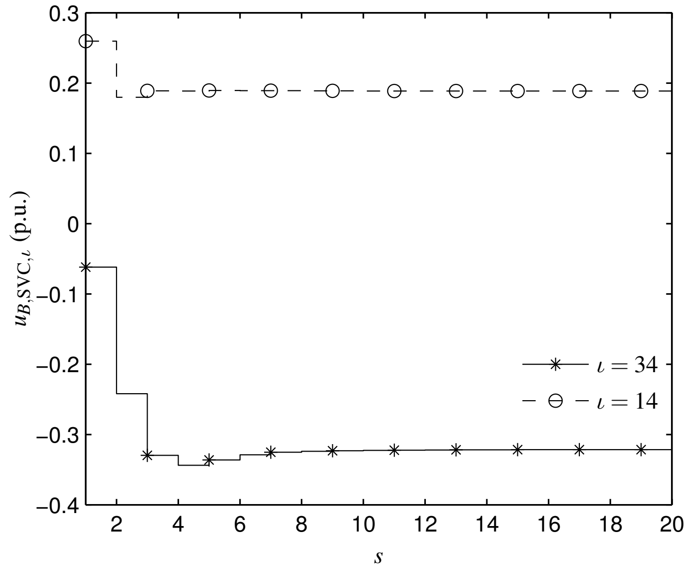


Figure 5.9: Convergence of the FACTS device settings over the iterations for the SVCs at buses 14 and 34 for scenario 1.

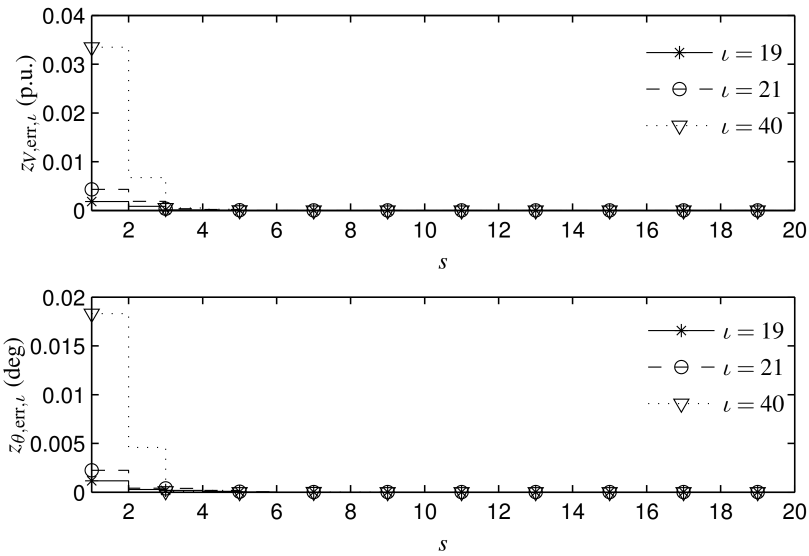


Figure 5.10: Convergence of the difference between the values of the voltage magnitudes (top) and the voltage angles (bottom) as considered by both control agents over the iterations for buses 19, 21, 40 for scenario 1.

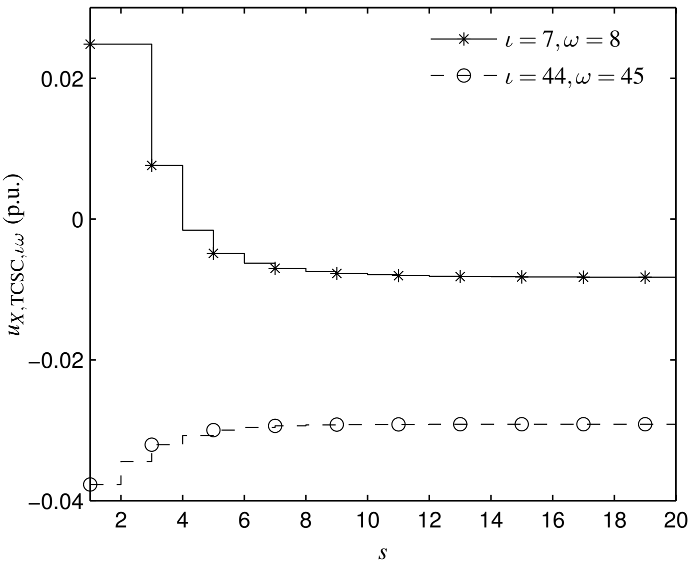


Figure 5.11: FACTS device settings for the TCSCs in lines 22 and 72, i.e., the lines between buses 7 and 8, and buses 44 and 45, respectively.

such that lines 7 and 60 are overloaded in the base case when the FACTS devices are set out of operation.

The results for the TCSC settings and the difference between the voltage magnitudes and angles for some common buses over the iterations are given in Figures 5.11 and 5.12, respectively. The control agent of subnetwork 1 sets the TCSC to its upper limit at the first few iterations. But after some additional iterations, the values that the control agents choose converge to their final values, which are again equal to the values obtained from an overall control agent.

In Figure 5.13 the line loadings of lines 7 and 60, i.e., the lines which are overloaded without FACTS devices in operation, are shown. Line 7 is immediately brought below its limit whereas for line 60, the loading approaches 100% in the course of the optimization process.

5.7 Summary

In this chapter we have focused on higher-layer multi-agent control using alternative ways to define subnetworks. While in Chapter 4 the medium control layer has used a model of the dynamics of the lower control layer and physical network, here the higher control layer uses steady-state characteristics only. While in the previous chapters we have defined subnetworks based on already existing control regions, in this chapter we have discussed how subnetworks can be defined based on the influence of actuators on the variables of nodes. When such an approach is used to define subnetworks, some subnetworks could be

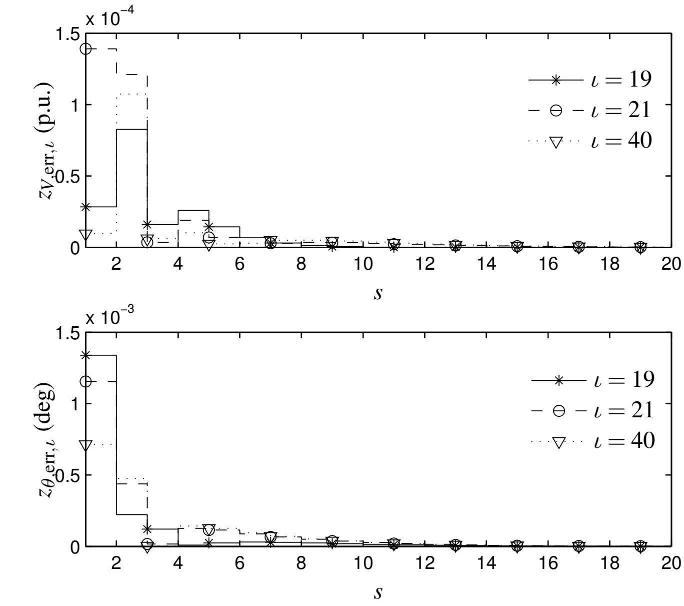


Figure 5.12: Convergence of the difference between the values of the voltage magnitudes (top) and the voltage angles (bottom) as considered by both control agents over the iterations for buses 19, 21, 40 for scenario 2.

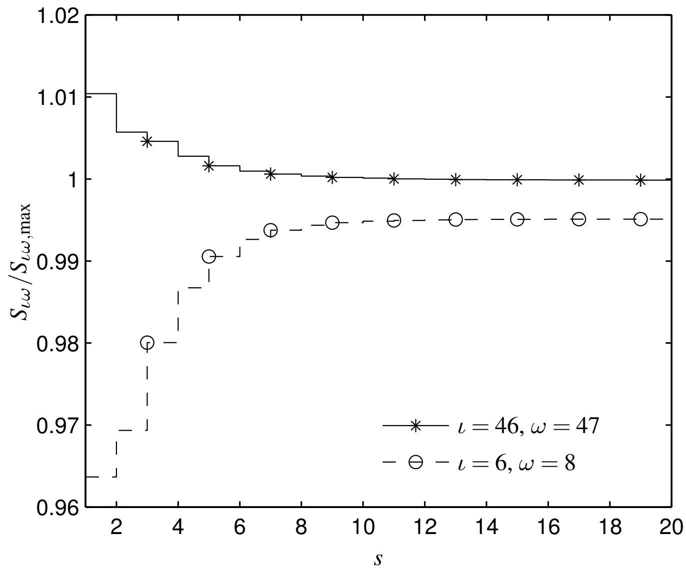


Figure 5.13: Relative line loadings of lines 7 and 60, i.e., the lines between buses 6 and 8, and 46 and 47, respectively, for scenario 2.

overlapping. Issues involving how to deal with the emerging common subnetwork then have to be dealt with. We have discussed these issues and proposed a method for higher-layer multi-agent control that can be used by control agents that control overlapping subnetworks. With simulation studies we have illustrated the potential of the approach. However, further research is still required, e.g., to determine formally when the approach converges and what the quality of the obtained solutions is, in particular when compared to an overall combined approach.

As application we have considered FACTS control in an adjusted version of the IEEE 57-bus power network. We have illustrated how the subnetwork of an actuator varies depending on the sensitivity threshold used, and we have applied the control approach that we proposed in this chapter for overlapping subnetworks to an optimal flow control problem using FACTS devices. The simulations illustrate that the proposed approach can in the considered cases achieve fast convergence to actuator values that are overall optimal. Future research should address further comparison with an overall single-agent control scheme, to gain more insight in the quality of the solutions and the time required to obtain these solutions.

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Samenvatting

Multi-Agent Modelgebaseerd Voorspellend Regelen met Toepassingen in Elektriciteitsnetwerken

Transportnetwerken, zoals elektriciteitsnetwerken, verkeersnetwerken, spoornetwerken, waternetwerken, etc., vormen de hoekstenen van onze moderne samenleving. Een soepele, efficiënte, betrouwbare en veilige werking van deze netwerken is van enorm belang voor de economische groei, het milieu en de leefbaarheid, niet alleen wanneer deze netwerken op de grenzen van hun kunnen moeten opereren, maar ook onder normale omstandigheden. Aangezien transportnetwerken dichter en dichter bij hun capaciteitslimieten moeten werken, en aangezien de dynamica van dergelijke netwerken alsmaar complexer wordt, wordt het steeds moeilijker voor de huidige regelstrategieën om adequate prestaties te leveren onder alle omstandigheden. De regeling van transportnetwerken moet daarom naar een hoger niveau gebracht worden door gebruik te maken van nieuwe geavanceerde regelstrategieën.

Elektriciteitsnetwerken vormen een specifieke klasse van transportnetwerken waarvoor nieuwe regelstrategieën in het bijzonder nodig zijn. De structuur van elektriciteitsnetwerken is aan het veranderen op verschillende niveaus. Op Europees niveau worden de elektriciteitsnetwerken van individuele landen meer en meer geïntegreerd door de aanleg van transportlijnen tussen landen. Op nationaal niveau stroomt elektriciteit niet langer alleen van het transmissienetwerk via het distributienetwerk in de richting van bedrijven en steden, maar ook in de omgekeerde richting. Daarnaast wordt op lokaal niveau regelbare belasting geïnstalleerd en kan energie lokaal gegenereerd en opgeslagen worden. Om minimumeisen en -serviceniveaus te kunnen blijven garanderen, moeten *state-of-the-art* regeltechnieken ontwikkeld en geïmplementeerd worden.

In dit proefschrift stellen wij verschillende regelstrategieën voor die erop gericht zijn om de opkomende problemen in transportnetwerken in het algemeen en elektriciteitsnetwerken in het bijzonder het hoofd te bieden. Om het grootschalige en gedistribueerde karakter van de regelproblemen te beheersen gebruiken wij *multi-agent* aanpakken, waarin verschillende regelagenten elk hun eigen deel van het netwerk regelen en samenwerken om de best mogelijke netwerkbrede prestaties te behalen. Om alle beschikbare informatie mee te kunnen nemen en om vroegtijdig te kunnen anticiperen op ongewenst gedrag maken wij gebruik van modelgebaseerd voorspellend regelen (MVR). In de regelstrategieën die wij in dit proefschrift voorstellen, combineren wij multi-agent aanpakken met MVR. Hieronder volgt een overzicht van de regelstrategieën die wij voorstellen en de regelproblemen uit de specifieke klasse van elektriciteitsnetwerken, waarop wij de voorgestelde regelstrategieën toepassen.

Multi-agent modelgebaseerd voorspellend regelen

In een multi-agent regeling is de regeling van een systeem gedistribueerd over verschillende regelagenten. De regelagenten kunnen gegroepeerd worden aan de hand van de autoriteitsrelaties die tussen de regelagenten gelden. Een dergelijke groepering resulteert in een gelaagde regelstructuur waarin regelagenten in hogere lagen meer autoriteit hebben over regelagenten in lagere lagen en waarin regelagenten in dezelfde laag dezelfde autoriteitsrelaties met betrekking tot elkaar hebben. Gebaseerd op de ideeën van MVR bepalen in multi-agent MVR de regelagenten welke actie zij nemen aan de hand van voorspellingen. Deze voorspellingen maken zij met behulp van voorspellingsmodellen van die delen van het algehele systeem die zij regelen. Daar waar de regelagenten in hogere lagen typisch minder gedetailleerde modelen en langzamere tijdschalen beschouwen, beschouwen regelagenten op lagere regellagen typisch meer gedetailleerde modelen en snellere tijdschalen. In dit proefschrift worden de volgende regelstrategieën voorgesteld en bediscussieerd:

- Voor de coördinatie van regelagenten in een regellaag wordt een nieuw serieel schema voor multi-agent MVR voorgesteld en vergeleken met een bestaand parallel schema. In de voorgestelde aanpak wordt aangenomen dat de dynamica van de deelnetwerken alleen uit continue dynamica bestaat en dat de dynamica van het algehele netwerk gemodelleerd kan worden met verbonden lineaire tijdsinvariante modellen, waarin alle variabelen continue waarden aannemen.

- In de praktijk komt het regelmatig voor dat deelnetwerken hybride dynamica vertonen, veroorzaakt door zowel continue als discrete dynamica. We bediscussiëren hoe discrete dynamica gevat kan worden in modellen bestaande uit lineaire vergelijkingen en ongelijkheden en hoe regelagenten dergelijke modellen kunnen gebruiken bij het bepalen van hun acties. Daarnaast stellen wij een uitbreiding voor van de coördinatieschema's voor continue systemen naar systemen met continue en discrete variabelen.

- Voor een individuele regelagent die richtpunten bepaalt voor regelagenten in een lagere regellaag wordt het opzetten van object-georiënteerde voorspellingsmodellen bediscussieerd. Een dergelijk object-georiënteerd voorspellingsmodel wordt dan gebruikt om een MVR-regelprobleem te formuleren. Wij stellen voor om de optimalisatietechniek *pattern search* te gebruiken om het resulterende MVR-regelprobleem op te lossen. Daarnaast stellen wij omwille van de efficiëntie een MVR-regelstrategie voor die gebaseerd is op een gelineariseerde benadering van het object-georiënteerde voorspellingsmodel.

- Regelmatig worden deelnetwerken gedefinieerd op basis van reeds bestaande netwerkregio's. Dergelijke deelnetwerken overlappen meestal niet. Als deelnetwerken echter gebaseerd worden op bijvoorbeeld invloedsgebieden van actuatoren, dan kunnen de deelnetwerken overlappend zijn. Wij stellen een regelstrategie voor voor het regelen van overlappende deelnetwerken door regelagenten in een hogere regellaag.

Multi-agent regelproblemen in elektriciteitsnetwerken

Elektriciteitsnetwerken vormen een specifieke klasse van transportnetwerken waarvoor de ontwikkeling van geavanceerde regeltechnieken noodzakelijk is om adequate prestaties te behalen. De regelstrategieën die in dit proefschrift worden voorgesteld worden daarom aan de hand van toepassing op specifieke regelproblemen uit elektriciteitsnetwerken geëvalueerd. In het bijzonder worden de volgende regelproblemen besproken:

- We beschouwen een gedistribueerd *load-frequency* probleem, wat het probleem is van het dicht bij nul houden van frequentie-afwijkingen na verstoringen. Regelagenten regelen elk hun eigen deel van het netwerk en moeten samenwerken om de best mogelijke netwerkbrede prestaties te behalen. Om deze samenwerking te bewekstellingen gebruiken de regelagenten de seriële of de parallele MVR-strategieën. We beschouwen zowel samenwerking gebaseerd op voorspellingsmodellen die alleen continue variabelen bevatten, als met gebruikmaking van voorspellingsmodellen die zowel continue als ook discrete variabelen bevatten. Met behulp van simulaties illustreren we de prestaties die de schema's kunnen behalen.

- In de nabije toekomst zullen huishoudens de mogelijkheid hebben om hun eigen energie lokaal te produceren, lokaal op te slaan, te verkopen aan een energie-aanbieder en mogelijk uit te wisselen met naburige huishoudens. We stellen een MVR-strategie voor die gebruikt kan worden door een regelagent die het energiegebruik in een huishouden regelt. Deze regelagent neemt in zijn regeling verwachte energieprijzen, voorspelde energieconsumptiepatronen en de dynamica van het huishouden mee. We illustreren de prestaties die de regelagent kan behalen voor een gegeven scenario van energieprijzen en consumptiepatronen.

- Spanningsinstabiliteiten vormen een belangrijke bron van elektriciteitsuitval. Om te voorkomen dat spanningsinstabiliteiten ontstaan is lokaal bij generatielokaties een laag van regelagenten geïnstalleerd. Een dergelijke lokale regeling werkt onder normale omstandigheden goed, maar levert ten tijde van grote verstoringen geen adequate prestaties. In dergelijke situaties moeten de acties van de lokale regelagenten gecoördineerd worden. Wij stellen een MVR-regelagent voor die tot taak heeft deze coördinatie te realiseren. De voorgestelde MVR-strategie maakt gebruik van ofwel een object-georiënteerd model van het elektriciteitsnetwerk ofwel van een benadering van dit model verkregen na linearisatie. We illustreren de prestaties die behaald kunnen worden met behulp van simulaties op een dynamisch 9-bus elektriciteitsnetwerk.

- Regeling gebaseerd op *optimal power flow* (OPF) kan gebruikt worden om in transmissienetwerken de *steady-state* spanningsprofielen te verbeteren, het overschrijden van capaciteitslimieten te voorkomen, en vermogensverliezen te minimaliseren. Een type apparaat waarvoor met behulp van OPF-regeling actuatorinstellingen bepaald kunnen worden zijn *flexible alternating current transmission systems* (FACTS). Wij beschouwen een situatie waarin verschillende FACTS-apparaten aanwezig zijn en elk FACTS-apparaat geregeld wordt door een regelagent. Elke regelagent beschouwt als zijn deelnetwerk dat deel van het netwerk dat zijn FACTS-apparaat kan beïnvloeden. Aangezien de deelnetwerken gebaseerd zijn op beïnvloedingsregio's kunnen verschillende deelnetwerken overlappend zijn. Wij stellen een coördinatie- en communicatieschema voor dat kan omgaan met een dergelijke overlap. Via simulatiestudies op een aangepast elektriciteitsnetwerk met 57 bussen illustreren we de prestaties.

Rudy R. Negenborn

Summary

Multi-Agent Model Predictive Control with Applications to Power Networks

Transportation networks, such as power distribution and transmission networks, road traffic networks, water distribution networks, railway networks, etc., are the corner stones of modern society. A smooth, efficient, reliable, and safe operation of these systems is of huge importance for the economic growth, the environment, and the quality of life, not only when the systems are pressed to the limits of their performance, but also under regular operating conditions. As transportation networks have to operate closer and closer to their capacity limits and as the dynamics of these networks become more and more complex, currently used control strategies can no longer provide adequate performance in all situations. Hence, control of transportation networks has to be advanced to a higher level using novel control techniques.

A class of transportation networks for which such new control techniques are in particular required are power networks. The structure of power networks is changing at several levels. At a European level the electricity networks of the individual countries are becoming more integrated as high-capacity power lines are constructed to enhance system security. At a national level power does not any longer only flow from the transmission network in the direction of the distribution network and onwards to the industrial sites and cities, but also in the other direction. Furthermore, at the local level controllable loads are installed, energy can be generated locally with small-scale generators, and energy can be stored locally using batteries. To still guarantee basic requirements and service levels and to meet the demands and requirements of the users while facing the changing structure of power networks, state-of-the-art control techniques have to be developed and implemented.

In this PhD thesis we propose several new control techniques designed for handling the emerging problems in transportation networks in general and power networks in particular. To manage the typically large size and distributed nature of the control problems encountered, we employ multi-agent approaches, in which several control agents each control their own part of the network and cooperate to achieve the best possible overall performance. To be able to incorporate all available information and to be able to anticipate undesired behavior at an early stage, we use model predictive control (MPC).

Next we give a summary of the control techniques proposed in this PhD thesis and the control problems from a particular class of transportation networks, viz. the class of power networks, to which we apply the proposed control techniques in order to assess their

performance.

Multi-agent model predictive control

In multi-agent control, control is distributed over several control agents. The control agents can be grouped according to the authority relationships that they have among each other. The result is a layered control structure in which control agents at higher layers have authority over control agents in lower layers, and control agents within a control layer have equal authority relationships. In multi-agent MPC, control agents take actions based on predictions that they make using a prediction model of the part of the overall system they control. At higher layers typically less detailed models and slower time scales are considered, whereas at lower layers more detailed models and faster time scales are considered.

In this PhD thesis the following control strategies for control agents at various locations in a control structure are proposed and discussed:

- For coordination of control agents within a control layer a novel serial scheme for multi-agent MPC is proposed and compared with an existing parallel scheme. In the approach it is assumed that the dynamics of the subnetworks that the control agents control are purely continuous and can be modeled with interconnected linear discrete-time time-invariant models in which all variables take on continuous values.

- In practice, the dynamics of the subnetworks may show hybrid dynamics, caused by both continuous and discrete dynamics. We discuss how discrete dynamics can be captured by systems of linear equalities and inequalities and how control agents can use this in their decision making. In addition, we propose an extension of the coordination schemes for purely continuous systems that deals with interconnected linear time-invariant subnetworks with integer inputs.

- For an individual control agent that determines set-points for control agents in a lower control layer, creating object-oriented prediction models is discussed. Such an object-oriented prediction model is then used to formulate an MPC control problem. We propose to use the optimization technique pattern search to solve the resulting MPC control problem. In addition, for efficiency reasons, we propose an MPC control strategy based on a linearization of the object-oriented prediction model.

- Commonly, subnetworks are defined based on already existing network regions. Such subnetworks typically do not overlap. However, when subnetworks are based on, e.g., regions of influence of actuators, then the subnetworks may be overlapping. For multiple control agents in a higher control layer, at which it can be assumed that the behavior of the underlying control layers is static, we propose an MPC strategy for control of overlapping subnetworks.

Multi-agent control problems in power networks

Power networks are a particular class of transportation networks and are subject to a changing structure. This changing structure requires the development of advanced control techniques in order to maintain adequate control performance. The control strategies proposed in this PhD thesis are applied to and assessed on specific power domain control problems. In particular, we discuss the following power network problems and control approaches:

- We consider a distributed load-frequency control problem, which is the problem of maintaining frequency deviations after load disturbances close to zero. Control agents each control their own part of the network and have to cooperate in order to achieve the best possible overall network performance. The control agents achieve this by obtaining agreement on how much power should flow among the subnetworks. The serial and parallel MPC strategies are employed for this, both when the prediction models involve only continuous variables, and when the prediction models involve both continuous and discrete variables. In simulations we illustrate the performance that the schemes can obtain.

- In the near future households will be able to produce their own energy, store it locally, sell it to an energy supplier, and perhaps exchange it with neighboring households. We propose an MPC strategy to be used by a control agent controlling the energy usage in a household. This control agent takes into account expected energy prices, predicted energy consumption patterns, and the dynamics of the household, including dynamics of local energy generation and storage devices. For a given scenario of energy prices and consumption patterns, the performance that the control agent can achieve are illustrated.

- Voltage instability is a major source of power outages. To prevent voltage instability from emerging, a lower layer of control agents is installed in power networks at generation sites. These agents locally adjust generation to maintain voltage magnitudes. Such local control works well under normal operating conditions. However, under large disturbances such local control does not provide adequate performance. In such situations, the actions of the local control agents have to be coordinated. We propose an MPC control agent that has the task to coordinate the local control agents. The MPC strategy that the agent uses is based on either an object-oriented model of the power network or on a linearized approximation of this model. The object-oriented model includes a model of the physical network and the local control agents. We illustrate the performance of the MPC control agent using the object-oriented model or the linearized approximation via simulations on a dynamic 9-bus power network.

- Optimal power flow control is commonly used to improve steady-state power network security by improving the voltage profile, preventing lines from overloading, and minimizing active power losses. Using optimal power flow control, device settings for flexible alternating current transmission systems (FACTS) can be determined. We consider the situation in which there are several FACTS devices, each controlled by a different control agent. The subnetwork that each control agent considers consists of a region of influence of its FACTS device. Since the subnetworks are based on regions of influence, the subnetworks of several agents may be overlapping. We propose a coordination and communication scheme that takes this overlap into account. In simulation experiments on an adjusted 57-bus IEEE power network the performance of the scheme is illustrated.

Rudy R. Negenborn

Curriculum vitae

Rudy R. Negenborn was born on June 13, 1980 in Utrecht, The Netherlands. He finished his pre-university education (*VWO*) in 1998 at the Utrechts Stedelijk Gymnasium, Utrecht, The Netherlands. After this, Rudy Negenborn started his studies in Computer Science at the Utrecht University, Utrecht, The Netherlands. He received the title of *doctorandus* (comparable with Master of Science) in Computer Science, with a specialization in Intelligent Systems, *cum laude* from this university in 2003. For his graduation project, he performed research on Kalman filtering and robot localization. The research involved in this project was carried out during a one-year visit to the Copenhagen University, Denmark, and was supervised by Prof.Dr.Phil. P. Johansen and Dr. M. Wiering.

Since 2004, Rudy Negenborn has been working on his PhD project at the Delft Center for Systems and Control of Delft University of Technology, The Netherlands. The research of his PhD project has been on multi-agent model predictive control with applications to power networks, and has been supervised by Prof.dr.ir. B. De Schutter and Prof.dr.ir. J. Hellendoorn. During his PhD project, Rudy Negenborn obtained the DISC certificate for fulfilling the course program requirements of the Dutch Institute for Systems and Control. Furthermore, he cooperated with and spent time at various research groups, including the Hybrid System Control Group of Supélec, Rennes, France, and the Power Systems Laboratory and Automatic Control Laboratory of ETH Zürich, Zürich, Switzerland.

Rudy Negenborn's more fundamental research interests include multi-agent systems, hybrid systems, distributed control, and model predictive control. His more applied research interests include applications to transportation networks in general, and power networks in particular.

Since 2004, Rudy Negenborn has been a member of the DISC and of The Netherlands Research School for Transport, Infrastructure, and Logistics (TRAIL). Moreover, from 2004 until 2007, Rudy Negenborn fulfilled the positions of public relations representative and treasurer in the board of Promood, the representative body of the PhD candidates at Delft University of Technology.