Agent-based provision of system services

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Abstract

The increasing complexity of power systems places special demands on management processes that must be performed to maintain stable and efficient system operation. The large amount of data to be processed poses great challenges for the central computing units of the system. Distributed systems, on the other hand, offer the possibility of distributing tasks and reducing the amount of computation required for centralized units. One form of these decentralized systems, where actors can model their own goals and interact to achieve common goals, are multi-agent systems that are proposed in this dissertation to model control schemes for providing system services. The presentation of multi-agent systems, including their functional principle, design aspects and constraints adopted in this dissertation, is preceded by a basic account of control in power systems, such as voltage regulation, congestion management and grid restoration.

The core of the work is the modeling of interactions between agents and their interactions in various systems management processes. The method for voltage control is modeled within the first system considered, in which the detection of critical system conditions is performed based on the results of load flow calculations. The cooperation and interactions between the agents are aimed at remedying voltage band violations and calculating new setpoints using the Jacobi matrix method. The control process proposes the strategy in which all agents can participate in the voltage control. Based on this, it is possible to select one or more of all the ways of providing reactive power proposed to remedy the voltage problem. The approach of calculating new set points based on the Power Flow Decomposition method is followed when presenting the problem of agent-based congestion management. In addition, it will be possible to make the redispatch efficient both from a technical and economic point of view with the introduction of the new merit order, which combines generation costs and sensitivity factors. The last aspect considered in this dissertation is agent-based grid restoration. The restoration strategy proposed uses a methodology based on the Dijkstra algorithm that determines the shortest path to restored components. The determination of weights required within this algorithm are adjusted based on the number of lines included in the restoration path. The smaller the number of components in the restoration path, the higher the likelihood that the same lines will be selected in the next path. This helps to minimize switching operations and makes it possible to find routes to prioritized loads according to their position in the system. In addition, the availability of components, such as lines and non-black start generators, during the restoration is checked regarding whether the restoration intended can be performed.

The problematic attained in the scope of this dissertation shows the complexity and importance of a correct assignment of agent tasks. The approaches presented show an overall example of decentralized agent-based energy management and demonstrate systems for decentralized information flow modeling.

Kurzfassung

Die zunehmende Komplexität von Stromversorgungssystemen stellt besondere Anforderungen an Managementprozesse, die ausgeführt werden müssen, um einen stabilen und effizienten Systembetrieb aufrechtzuerhalten. Die große Menge an zu verarbeitenden Daten bringt große Herausforderungen für die Rechenprozesse in zentralen Einheiten des Systems mit sich. Dezentrale Systeme hingegen bieten die Möglichkeit der Aufgabenverteilung auf verteilte Systeme und reduzierten Rechenaufwand für zentrale Einheiten. Eine Form dieser dezentral organisierten Systeme, in dem Akteure ihre eigenen Ziele selbst modellieren und zur Erreichung gemeinsamer Ziele interagieren können, sind Multi-Agenten-Systeme, die in dieser Dissertation zur Modellierung von Steuerungsprozessen zur Bereitstellung von Systemdienstleistungen vorgeschlagen werden. Der Darstellung von Multi-Agenten-Systemen einschließlich deren Funktionsprinzip, Design-Aspekten und Randbedingungen, die in dieser Dissertation angenommen werden, geht eine grundlegende Darstellung über die Steuerung in Stromversorgungssystemen wie Spannungsregelung, Engpassmanagement und Netzwiederherstellung voraus.

Der Kern der Arbeit besteht in der Modellierung von Beziehungen zwischen Agenten und deren Interaktionen in verschiedenen Systemmanagementprozessen. Innerhalb des ersten betrachteten Systems, in dem die Erkennung von kritischen Systemzuständen basierend auf Ergebnissen von Lastflussberechnungen durchgeführt wird, wird das Verfahren zur Spannungshaltung nachgebildet. Die Kooperation und Interaktionen zwischen den Agenten zielen darauf ab, Abhilfemaßnahmen bei Verletzung von Spannungsbändern durchzuführen und neue Sollwerte mithilfe der Jacobi-Matrix-Methode zu berechnen. Im Steuerungsprozess wird die Strategie vorgeschlagen, in der alle Agenten an der Spannungssteuerung teilnehmen können. Darauf aufbauend es ist möglich, eine oder mehrere von allen vorgeschlagenen Möglichkeiten der Blindleistungsbereitstellung auszuwählen, um das Spannungsproblem zu beheben. Bei der Darstellung der Problematik eines agentenbasierten Engpassmanagements wird der Ansatz verfolgt, neue Sollwerte basierend auf der Power Flow Decomposition Methode zu berechnen. Darüber hinaus wird mit der Einführung der neuen Merit-Order, welche Erzeugungskosten und Sensitivitätsfaktoren verbindet, die Möglichkeit geschaffen, den Redispatch, sowohl aus technischer als auch aus wirtschaftlicher Sicht effizient zu gestalten. Der letzte innerhalb dieser Dissertation betrachtete Aspekt ist der agentenbasierte Versorgungswiederaufbau. In der vorgeschlagenen Strategie wird eine Methodik eingesetzt, die auf dem Dijkstra-Algorithmus basiert und den kürzesten Weg des Wiederaufbaus bestimmt. Die innerhalb dieses Algorithmus erforderlichen Gewichte zur Bestimmung des kürzesten Weges werden basierend auf der Anzahl der Leitungen angepasst, die in dem Wiederaufbauweg enthalten sind. Je kleiner die Anzahl der Komponenten im Wiederaufbauweg, desto höher ist die Wahrscheinlichkeit, dass dieselben Leitungen im nächsten Weg ausgewählt werden. Dies trägt zur Minimierung von Schaltvorgängen bei und ermöglicht es, Wege zu priorisierten und Lasten entsprechend ihrer Position im System zu finden. Zusätzlich wird während des Wiederaufbaus die Verfügbarkeit von Komponenten wie Leitungen und Nicht-Schwarz-Start-Generatoren geprüft und darauf aufbauen, ob der vorgesehene Weg des Wiederaufbaus ausgeführt werden kann.

Das im Rahmen dieser Dissertation dargestellte Vorgehen zeigt die Komplexität und Wichtigkeit einer korrekten Zuordnung von Agentenaufgaben. Die vorgestellten Ansätze zeigen ein Gesamtbeispiel zum dezentralen agentenbasierten Energiemanagement und demonstrieren Systeme zur dezentralen Informationsflussmodellierung.

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$\lvert\Delta u_i\rvert$	absolute voltage difference
a_i	load priority
C	generation costs
$\underline{i}_{\mathrm{K}}$	nodal currents
$\underline{i}_{\mathrm{K,G}}$	generator currents
$\underline{i}_{\mathrm{K,L}}$	load currents
$\underline{i}_{\mathrm{T}}$	terminal currents
$\boldsymbol{J}_{\mathrm{KK}}$	Jacobian matrix
$\boldsymbol{K}_{\mathrm{KT}}$	topological matrix
L_i	load demand in bus *i*
M	new merit order
N_{DG}	number of generation units
N_{L}	number of loads in system
P_{gen}	active power set point initially calculated
P_{max}	maximal active power generation
P_{overload}	value of line overload
P_{red}	active power change
$P_{\mathrm{red,dec}}$	active power change
$P_{\mathrm{red,inc}}$	active power change
$P_{\mathrm{set,new}}$	corrected active power set point
$Q_{\mathrm{DG}}(k-1)$	values of reactive power calculated in previous iteration
$Q_{\mathrm{DG}}(k)$	currently calculated value of reactive power
$Q_{\mathrm{DG},i}$	reactive power provision by *i*-th generation unit
$Q_{\mathrm{G,max},k}$	maximum capacity for *k*-th generation unit
$Q_{\mathrm{G,min},k}$	minimum capacity for *k*-th generation unit
Q_k	reactive power generation of *k*-th unit
$\underline{S}_{\mathrm{K}}$	apparent power flow
T_{res}	restoration time
U_k	bus voltage
$\underline{u}_{\mathrm{K}}$	nodal voltage vector
U_{max}	maximal voltage limit
$U_{\mathrm{max},k}$	maximum voltage limit in bus *k*
U_{min}	minimal voltage limit
$U_{\mathrm{min},k}$	minimum voltage limit in bus *k*
y_i	status of load restored
$\underline{\boldsymbol{Y}}_{\mathrm{K,L}}$	admittance matrix for loads
$\underline{\boldsymbol{Y}}_{\mathrm{KK}}$	bus admittance matrix

$\underline{\boldsymbol{Y}}_{\mathrm{KK,L}}$	nodal admittance matrix based on generating currents
$\alpha_{1,1}$	sensitivity coefficient describing relation between reactive power and voltage changes in bus
ΔQ_1	required change in reactive power
$\Delta\boldsymbol{u}$	vector of voltages
ΔU_1	desired voltage change in bus 1
Δu_i	voltage difference
η	sensitivity factor for redispatch purposes
η_{dec}	sensitivity coefficients for downwards redispatch
η_{inc}	sensitivity coefficients for upwards redispatch

V List of abbreviations

ACL	Agent Communication Language
BSUA	Black Start Unit Agent
BSU	Black Start Unit
CFP	Call for Proposals
DG	Distributed Generation
EnWG	Energiewirtschaftsgesetz, German Energy Act
FIPA	Foundation for Intelligent Physical Agents
GA	Generator Agent
IG	Induction Generator
ISO	Independent System Operator
JADE	Java Agent Development Framework
JVM	Java Virtual Machine
LiA	Line Agent
LoA	Load Agent
LTC	Load Tap-Changing transformers
MAS	Multi-Agent system
NBSA	Non-Black Start Agent
NBSU	Non-Black Start Unit
PFD	Power Flow Decomposition
p.u.	Per Unit
RES	Renewable Energy Source
SA	Simulation Agent
SG	Synchronous Generator
TSO	Transmission System Operator

1 Introduction

1.1 Introduction and motivation

The increasing amount of volatile distributed generation (DG) has become a great challenge for transmission and distribution system operators. Due to their small capacity, most of the DG sources are connected to low and medium voltage levels which are not fully observed. Since measurement devices are sparsely spread in distribution networks, centralized control methods, requiring measurement data from each node, cannot control such power systems. Introduction of decentralized control methods allows one to overcome the limitations associated with centralized control, such as the failure of the main controller. Keeping in mind the typically simple topology of such grids, setting up an overdetermined measurement infrastructure, which would be comparable to the transmission layer, is not considered cost-efficient. This raises several questions concerning a safe, secure and reliable operation of such grids:

- How uncertainties be dealt with if they lead to situations in which an endangerment of system security cannot be identified?
- How much uncertainty will be acceptable in future grids?
- Which information will be necessary for grid operation and who is obliged to offer or allowed to receive information?

Concerning the questions above, it is necessary to develop methods and tools allowing data modeling and exchange.

A possible approach which is suitable to independently model the different interests, the behavior of the grid participants and information flows are multi-agent systems (MASs). They offer a perfect test-bed for future challenges of the German energy transition. Due to their inherent benefits, such as increased autonomy, reactivity, proactivity and social abilities, they can perform management processes in an intelligent way, on the one hand, and ensure the fulfillment of operational requirements of a system, on the other hand. This type of system modeling has been chosen, since interacting communicating abilities enable the decomposing and distribution of tasks among agents, thus, reconciling conflicts and achieving the goals desired. Moreover, MASs ensure flexibility of system structure, allowing dynamic reconfiguration by means of adding or removing network participants if necessary. Multi-agent systems are used in solving complex tasks and computationally intensive problems in environments with high dynamics of change and unpredictability with a large influx of information with which people would not be able to cope.

The MAS can carry out structural changes which are performed through a multilateral decision-making process by using negotiations. It is possible to find optimizations for the overall system or a task area depending on the structures in which the agents are integrated. Therefore, the current capabilities of the system are exploited by the search and linking of the individual abilities of the agents under the circumstances given. The decision strategies of the individual agents, which allow the achievement of results, are of great importance. The resources required for decision-making, such as time and computing power, are integrated into the strategies so that real-time capability can be guaranteed. If the resources are limited, at least one suboptimal variant is implemented which provides the performance required in a still permissible quality.

1.2 The aim of the dissertation

The methodology proposed and explained within this dissertation aims at the question how agents can be organized in the system to fulfill the goals desired in the case of possible disturbances in a system. The proper assignment of agent tasks and information flow plays a significant role at this point. The focus of this dissertation lies on the modeling of information flow and interactions between agents during the solving of selected management problems in modern power systems and, therefore, aims at the future vision and functionality of MASs, especially in the case of systems where complex management decisions must be made.

The MAS proposed, however, encompasses the problem of modeling of agent behaviors and their interactions to solve the problems given. Results of load flow calculations providing information about system stability are available in the methodology proposed and, from this point, agents recognize problems and react in a desired manner. The general idea regarding limitations assumed in this work is presented in Figure 1.1.

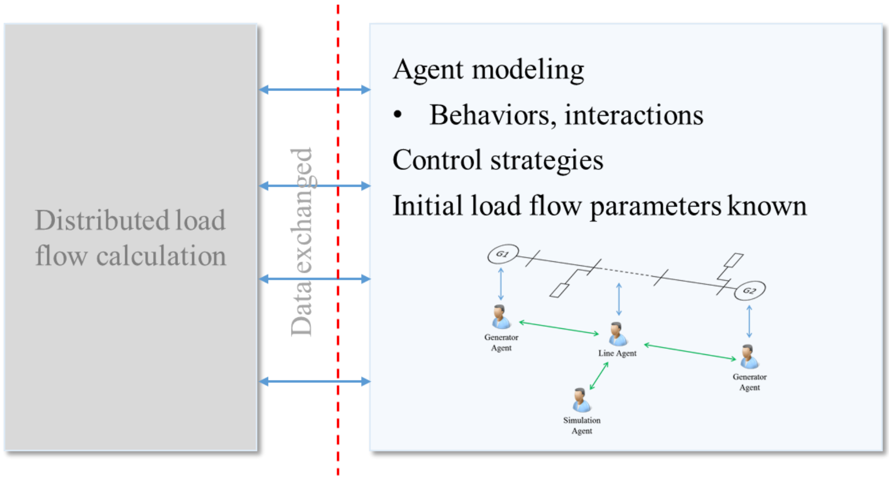

Figure 1.1 Limitation of consideration in this dissertation

Furthermore, agents in the modeling proposed have access to optimization functions in a Matlab environment and the possibility of using computationally effective software. This constitutes a modeling platform where selected power systems are simulated, and load flow calculations performed. The decision layer, in turn, serves as a platform where agents, through their mutual communication, decide on new operation points. Simulations show possible situations that can occur in real systems in which remedial actions need to be performed to restore the system to its stable state. Providing selected situations to the model simulation can illustrate how agents can deal with different management strategies and how this can influence the final results. Consequently, each management scheme presented constitutes a reference model for a multi-agent structure having different types of agents. The system's functionality is limited by the complexity of the behaviors used and can be further extended. The solutions proposed show a potential agent organization for decentralized energy system management.

The aim of the agent-based voltage control, being the first MAS strategy considered, is to present a way in which agents can organize themselves to recover stable system operation under the consideration of assumed agent behaviors. Remedial actions are performed by reactive power provision. A corresponding agent initiates a control process depending on the localization of the voltage problem. A sensitivity-based approach is used for calculating the change of reactive power required. The agent-based decision process introduced constitutes the proposal of agent interactions in a decentralized manner. From the agents' point of view, after the management process is completed, the influence of a newly calculated working point on power system operation is proven.

In turn, the aim of the second approach, in which agent-based congestion management is introduced, is to present the possibility of modeling agent interactions reacting to a given system situation in a decentralized way. Here, redispatch measures are applied using active power to alleviate the congestion. Sensitivity factors based on the Power Flow Decomposition methodology are calculated to compute the change in active power required using appropriate Matlab functions executed by entitled agents. Two selected generation units realize power adjustments upwards and downwards. In the case of insufficient active power provision by one unit, other generators cover the missing amount of active power, after considering the correction resulting from different sensitivity coefficients.

The aim of the third approach, in which agent-based grid restoration is considered, is to present what interactions between agents are necessary to perform the grid restoration in a decentralized way. In this case, an illustrative power system representing an island will serve as a platform to test the restoration strategies selected. In the approach considered, the restoration path is found by using Dijkstra's algorithm, which uses weights adjusted after each step of restoration based on the restoration readiness of components included in the restoration path. The access to Matlab functions for computing the shortest path using assumed weights relieves the computational intensity of an agent platform responsible for decision-making. The selection of non-black start generation units to initiate the restoration process is based on the minimal starting time resulting from thermal features of a generating unit. Additionally, priority and increased demand of load at the beginning of the restoration determine the direction of restoration actions.

1.3 Structure and scope of the dissertation

As an introduction, Chapter 2 presents information regarding control in power systems and provides a description of processes, such as voltage control, congestion management and grid restoration. Basic aspects of specific management schemes have been outlined with different methodologies, their requirements and applications in the power system in each subchapter.

Chapter 3 contains the presentation of MASs, their properties and structures. The definition of an agent, including its components, social properties and architecture, constitutes an introduction to the MAS further described. Differences between centralized and decentralized control strategies and their relation to varied MAS architectures and applications are presented. Additionally, this chapter contains a brief description of the development software JADE (Java Agent Development Framework), including its properties and platform structure used in this dissertation to model different multi-agent management strategies.

Chapter 4 provides modeling details of the MAS proposed and constitutes an introduction to the practical implementation of the management schemes proposed. This chapter includes information about data exchanged between the main types of agents, different data exchange schemes, interaction protocols and message performatives used to model agent behaviors.

Chapters 5-7 present three approaches of agent-based provision of ancillary services: voltage control, congestion management and grid restoration, which have been considered in static operation. No dynamic aspects of control actions were needed for the modeling of information flow and agent interactions and have not been further investigated. In subsequent subchapters, descriptions of the management processes selected are provided. Simulations of the agent interaction in the frame of each aspect are followed by the description of the MAS design, including types of agents involved in the control scheme, interactions and information flow between agents, and modeling of agent behaviors.

The written dissertation closes with the summary and outlook.

2 Power system operation[1]

2.1 Introduction

Appropriate transmission infrastructure, organization and reliable operation of the system depend on various types of services provided by power plant and grid operators as well as consumers. It is, therefore, very important to coordinate the roles of the individual components in maintaining system security. From a physical point of view, a safe electricity supply takes place if the following conditions can be met [1], [2]:

- The voltage stability limit – related to the ability of the power system to provide reactive power and maintain node voltages at the required level in case of system disturbances accompanied by loss of capacity. Voltage characteristics of loads and generation units providing reactive power influence voltage stability significantly.
- The rotor angle stability limit – applied to active power transmission limits related to the risk of loss of synchronism between generators. Angle stability is conditioned mainly based on turbine and generator characteristics and their control systems. There may be active power oscillations with low attenuation at some generator working points, threatening rotor angle stability, which can be prevented by so-called power system stabilizers, introducing additional control signals to generator controllers.
- The thermal transmission limit – resulting from the permissible temperature of transmission lines. The corresponding power transmission capacity is not constant and depends on factors such as ambient temperature, wind speed and direction.
- Frequency stability – related to the ability of the power system to maintain frequency at the required level. A potential frequency instability may occur during a severe system interruption, resulting from a significant imbalance between the power generated and consumed.

It is often challenging to meet the conditions above since the expansion of the power system cannot be avoided due to increased development and penetration of renewable energy sources. In less advantageous cases, infringement of permissible operational limits can lead to severe system outages. Therefore, an efficient control of the power system is required to achieve high reliability and robustness. Voltage and frequency control, congestion management and, in extreme situations, grid restoration belong to the actions network operators take to prevent or restore power systems after an outage.

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[1] This chapter contains materials from my publications [58], [93].

2.2 Voltage control

Voltage and reactive power control are major issues regarding power system operation. Different control strategies have been developed because differences between distribution and transmission networks are significant. The basic function of voltage control in system operation is to keep the nominal voltage defined within a permissible range all the time. This can be achieved either by adjustment of a generated power or direct voltage control realized by regulation of generator excitation. The control of voltage for transmission networks corresponds to the control of reactive power. A change in reactive power at a bus exerts voltage changes in its surrounding network [3].

Devices normally utilized for voltage and reactive power control include on-load tap-changing transformers, bus voltage regulators, line voltage controllers and switched capacitors [4]. The basic methodologies considered are used mostly in networks with one direction of power flows and the voltage reduction along the feeder is significant, from the substation to the remote end [5].

2.2.1 Voltage quality

Norm EN 50160 defines the voltage quality for end users in public electrical distribution networks and presents a set of different voltage characteristics. It is the task of distribution network operators to dimension and operate their networks in such a way that the requirements of EN 50160 can be met at all times [6]. In some distribution network regions, however, due to a high local feed-in power, the voltage quality can be reduced through infringement of permissible limit values regarding individual voltage parameters. The standard mentioned, among others, determines the “slow voltage changes” feature to a range of ± 10 % of the respective nominal voltage. This voltage range must be maintained in 95 % of the ten-minute mean values within a week [7]. Figure 2.1 illustrates, together with corresponding characteristic, other voltage phenomena occurring in the power system.

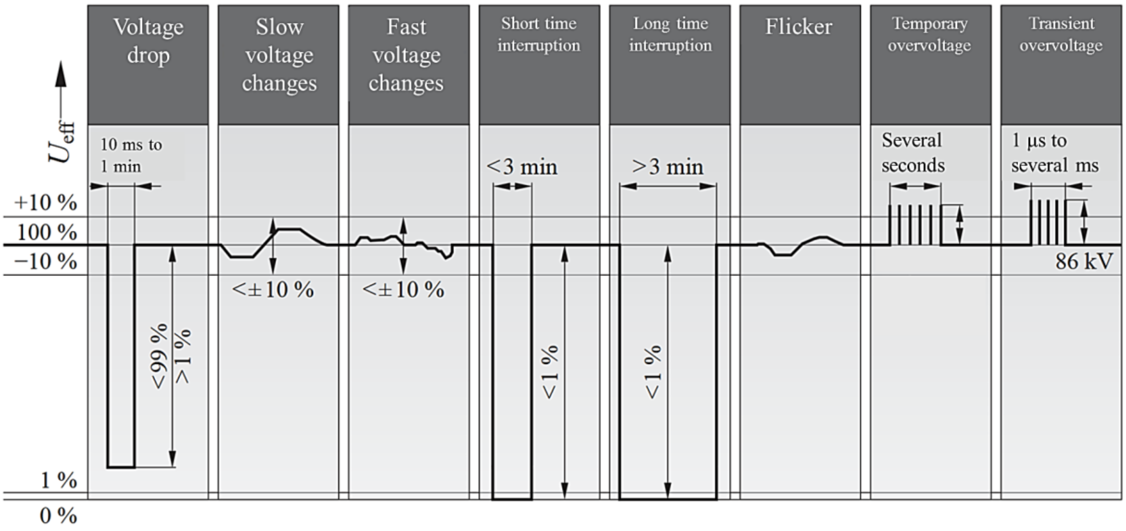

Figure 2.1 Definition of the quality characteristics of the voltage [17]

2.2.2 Voltage drop in a distribution network

A one-line diagram in Figure 2.2 shows the principle of voltage drop in a radial power system. The voltage tendency changes will increase or decrease depending on the load and generation level. The current $\underline{I}$ constitutes a function of the load complex apparent power $\underline{S} = P_L + jQ_L$ and the load voltage $\underline{U}_2$ can be expressed as

$$\underline{I} = \frac{\underline{S}^*}{3\underline{U}_2^*} = \frac{P_L - jQ_L}{3\underline{U}_2^*} \tag{2.1}$$

Thus, the voltage drop on the feeder will be given by

$$\left|\underline{U}_1 - \underline{U}_2\right| = \left|\underline{I} \cdot (R_{LN} + jX_{LN})\right| \tag{2.2}$$

Which results in

$$\left|\underline{U}_1 - \underline{U}_2\right| = \left|\frac{(R_{LN}P_L + X_{LN}Q_L) + j(X_{LN}P_L - R_{LN}Q_L)}{3\underline{U}_2^*}\right| \tag{2.3}$$

The voltage drop $\Delta U = U_1 - U_2$ for a small power flow can be approximated (resulting from the small voltage angle between U_2 and U_1) [5]

$$\Delta U \approx \frac{R_{LN}P_L + X_{LN}Q_L}{3U_2} \tag{2.4}$$

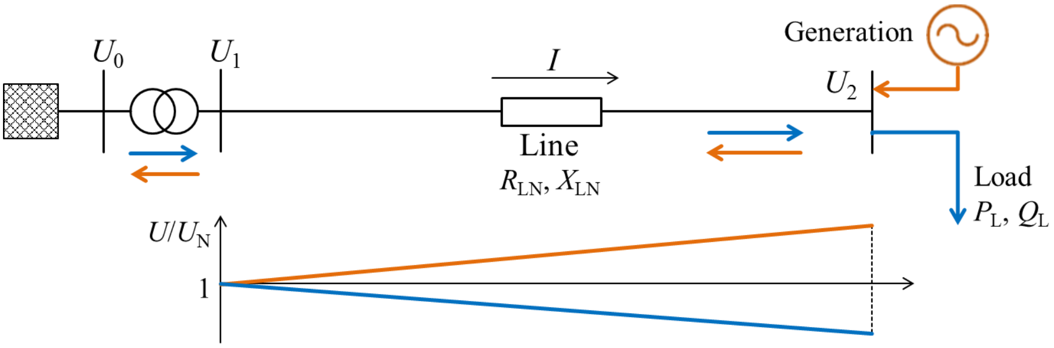

Figure 2.2 Voltage changes in a radial network with maximal load and maximal generation [8], [5]

2.2.3 Voltage and reactive power control

A prerequisite for the maintenance of voltage stability is a locally balanced reactive power and a corresponding reactive power reserve of the power stations. It is not possible, from a technical point of view, to transport reactive power over long distances via power lines due to considerably large voltage drops. Therefore, it is impossible to generate reactive power centrally and then distribute it. The provision of reactive power must be carried out in the vicinity of the reactive power consumers and distributed regionally. In terms of voltage stability, it is also advantageous if all generation units contribute to the provision of reactive power. Other important sources and sinks of reactive power in power systems include [3]:

- Overhead lines providing reactive power under low load conditions and absorbing reactive power under high load conditions.
- Underground cables providing reactive power.
- Transformers with an adjustable ratio which can shift reactive power between their primary and secondary sides.
- Shunt capacitors providing reactive power.
- Shunt reactors absorbing reactive power.
- Inductive loads absorbing reactive power.
- Synchronous generators and condensers as well as static VAr compensators providing or absorbing reactive power.
- Series capacitors, which are connected in series with highly loaded lines, reduce their reactive power losses.

Power plants must be able to participate in the voltage maintenance of the grid. A distinction between static voltage maintenance and dynamic grid support can be presented depending on system operating conditions.

2.2.4 Static voltage control

The static voltage control is intended to ensure that slow voltage changes are maintained within the tolerable range. For this purpose, the network operator has the possibility of carrying out an active and reactive power adjustment at various generating plants. This is intended to ensure fast restoration of the system security in hazardous situations. Generation plants must, therefore, be able to operate with a reduced power output. A possible loss of income must be reimbursed by the network operator [9].

The voltage at the grid connection point can be specifically influenced by a targeted reactive power feed-in in areas where the limits of voltage drop have already been reached, for example, rural regions characterizing themselves with radial network structures.

The network operator can specify a fixed value or a characteristic curve within power factor limits [9], [18].

2.2.5 Dynamic voltage support

The dynamic voltage support is intended to prevent the simultaneous disconnection of generation plants in the event of faults. Instead, the systems need to support the grid voltage by provision of reactive current [9]. A sufficient amount of short-circuit power is required for dynamic voltage support, which should be evenly distributed in the system to avoid excessive equipment overload in case of a fault [18].

“Power plants must participate generally in the dynamic grid support, even if it is not required by the network operator at the time of the connection to the grid” [10]. This means that generation units must be technically capable of [10]:

- remaining connected to a feeder in the event of faults,
- supporting the feeder voltage by reactive power provision to the network and
- suspension of intake of reactive power after the fault.

The behavior of generation units in case of a disturbance can be distinguished according to the power plant type. Type 1 indicates synchronous generators connected directly to the grid. They cannot be disconnected from the network if the voltage drops are above the limit curve represented by Characteristic 1 (see Figure 2.3). In turn, Type 2 constitutes all other plants connected to the network that cannot be disconnected from the grid faster than 150 ms for voltage drops up to 0 % of the voltage at the coupling point U_c [10].

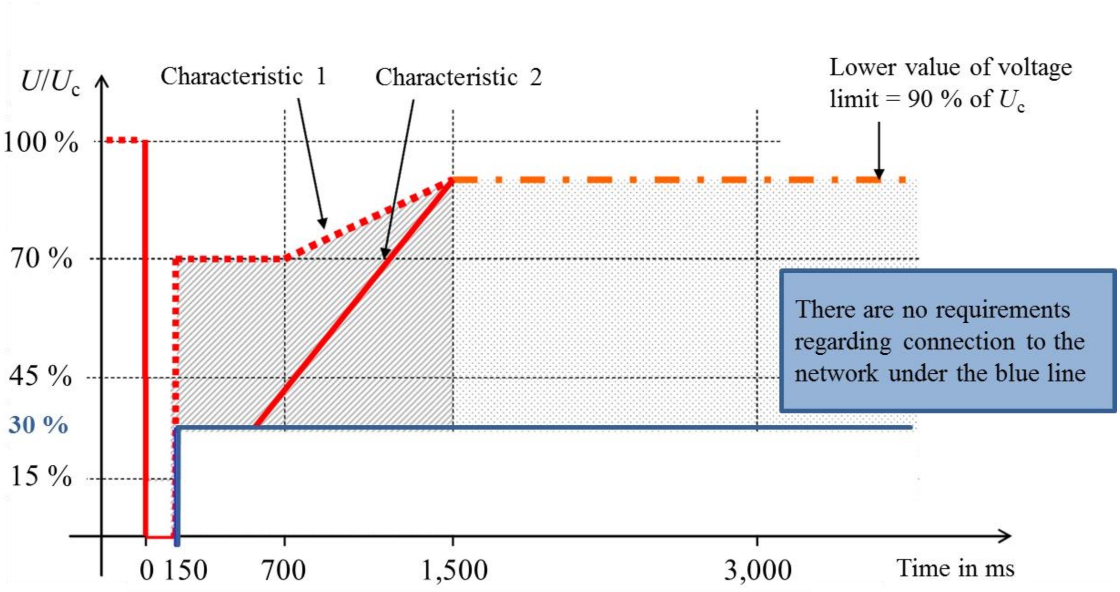

Figure 2.3 Voltage curves at the grid connection point for power plants [10]

2.2.6 Control characteristics

Grid operators specify either a fixed set point value or a value for the reactive power adjustments, which can be changed through remote control systems (or other control techniques). The possible characteristics are either [9]

- a fixed power factor cos(φ),
- an active power-dependent power factor cos(φ) = $f(P)$,
- a fixed reactive power provision in Mvar or
- a reactive power/voltage characteristic $Q = f(U)$.

"The reactive power range determined must be available within a few minutes and as often as required. If a characteristic curve is specified by the network operator, each reactive power value resulting from the characteristic curve must be automatically provided within 10 s for the cos(φ) = $f(P)$ characteristic curve or must be adjustable between 10 s and 1 min for the QU-characteristic (specified by the network operator)" [9]. Figure 2.4 presents examples of the control characteristics.

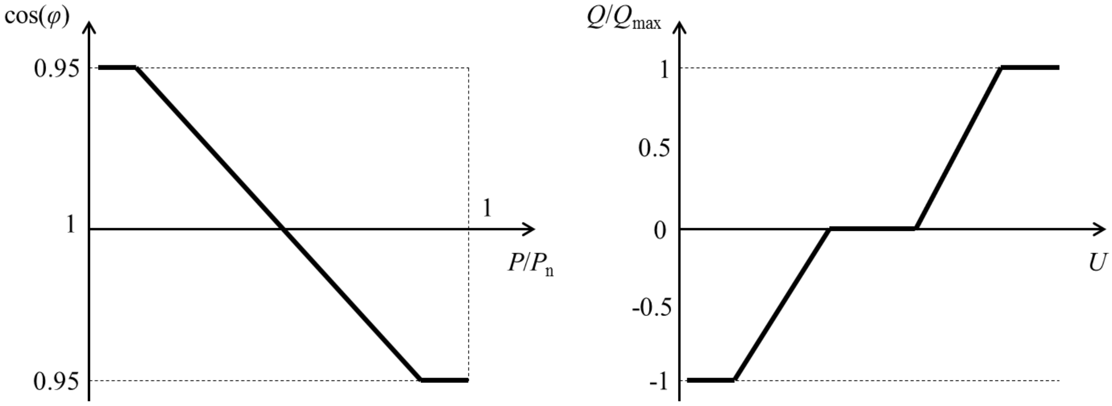

Figure 2.4 Qualitative representation of active power-dependent power factor (left) and *QU*-characteristic (right) [4], [9]

Decentralized generation units participate in voltage control by reactive power generation or consumption. Network operators can specify control strategies corresponding to the generation: $Q = f(P)$, $Q = f(U)$, $\cos(\varphi) = f(U)$. A coordination concept for all methods of voltage regulation used is indispensable, since strategies used separately can only be changed after a certain time and with great effort [11].

If compliance with the voltage limits can no longer be guaranteed, the relevant distribution system operator must take additional measures to maintain voltage. These additional measures can include network reinforcements, providing strengthening of the network and reduction of the grid impedance [8]. This, however, increases the costs for the network integration of decentralized generation plants. While photovoltaic systems are always connected to the public grid via an inverter, there are various grid connection concepts for wind power plant installations. Table 2.1 gives an overview of the most common connection concepts and shows which variants are suitable for the provision of reactive power and, thus, can contribute theoretically to voltage maintenance. However, the actual dynamic controllability of the reactive power supply is also dependent on the converter topologies used [7].

Table 2.1 Overview of the most common connection concepts [7]

Connection concept	Reactive power provision		Reactive power dynamically controlled
	Capacitive	Inductive	
Directly connected IG	-	+	-
IG with full converter	+	+	+
Doubly fed IG	+	+	+
SG with full converter	+	+	+
Directly connected SG	+	+	+
Photovoltaic with power converter	+	+	+

IG – induction generator, SG – synchronous generator

2.2.7 Control structures

Several main control structures can be distinguished depending on various voltage regulation strategies and the communication infrastructure designed [12], [13], [14], [15], [16], [54], [55], [96], [97]:

- Centralized control: In this strategy, the central controller is responsible for the coordination of control strategy. The central system collects the information from the whole network and calculates control variables for each control device.
- Hierarchical control: This control strategy is based on the structure of the power network. "The coordinator at a higher level calculates the set points, which are the reference signals for the lower level control. The main role of the controllers of the higher level is to ensure concordant behavior between the lower local controllers leading to improved overall global performance" [14]. The hierarchical scheme is commonly realized by implementation of three control levels: Primary, secondary and tertiary voltage control.
- Decentralized control: This strategy is performed locally through decentralized generation. Only local information is used in this strategy. The effect of the control action on the overall system is unknown since no information exchange takes place.
- Decentralized peer-to-peer coordination: In this control strategy, all controllers have equals rights and can coordinate with each other by exchanging the action generation plans, i.e. to achieve a system-wide objective. In this case, local information completed by information from neighboring nodes is used.

The detailed explanation of the methodology implemented for agent-based voltage control, including mathematical background and the structure outlining the MAS, is provided in Chapter 5.

2.3 Congestion management

The energy transition of the European and especially the German power system towards smart grids and energies based on renewable technologies leads to changes in the network structure. Additionally, the privatization of energy markets and unbundling of the energy sector contributed to separate generation and distribution areas. As a result, energy trade does not consider limitations regarding the transmission and distribution capability, which, in turn, translates into higher transmission powers causing higher loadings of network equipment. Thus, systems are operating close to their limits, which, in less advantageous conditions, lead to congestions. Congestion management issues have become more and more important in the last few years since grid reinforcements cannot be ensured due to economic reasons and long-term planning periods (see Figure 2.5) [19].

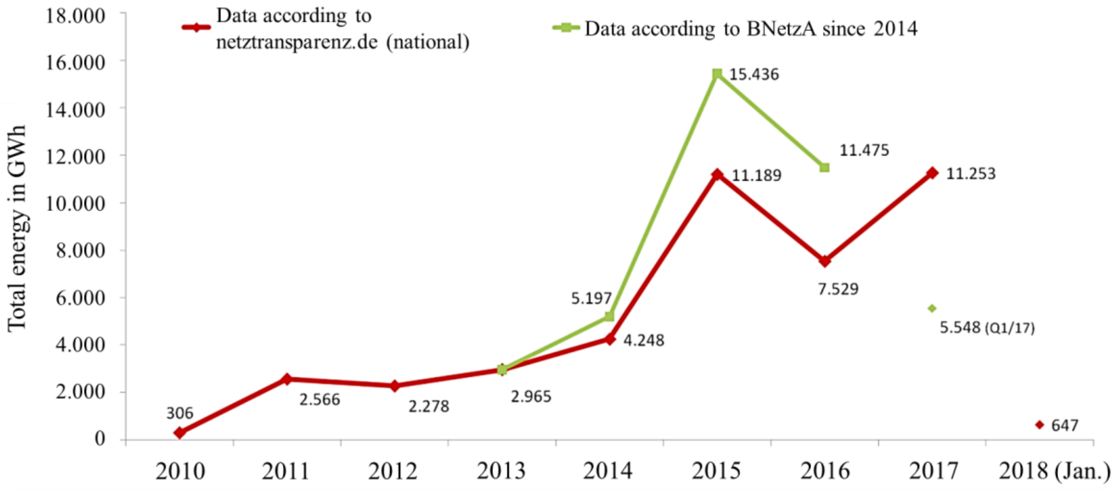

Figure 2.5 Redispatch volume annually in Germany [20]

Congestion management is one of the technical challenges in the privatization and deregulation of the power system. The increased load demand and high penetration of DG units, based on renewable energy sources, contributes to stressing existing power systems. Therefore, it is challenging to ensure the flexibility and robustness of the transmission system which needs to consider the increasing demand, unpredictable character of DGs and aspects of competitive electricity markets [58].

2.3.1 Congestion management problem

An example explaining a network congestion is presented in Figure 2.6. Assuming the situation in which the load has a high demand, increased power provision by unit 1 causes the congestion on the line. Based on the overload value, the amount of power is calculated by which both plants will adjust their generation. In this case, unit 1 will decrease its generation. In turn, unit 2 will increase its generation by the same value. Congestion is alleviated by adjusting both generation units by the value ΔP previously calculated.

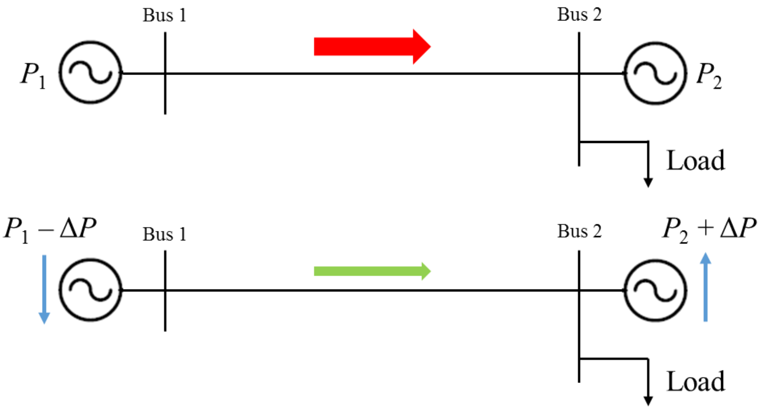

Figure 2.6 Example of a transmission congestion [21]

”Market-made schedules of power plants (dispatch) have to be modified (redispatch) to avoid congestions in the grid. The objectives in congestion management are technical and economical optimization. A technically optimized solution minimizes the displaced power as it considers the technical effectiveness of redispatch measures, determined by calculating the sensitivities of power plants infeed on the congestion. On the contrary, a cost-effective intervention is based on the resulting costs for the modified power. This can, however, lead to higher amounts of shifted powers or a high number of generation units involved, which increases the management effort” [19].

2.3.2 Congestion management problem formulation

The congestion management problem can be formulated as a multi-objective optimization problem. Considering different applications, the formulation can include different factors, such as fuel costs. The first objective function is to minimize the redispatch cost (F_T), and can be expressed by [23], [22]

$$F_\mathrm{T} = \sum_{i=1}^{N_G} f(\Delta P_{\mathrm{G}i}) \tag{2.5}$$

where:

$\Delta P_{\mathrm{G}i}$ is the active power generation of the i-th generator, which is shifted due to redispatch,

$f(P_{\mathrm{G}i})$ is the generation cost function of the i-th generator and

N_G is the total number of generators in the system.

Function $f(P_{\mathrm{G}i})$ can be expressed by [23]

$$f(P_{\mathrm{G}i}) = \sum_{i=1}^{N_G} (a_i P_{\mathrm{G}i}^2 + b_i P_{\mathrm{G}i} + c_i) \tag{2.6}$$

where:

N_{G} is the number of generation units considered, and

a_i, b_i and c_i are fuel costs coefficients for the i-th generation unit.

The quadratic generation function, normally used for thermal power plants, results from their "input-output" characteristics. In the case of other types of power plants, quadratic or even cubic cost functions provide more accurate models of the actual behavior of generation units where the fuel is oil, coal or gas [24].

The second objective function is to minimize the amount of the redispatch power (eq. 3.7) under consideration: The sum of positive and negative redispatch power should be equal 0 (eq. 3.8)

$$\min \sum_{i} |\Delta P_i| \tag{2.7}$$

$$\sum_{i} \Delta P_i = 0 \tag{2.8}$$

where:

ΔP_i is the redispatch power of the i-th generation unit.

2.3.3 Types of congestion

The congestions can be categorized based on their location and occurrence frequency. The location-based congestions can be divided into zonal and cross-border congestions. Zonal congestions occur inside one of the dispatching areas whose alleviation needs to be performed under the responsibility of one transmission or independent system operators (TSO/ISO). This issue can be managed by local facilities, which fulfill necessary requirements regarding the regulation of cross-border trading contracts. By contrast, the cross-border congestions arise as a result of exceeding the transmission capacity of interconnectors and all operators in the areas involved jointly solve these congestions. The division based on persistence includes regular and irregular congestions. Regular congestions have more severe consequences resulting from the infringement of certain operational limits in terms of occurrence frequency or duration. This type of congestion can only be resolved through grid reinforcements. Irregular congestions, in turn, are mostly changeable and can be alleviated or avoided through the appropriate allocation of costs [58].

2.3.4 Congestion management actions

Counter trade

In the case of countertrading (buyback system), participating producers and consumers are sorted according to their marginal production costs offered. The TSO in the importing region "buys" the additional quantity to be produced from them. In turn, the TSO in the exporting region "sells" a corresponding quantity of electricity. The power stations within the export region have already sold their electricity on the OTC or the stock exchange and now have to reduce their production. Consequently, they "buy" the excess electricity sold by the TSO (buyback). The price is below the market price as the producers participating are paid for the provision of productive flexibility. On the other hand, production is increased. However, the TSO pays the producers participating a price above the market price to cover the marginal costs, since, in the case of a short-term adjustment, flexible power stations must be used whose marginal costs can exceed those of the limit power station [29].

Redispatch

This method of congestion management is based on the impact of adjustments of power generated on flows, which can be determined using either sensitivity theory or electricity tracking [19], [27]. The redispatch procedure selects pairs of generation units that change their generation schedule over a defined time. The power of the plant on the surplus side is reduced and the power on the deficit side needs to be increased [56], [57], [58]. If the power to be transferred is too high, the power flow can be decreased by shifting the power generation. The adjustments are carried out until the (n-1) criterion is fulfilled again.

Chapter 6 provides a detailed description regarding the redispatch principle. It encompasses a mathematical description of the redispatch process together with an introduction to the MAS proposed used to test assumed management strategies.

Emergency remedial actions

Emergency actions need to be executed in the case when network- and market-based actions are insufficient to alleviate the congestion. For this purpose, feed-in management and load shedding constitute remedial actions provided to bring stability to the system operation.

According to §11 to §14 of the German Energy Act (Energiewirtschaftsgesetz – EnWG [81]), the transmission system operators and, accordingly, the distribution system operators bear the responsibility for system security. They are entitled to do everything necessary to prevent large-scale outages and the breakdown of the power supply. Situations of extreme wind infeed and low load, whose control is not possible without the reduction of feeders in the distribution grids, are increasingly critical for system security. That is why the network operator also uses the network security management as a technical basis for these purposes. Feed-in management is a specially regulated network security measure to relieve network congestions. However, according to the legal issues, feed-in management is only used if the network congestion cannot be sufficiently relieved by other suitable measures, particularly by a generation reduction of conventional power plants. If renewable energy sources or combined heat and power units are regulated by feed-in management, the plant operator is entitled to compensation from its grid operator [25], [26].

Load shedding is usually the last option if it is no longer possible to adapt the generation of the power plants in the respective congestion region. The redispatch will require power plant operators to resubmit their generation schedule with the amount of electricity they will be required to produce the next day to the transmission system operators responsible for grid stability [28].

2.4 Grid restoration

The increasing complexity of the power system creates many challenges in power system operation. The high penetration of DG based on renewable energy sources and the fluctuating character of generated power can cause changes in power flow directions and contribute to instabilities or stressed conditions. Congestions occurring may lead to partial system outages and interruptions. Furthermore, temporary faults, such as those caused by lightning, even if cleared immediately, can initiate a domino effect that might lead to a partial or complete outage, involving network separation into several subsystems. Therefore, improper operations during certain failures can worsen the system state and lead to severe chain reactions, which, in turn, may finally cause a large-scale and extensive blackout [30]. Table 2.2 presents a list of major blackouts.

Table 2.2 Lists of major blackouts in the world [82], [83], [84], [85], [86], [87], [88], [89]

Blackout		No. of affected people, in million	Interrupted load, in MW	Restoration time, in hours
Date	**Affected areas**			
09.11.1965	USA, Canada	30	20,000	13.5
13.07.1977	New York	9	6,000	26
19.12.1978	France	3.6	30,000	4
02.07.1996	West USA, Canada	2	11,850	7
10.08.1996	West USA, Canada	7.5	30,000	9
21.01.2002	Regions of Brazil	45	23,766	4
14.08.2003	East USA, Canada	50	61,800	112
28.09.2003	Italy	55	25,000	15
18.08.2005	Indonesia	100	5,000	11
01.08.2006	Canada	4.5	-	24
04.11.2006	Germany, France, Italy	10-15	-	-
24.01.2008	China	4.6	-	336
11.03.2011	Japan	4	-	-
30.06.2012	India	670	-	12
22.05.2013	Vietnam, Cambodia	8	9,4	8
01.11.2014	Bangladesh	100	-	10
31.03.2015	Turkey	76	21,870	9
28.09.2016	South Australia	1.7	-	7.5
15.08.2017	Taiwan	23	-	4

The lack of energy in the area separated and the enormous costs connected with that imposes the need for fast and efficient actions to bring power systems back to normal operation. Power system restoration is well recognized as one of the most important tasks for electric power grids. Following a power outage, system operators in the control center prepare a restoration plan and work with the field crews to reestablish the generation and transmission systems and then to restore loads and power supply. System reliability depends heavily on the efficiency of the system restoration. A proper restoration plan determines the efficiency of the grid restoration [31].

2.4.1 Aspects of system restoration

Despite the fact that each power blackout and restoration process is a unique event, certain objectives and steps are common to all restoration procedures. The aspects of restoration are shown in Figure 2.7. They encompass most of the issues regarding the power system operation and planning [32].

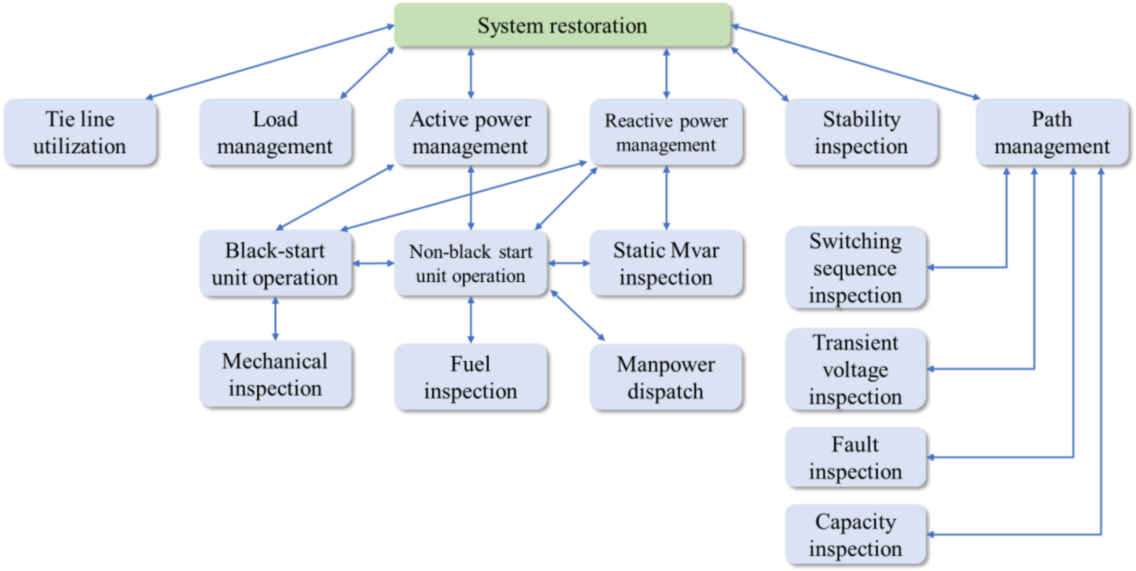

Figure 2.7 Power system restoration aspects [30]

Nowadays, the restoration of the network after complete or large-scale outages is carried out according to a central concept through the start-up of large black start power plants in the transmission network and forming individual islands at the beginning of the system restoration process. After the main power stations are restored, transmission lines are connected to the system step by step. The entire process, accompanied by an increase in subordinate voltage levels, reconnection of loads and other power stations, is based on the continuous availability of black start power plants connected to the transmission network [32].

Power system operators normally rely on off-line restoration plans to prepare the sequence to energize the system, which include the assessment of system conditions, restart of the generating units and establishment of transmission structure to activate other non-black start generating units [33]. The black start capabilities must be provided by the operator of the generation plant if the network operator requires this for technical reasons for network operation purposes. The site-specific conditions will be agreed between the operator of the power plant and the TSO [35].

2.4.2 Formulation of restoration problem

From a mathematical point of view, the restoration process can be formulated as a constrained multi-objective optimization problem. Each restoration process aims at minimizing the total restoration time and maximizing the amount of load to be restored [93]:

$$\min T_{\mathrm{res}} \tag{2.9}$$

$$\max \sum_{i \in N_{\mathrm{res}}} S_i \tag{2.10}$$

where:

T_{res} – total restoration time,
N_{res} – number of restored buses and
S_i – total power of restored loads at node i.

The objective functions presented relate, however, to the power system where generation units are stable by means of the continuity of the power generated. Regarding the fact that renewable energy generations are presently widely integrated into the network, it is important to consider their fluctuating character. Generated power may not correspond to the actual load demand due to changing weather conditions. Thus, it is crucial to perform a restoration process which minimizes this kind of risk. Additionally, during the restoration process, power system operation needs to be kept within permissible constraints, which includes current, voltage, and active and reactive power generation limits [93]. More detailed considerations regarding stability issues are provided in subchapter 2.4.6.

2.4.3 Restoration steps

Each restoration procedure that follows a complete or partial blackout of a power system can be divided into the following steps [30]:

Identification of the system status.

After a system outage resulting in a significant loss of customer load, determination of transmission and generation loss, as well as equipment damage, plays a significant role. Overloading and disconnecting of specific transmission lines may result in separation of the system into subsystems. In the case where the island area has no connections with neighboring systems, it is necessary to determine the black start capabilities and critical loads in each subsystem. Appropriate system assessment leads to a better estimation of the restoration times of the power system transmission and preparation for customer load restoration can be made more accurately [43], [44].

Black start of large power plants.

Assessment of the black start capability is an important point during the preparation of the power system restoration plan [36]. Large power plants have to be restarted within a certain period of time. Hot restart of drum type boilers, for example, is only possible within thirty minutes. If it cannot be accomplished and the boiler is not available for four to six hours, a cold restart has to be performed. Thermal power plants can be restarted by means of smaller units with black start capability, i.e. power plants that can be started and brought online without external help and within a short period of time. Hydro, gas or diesel power plants have black start capability. After such a power plant has been brought to normal operation, a high-voltage path to a large thermal power station is restored and the unit's auxiliaries, which are driven by large induction motors, are started [37], [43].

Energization of subsystems.

The whole restoration process involves the restart of many generation units. Sequential system restoration would be time-consuming and can threaten the stability of the system. Since overall restoration time is an important issue, minimization of the time needed to restore the whole system is realized through parallel restoration of the sectioned power system. This is especially important in the case of a large power blackout, where quick restoration translates mainly into lower operational costs. After islands have been determined, large generation units contribute to restoring the main transmission path of the bulk power system. In the next step, major load centers and other power plants are then connected to the system. After restoration of a system skeleton, the network is stable enough and prepared to connect further load and other generating units [40], [43].

Interconnection of subsystems.

If subsystems have stable operating conditions, the islands can be interconnected, creating an original power system structure. In this step, subsystems are tied together using breaker relays with checking of synchronism. The frequency difference between the islands needs to be minimized during the reconnection procedure to avoid any severe transients after synchronization. In the final step, remaining loads are connected to the network and the system performs its transition to the alarm or normal state [43].

2.4.4 Power system restoration planning

A reliable restoration plan should be prepared and established quickly to serve as a support for system operators in the network control center. Based on the restoration steps proposed, operators can take control actions or dispatch field crews to execute the restoration plan, which can be represented as a sequence of switching operations leading to the final network configuration.

"Restoration plans can be generated automatically using smart optimization procedures, reducing the cost and the inconvenience caused by blackouts. A restoration plan consists of a set of repair actions, such as connecting or disconnecting components. The primary objective is to isolate faulty equipment while maximizing the percentage of load recovery. The problem has a time dimension related to the ordering of the repair actions. This ordering has a direct influence on the load recovery over time" [60]. Additionally, an important aspect is the system generation capability, which has to be maximized during the restoration. "Given limited black start resources and different system constraints on different generating units, the maximum generation available can be determined by finding the optimal start-up sequence of all generating units in the system" [34]. The proper organization and realization of a restoration plan contributes to its success considerably. Reports related to the actual deployment of restoration procedures can be found in [44], [94] and [95].

2.4.5 Types of restoration approaches

Outages can generally be classified into the following situations [41]:

- regional/local supply failure,
- stable subnetwork after load shedding (brownout),
- blackout with voltage set point from the neighboring TSO and
- blackout without voltage set point from the neighboring TSO.

In the event of a major disruption, the TSOs must be prepared accordingly. The obligations of the TSOs in the event of a major disruption are provided in the Transmission Code. Appropriate concepts for preventive and operational measures must be developed by the TSOs to provide the "restoration service" and include [41]:

- failsafe communication systems,
- contractual protection of ancillary services that must be used in the event of major disruption, such as
  - black start capability of power plants owned by power plant operators (hydroelectric power plants, gas turbine power plants),
  - island operation capability of power plants owned by power plant operators (thermal power plants) and
  - areas allowing active and reactive power exchange from the neighboring TSO.
- strategies for grid restoration in the case of various major disorders and tools for the on-duty staff of the network control centers.

The basic strategies for network restoration after blackout with or without a voltage set point from the outside power system are presented in the following. The general initial state is characterized itself by the de-energization of the entire network with all subordinate levels. Firstly, a defined switching state is determined, including [41]:

- horizontal separation: opening connections to neighboring TSOs and
- vertical separation: switching off the voltage levels subordinate to the extra high-voltage network.

The following actions differ according to whether there is a voltage set point available from the neighboring system or not. In the first case, voltage is provided to at least one of the coupling nodes of the neighboring TSOs, which can be used for network restoration. The procedure is as follows [41]:

- stepwise connection of the lines starting from the coupling nodes in the direction of thermal power plants,
- restoration of partial loads and compensation inductances while observing the limits permissible for active and reactive power at the coupling nodes,
- connecting black start power plants to the energized lines and possible takeover of active and reactive power,
- synchronization with the thermal power plants operating on their own demand,
- takeover of active power by the thermal power plants and the restoration of additional loads, and
- synchronization of the resulting subsystems at suitable network nodes.

In the second case, there is no voltage available at the coupling nodes to neighboring TSOs. The procedure is then as follows [41]:

- starting the black start power plants, such as pumped storage or gas turbine power plants,
- gradual connection of the lines starting from the black start power plants in the direction of thermal power plants,
- partial restoration of loads and compensation inductances, considering the performance diagrams of the feeding generators, and
- synchronization with the thermal power plants running on their own demand; further procedure as in the first case.

Several more detailed strategies can be distinguished in the process of power system restoration based on a system-specific definition of restoration procedures and their integration into a target system using generic restoration actions [32]. Differences in restoration approaches result from differences in system characteristics. Separate restoration plans need to be developed for individual power systems. However, there are some common stages in each restoration plan which can be called tactics. Power systems generally characterize themselves by certain behaviors, which are common during the restoration process [38], [42].

Build upward

This methodology is based on the availability of electrical islands having generation units with black start capabilities which can start quickly and restore critical loads [36], [38]. After every island is restored, the resynchronization and connection of islands is performed. Start-ups of black start units, energization of non-black start units, islands restoration and synchronization of islands are steps in the frame of the strategy [32].

Build downward

Most of the outages generally involve only a part of the power system that can be restored with the help of neighboring power grids. In this strategy, the transmission network is restored starting from energization of black start power units, providing cranking power to non-black start units [38]. The methodology encompasses start-ups of black start units, transmission network energization and restoration of non-black start units. In this case, energization of the high-voltage network is followed by restoration of the lower voltage networks [39].

Build inward

This restoration strategy can be used if there are network-supporting tie lines available. The power station and generation units chosen can be energized by these tie lines. Based on that, the further restoration process is performed, including restoration of remaining power sources. This methodology includes the following stages: Reconnection of the tie line, restoration of transmission networks and cranking of non-black start units [32].

Build outward

This strategy can be used if the restoration of a network with ring configuration is not possible by using tie lines. The grid restoration is then performed from the ring outward. The strategy process includes start-ups of black start units, energization of the ring network and cranking of non-black start units [42].

Build together

This strategy encompasses energization of main power corridors. Smaller stations are restored as black start units. Together with serving local loads, these actions constitute major tasks in this strategy [32].

Serve critical

In this strategy, major generation units, such as nuclear power plants, are restored through the main transmission paths within each island. Start-ups of black start units and energization of critical loads are tasks in the frame of this strategy [32].

2.4.6 Restoration stability issues

The restoration sequence is a dynamic process where both steady-state and transient operating conditions need to be considered [42]. The following aspects play significant roles regarding the stability of the restored system:

Active power balance and frequency control

Maintaining the frequency during the restoration process is a crucial issue. This can be accomplished by gradual load energization. This, however, can contribute to the increase of restoration time. On the other hand, the fast restoration of a large amount of load can lead to under frequency conditions and cause renewed system outage. Consideration of the allowable rate of load pickup as a function of generation capacity can maintain permissible frequency limits [40].

Voltage control

Certain actions need to be performed to keep system voltages within the permissible limits, including energization of high-voltage lines, adjustment of generated reactive power, deactivation and activation of static capacitors and shunt reactors or transformer taps regulation [40].

Switching transient voltage

Switching operations during an energization of equipment may result in overvoltage conditions. Energizing of lines can cause large inrush currents which are dangerous for the power system components. Synch-check devices checking closing conditions of a breaker are used to limit these inrushes. However, inappropriate settings may cause damage to power system equipment or unnecessary blocking and delay of line reconnection [40].

Cold load pickup

Re-energization of the disconnected loads, including motors, transformers or lighting, causes unwanted electromagnetic transients resulting in so-called inrush current which can be even up to ten times the nominal value. Moreover, inrush current contributes to maloperation of system protections causing unnecessary tripping operations. This can be especially noticeable in the case of differential protection of transformers. Since inrush current shares a considerable level of second harmonic, appropriate adjustment of protection makes it insensitive to such phenomenon [45].

Protection systems and load control

The restoration process is accompanied by changing system configuration translating into changing operating conditions, which can cause undesired operation of protection devices. In cases of over and under frequency conditions during the restoration procedure, remedial actions, such as load shedding, need to be performed [42].

2.4.7 Expert systems in grid restoration

The system restoration, as a combinatorial problem due to many possibilities of switching operations, requires decisions and actions which will result in fast and reliable restoration of power supply to the customers. The restoration plans are normally prepared for a specified parts of the system before the blackout. System operators used to “manually” perform power system restoration based on defined procedures resulting from the operator’s knowledge and experience. Considering a variety of disturbances occurring, proposed recovery procedure may not correspond with the scenario taking place. Therefore, most of the research in the field of grid restoration is focused on artificial intelligence approaches [93].

The implementation of the operator knowledge in the form of heuristic rules plays an important role during the development of expert-based restoration systems. Hence, it is crucial to ensure an optimal engagement of appropriate methodologies and processes responsible for structuring and further data deployment. Artificial intelligence strategies, such as fuzzy logic [89] or genetic algorithms [90], can be applied to power system restoration. Moreover, as a connection of methods mentioned, hybrid approaches based on expert systems or the application of neural networks [91] create a starting point in the development of efficient grid restoration procedures. Additionally, systems based on social behaviors, interactions and decentralized decision-making play a significant role considering data uncertainty and limited information flow [92], [93]. As an example, MASs which can prove integrated functionality using the combination of optimization methods and experience-based knowledge constitute an important and innovative path in the future power system management.

3 Multi-agent systems

3.1 Definition of an agent

Agents are widely used in computer science and systems where an intelligent control approach is required. They can be applied to various types of actors, control processes and finite state machines which monitor given processes. An agent can be generally considered as a form of entity or structure able to sense, decide and interact with its environment [46]. The accurate definition of an agent, however, depends on its application and functionality. An agent generally constitutes the basic unit of intelligence that can be considered for decision-making. Figure 3.1 presents general components of an agent. An agent in the electric power system can offer a series of complex services, such as management, stabilization and protection of power networks. Moreover, estimation, energy distribution and grid restoration are the possible agent tasks depending on the application state.

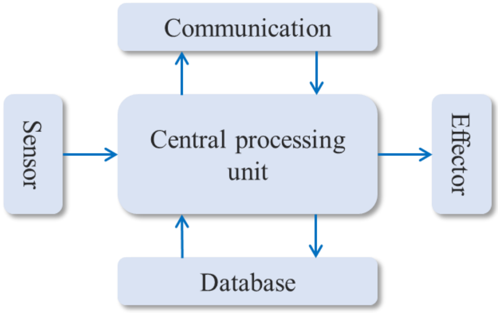

Figure 3.1 Components of an agent [61]

An agent, as an intelligent entity with flexible autonomy, has the following three characteristics [46], [51], [73]:

- Reactivity, enabling reaction to changes in the agent's environment and taking appropriate actions based on those changes and operational conditions according to the functionality that an agent is designed to represent.

- Proactivity, indicating that intelligent agents represent goal-directed behavior. Through changes in environment resulting in different working points, an agent will adjust its behavior dynamically to achieve the goals desired. A loss of communication is one example in which a given agent whose services are required to fulfill its tasks will search for other agents that provide the same services. This behavior relates to an agent's ability to take over the initiative.

- Social ability, allowing interactions between intelligent agents. However, this property connotes more than simple data exchange, which takes place in many traditional systems. Social ability includes the ability to negotiate and interact in a cooperative manner. Consequently, agents can not only simply pass data, but also converse.

3.2 Agent architecture

The information processing takes place according to defined rules and the environment data available. The general functions of each agent operation encompass data filtering, interaction with other agents and fulfilling of tasks based on assumed goals. The illustrative architecture of an agent (Figure 3.2) represents practical reasoning of an agent and is comprised of the seven main components: Beliefs revision function, Beliefs, Option generation function, Desires, Filter, Intentions, and Action selection function [47].

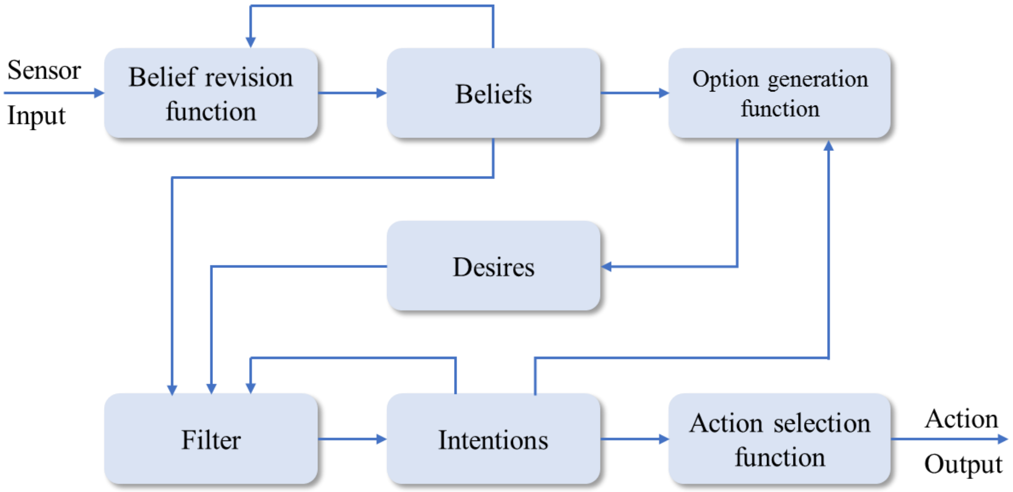

Figure 3.2 Beliefs-desires-intentions agent architecture [48]

Beliefs represent information that an agent has about its environment. They are stored in a database and can be updated depending on the environment changes that occur. They can be called a belief base or a belief set. A belief revision function constitutes a perceptual input of the agent’s beliefs and is responsible for determining a new set of beliefs based on defined inference rules relating to the environment data available. An option generation function determines the options available for an agent, based on their current environment data (beliefs) and current intentions. Desires represent the motivational state of an agent. They represent objectives that an agent is intended to accomplish. Examples of desires can be: Find the best price or restore power supply as fast as possible. A filter (filter function) is responsible for representing the agent’s deliberation process and determines its intentions based on current beliefs and desires. Intentions indicate the agent’s current objectives. In turn, an action selection function chooses actions that need to be performed to achieve planned goals based on current intentions [48].

3.3 Multi-agent system characterization

The MAS is a set of agents cooperating with each other, aiming at finding a solution to a given problem. Depending on application and system complexity, various types of agents are required to accomplish the tasks desired. Reliability and operational robustness of the system depends highly on the model consistency and proper information flow between agents. Since an agent has to control only certain parts of the system, the cooperation between agents allows to find a solution to a given problem which can be satisfactory for all agents in the system. Figure 3.3 represents the general structure of a MAS [49].

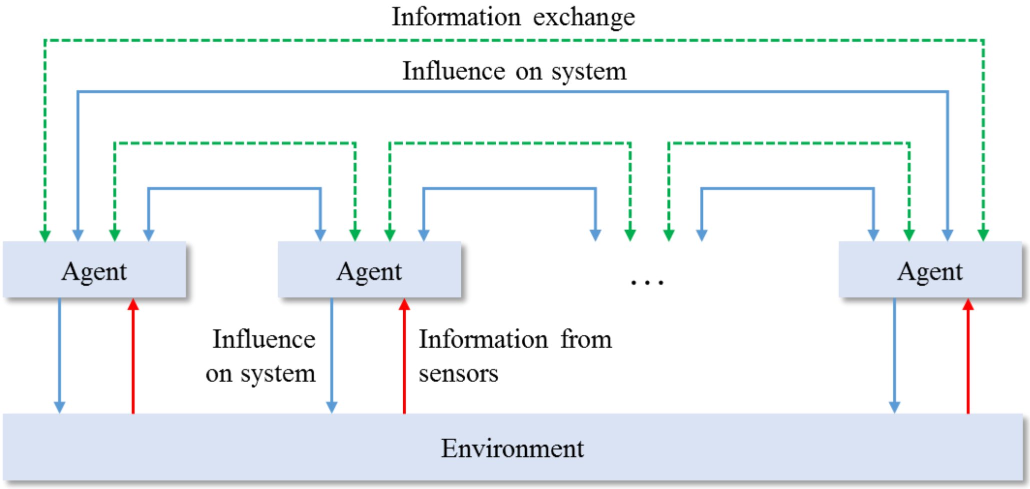

Figure 3.3 Communication and information exchange in a MAS [49]

3.3.1 Centralized and decentralized control

The rapid development of the power system creates new challenges in its efficient control. The increased amount of data that needs to be processed imposes special computation requirements on various optimization controllers. Two approaches of control strategies are presented in Figure 3.4. Most of the information about the entire system is required in the case of centralized methodology. This contributes to increased computation time and additionally imposes specific requirements on the operation reliability of the central controller. The maloperation or disturbance of its operation causes interruptions or incorrect system functionality [50].

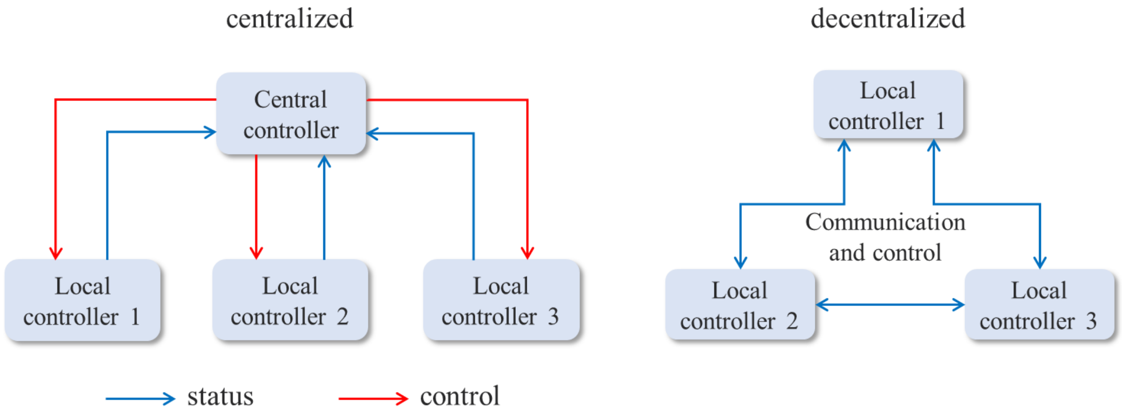

Figure 3.4 Differences between a centralized and agent-based control approach [50]

The decentralized approach, in turn, provides operational flexibility. Each of the local controllers tries to solve the problem which occurs on a regional scale. Here, the information about the entire system is unnecessary and the local controller only needs data from its local environment. The failure of one of the controllers does not affect the operation of other controllers. The decentralized control approach allows the distribution of tasks among local controllers and increases flexibility of the control structure [50].

3.3.2 Architecture of a multi-agent system

Based on the definition of a MAS, a certain number of agents must be coordinated in a common architecture to achieve a global goal [52]. Different MAS architectures are presented in Figure 3.5.

In a centralized approach, a managing agent coordinates the operation of each agent ensuring consistent system functionality and management. In this architecture, a high-performance central computer is required to process often large amounts of data [51].

The hierarchical organization is the most conventional architecture used for power system management. In this architecture, information is gathered by the lower level agent and passed to the upper level agent. The advantages of this method include a very simple information flow. Data jams are limited since the sending of information by many agents to the same agent is avoided. The possibilities of finding optimal solutions can be limited due to the lack of information caused by agent maloperation or communication interruptions [51].

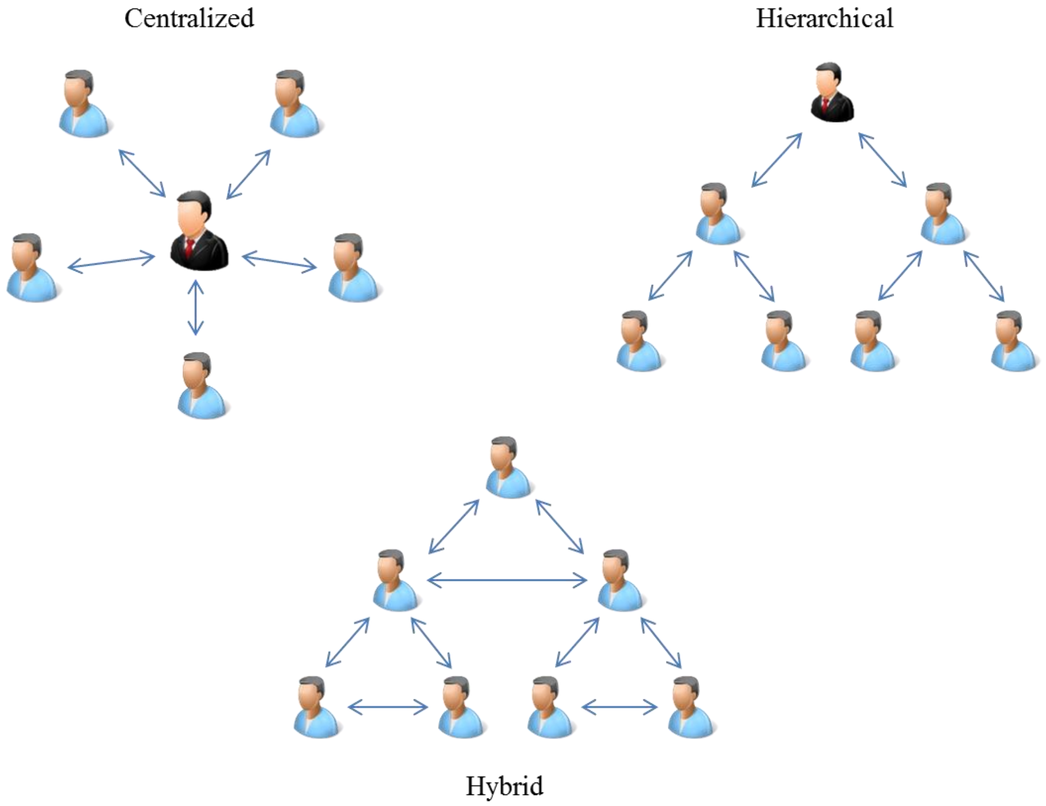

Figure 3.5 MAS architectures [51]

Both a centralized and decentralized functionality of finding an optimal solution is applied in the hybrid MAS architecture. In this approach, agents make autonomous decisions, since they do not depend on centralized information flow. Since management processes are performed in a decentralized manner, operational failures or communication interruptions do not affect MAS considerably. Depending on the information flow designed, agents at each level can exchange information with each other [51].

3.3.3 Multi-agent systems application fields

Agent-based technology offers two main approaches which can be introduced for developing modern applications. One approach relates to the construction of robust, flexible and extensible systems. Since autonomy indicates that an agent can schedule their own operation, flexibility connotes the ability to choose the most appropriate option in this schedule based on environmental conditions and allows a proper response to dynamic situations. Fault tolerance in such systems is also a crucial issue. If a part of the system fails for whatever reason, the system should not lose its objectives and should complete its designed goals. If it is not possible, it should determine what part of the tasks imposed it can fulfill without support from other systems. Due to the fast development of power system applications, an agent-based system should ensure the extension of its functions, upgrading existing functionality. This relates to systems where, for example, new sensors need to be added. However, the real extensibility indicates inserting new functions without renewed system implementation [59].

As a modeling approach, MASs allow a representation of the surrounding world through processes similar to behaviors recognized in nature. Object-oriented modeling has the advantage of a natural representation of processes. Connected with that, data-encapsulation decomposes data into structures with attributes, which are hidden for external objects but can be accessible through standard interfaces or method calls. Based on that, systems, such as market interactions, can be simulated through modeling of each market participant having certain attributes and possible actions [59].

Considering the issues above, MASs should be applied for systems characterizing themselves by one or more of the following properties [59]:

- Requirements for interaction between different control subsystems or plant components, including management of a microgrid while considering the voltage control or renewable resources generation level.
- Need for interaction between many entities, which would be impossible to model explicitly to represent the overall system behavior. This includes, for example, energy market simulations where each system participant is modeled individually.
- Enough local data/information to allow the performance of analysis/decision-making without the need for information exchange with a central unit, for example, a control center or main substation.
- Implementation of new functions within existing items or control systems, for example, by adding data interpretation functions in plant-based monitoring equipment.
- Requirements for a further extension of functionality over time, for example, asset management using real-time condition monitoring on multiple plant items.

Agent-based control strategies can be found in various fields of engineering. In the field of electric power systems, agents can contribute to the improvement of complex systems operation, including transmission and distribution network management [61], [63], scheduling of load consumption and power generation [69], [70] as well as control, communication but also protection of the power system [62], [72]. Since the applications of MASs are common in the field of power engineering, the following problems and challenges can be solved [71]:

- Voltage stability: The maximum possible active power of DG sources is injected without reactive power control, which can contribute to overvoltages at the injection point. Overvoltages can be avoided by cooperation between particular DG sources in providing reactive power. The adjustment of reactive power can be performed locally using an agent-based approach.
- Automation: Since the level of automation is currently relatively low in distribution networks, fault clearance and supply restoration have to be carried out manually. The shortage of the whole process of grid restoration by means of decentralized decision-making will help local utilities to save costs and reduce outage time.
- Switching operations: Since the distribution grid may not be fully observed, the result of switching operations, which are carried out manually, cannot be determined exactly. In this case, switching operations are performed by the staff based on plans prepared previously. Here, MASs provide an advantage in faster decision-making based on a larger amount of information.
- E-mobility: One of the indications of smart grid development is the integration of electric vehicles into the distribution grid. Since distribution grids are not adopted to serve this amount of new load, modern management systems are needed which will ensure charging the car batteries at the time desired.
- Microgrids: These intelligent electric islands require a dedicated automation and advanced energy management systems due to their specific operation conditions. Because the operation of a microgrid can be highly unstable, a fast and reliable control strategy is required enabling, for example, dealing with power demand fluctuations.

3.3.4 Java Agent Development Framework[2]

Multi-agent systems can be implemented using several programming environments. One of them is Java Agent Development Framework (JADE). This is fully implemented in JAVA language and provides standardized agent technologies offering the developer some features with the aim of simplifying the development process, such as [74]:

- Provides an agent environment compatible with Foundation for Intelligent Physical Agents (FIPA) specifications, which includes the Agent Management System (AMS), the Directory Facilitator (DF) and the Agent Communication Channel (ACL). These components are automatically started when the development environment is activated;

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[2] This subchapter contains materials from my publication [93]

- Visual interface supporting the management of several agents and sets of agents, even remotely. It provides tools supporting the development and debugging of multi-agent applications implemented in JADE;
- Supports multiple, parallel or concurrent executions of agent activities through the behavioral models available in the Application Programming Interface;
- Availability of a library of FIPA protocols for ready-to-use agent interaction;
- Automates the registration and removing of agents' records on the platform in the Agent Management System, allowing the agent registration to be transparent for the developer;
- FIPA-ACL message transportation within the same agent platform;
- FIPA-compliant naming service, allowing agents to receive a unique identifier at start-up which is valid for every environment; and
- Provides mechanisms that enable integration with external agent applications.

Another feature of JADE is that its agent platform can be distributed across multiple hosts, each of which runs only one Java Virtual Machine (JVM). Agents are implemented as Java threads and inserted into agent repositories called containers, which provide full support for agent execution and represent the environment for agent applications. Every container is equivalent to a process. In addition, different agents may exist in the same container, since each agent has its own thread execution supported by a Java Virtual Machine environment. Communication between JVMs is carried out through Remote Method Invocation. Figure 3.6 shows the structure of the JADE agent platform distributed by several hosts. The main container, located in Host 1, constitutes the container where the AMS, DF and Remote Method Invocation (RMI) are located. A RMI record is used to register and retrieve references to objects through their names and enable connection of other agent containers to the platform [74].

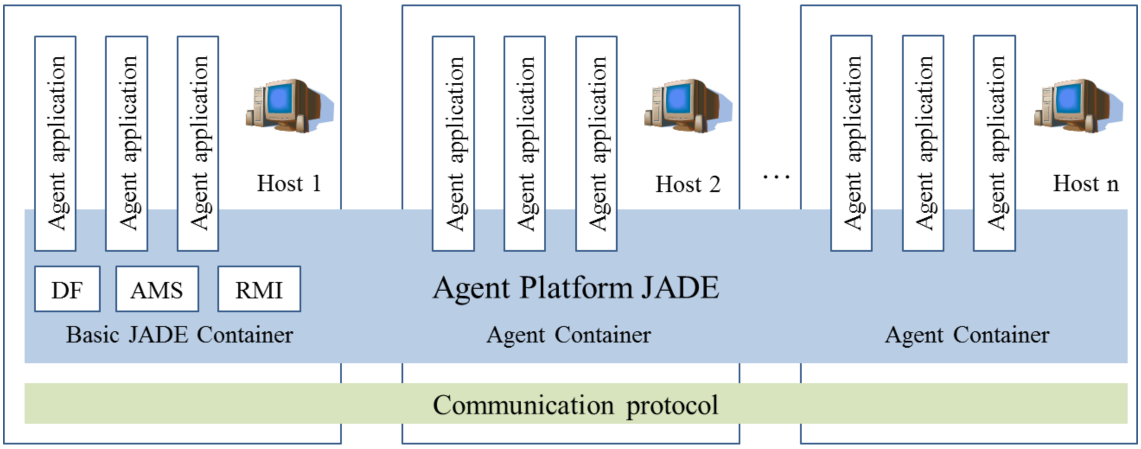

Figure 3.6 JADE agent platform distributed by several containers [53]

Information exchange between agents is realized by the passing of asynchronous messages, according to the ACL standard. The mailbox concept (Figure 3.7) enables the gathering of incoming messages and their processing when an agent has fulfilled tasks scheduled earlier. Agents perform particular tasks depending on the problem to be solved. Tasks can be combined creating more sophisticated behaviors depending on the complexity of the problem (Figure 3.8) [93].

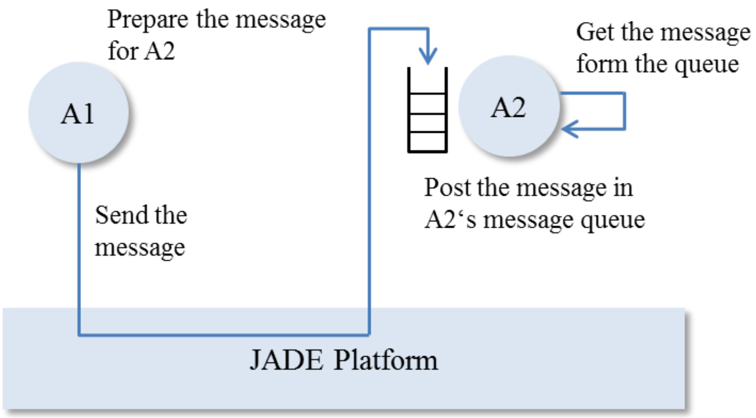

Figure 3.7 Mailbox concept [93]

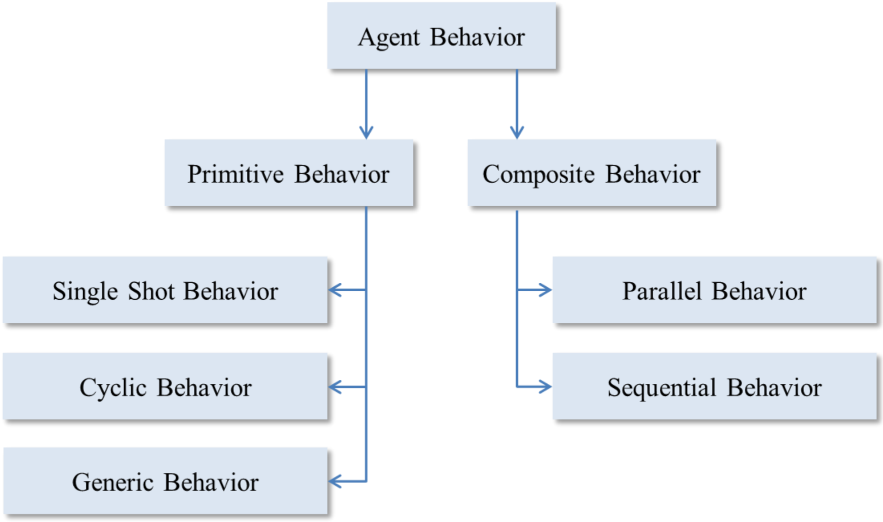

Figure 3.8 Agent behaviors [93]

4 Multi-agent system design

4.1 Design approach

A top-down or a bottom-up approach can be considered when analyzing and designing a MAS. In the first, a specification of a system architecture and agent tasks based on the complete system and its properties is determined. The second comes from a precise definition of agent behaviors and tries to determine the properties of society as a result of the interactions between agents. In the approaches proposed, the second methodology was considered. The top-down methodology can generally be used to roughly determine the structure of the system. This includes selection of agent types and basic interactions corresponding to the problem selected. The bottom-up approach is intended to specify agent tasks and analyze more detailed agent environment and interactions between other agents. After these considerations, new agents can be involved in the control scheme if necessary. This, in turn, will result in the adjustment of the system architecture assumed previously to the new final form [65]. The idea of the integrated MAS modeling is presented in Figure 4.1.

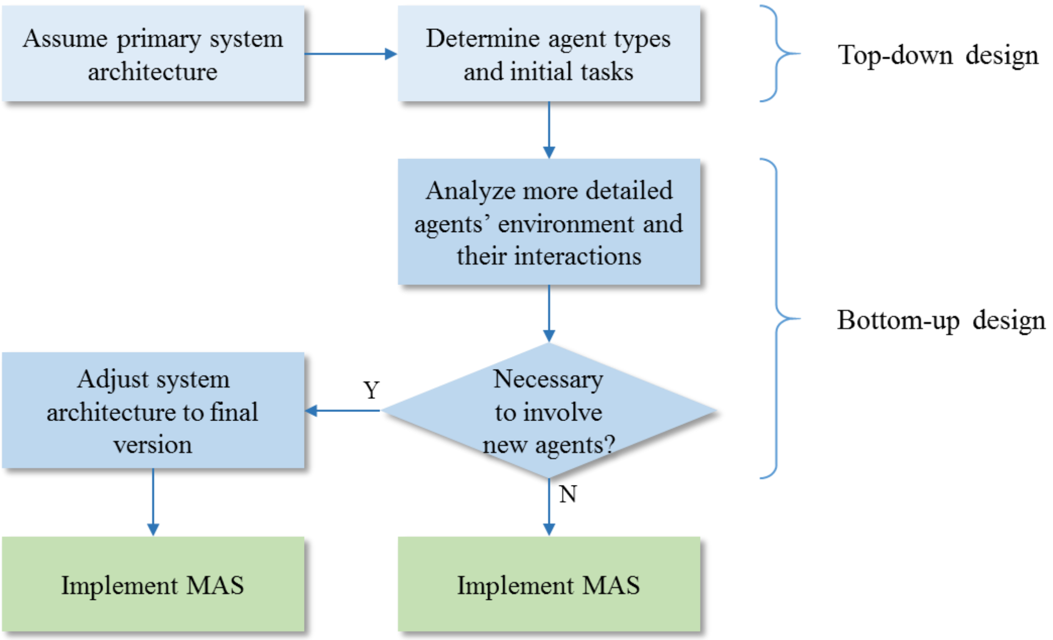

Figure 4.1 Top-down and bottom-up methodology of MAS design [65]

The agents and their organization influence each other. The organization is the result of the interactions between the agents. The behavior of agents is restricted by the organizational structures [65].

4.2 Modeling of agent interactions

Interactions between agents become a crucial issue to solve a problem efficiently. In the modeling proposed, the information about system states is derived from the load flow calculation performed by the simulation agent (SA), who is also responsible for notifying selected agents about system instability. Selection of the agents intended to perform specified actions depends on the strategy used. Depending on the current state of the system, a selected agent can compute their own operating point by accessing the appropriate Matlab functions. The communication between other agents is necessary if the current agent cannot find a stable working point, due to limited generation capabilities. An advantage of this solution is characterized by the flexibility of operational features, since the decision layer structure remains the same or can be adjusted slightly depending on the tasks performed. The interactions between agents are presented in Figure 4.2.

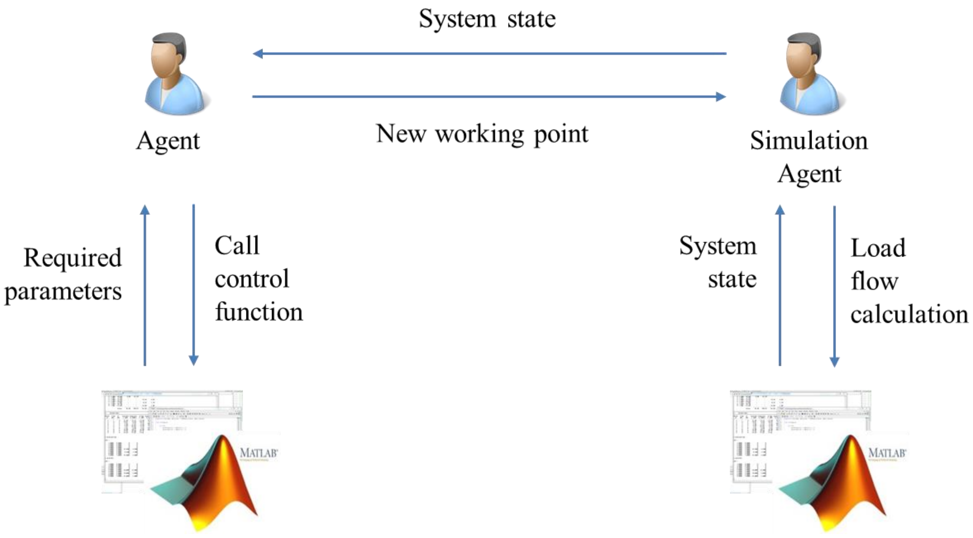

Figure 4.2 General scheme of information exchange

Figure 4.3 shows the information exchange between an agent and a Matlab function illustratively. The system functionality proposed assumes that each agent can start only one Matlab session, in which necessary variables can be set and called, and functions that allow the calculation of all necessary parameters. Sessions, however, are not interconnected and an update of corresponding functions needs to be carried out in all stations.

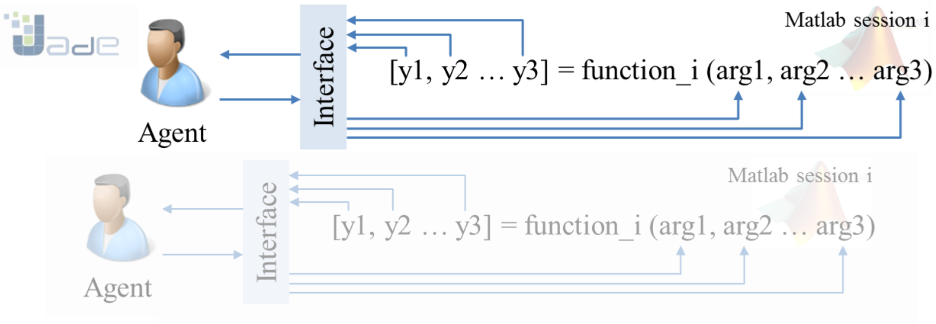

Figure 4.3 Illustrative representation of data exchange between agent and Matlab function

Regarding information exchange between agents, possible schemes are presented in Figure 4.4 and assume limited information flows in different manners. In the examples considered, agents 1, 2, 3 and 4 send information a, b, c and d, respectively. The aim of data exchange is to ensure that each agent will have a full data set including information a, b, c and d. Different exchange schemes can be applied to do that. In the left scheme, each agent is communicating with different agents. In this case, each agent needs to send *n*-1 messages, while *n* corresponds to the total number of agents involved in the information exchange. In the case of communication interruptions, the given agent will only have a part of information. Another methodology assuming limited information flow is presented on the right-hand side of Figure 4.4. In this case, an agent does not have to send data to all agents, but the message is passed to the subsequent agent containing his own data complemented with data from the last agent sending. Although such an approach ensures a smaller amount of data exchanged, in case of interruption, there is a risk that one agent will miss a majority of information. The way that agents can exchange their data can be further extended and can include mechanisms which will be executed in the case of a timeout received or communication interruption. In the approaches proposed, the first solution for data exchange has been realized.

Agents use different communication protocols to exchange messages and information. Interactions between agents can be performed based on the tasks designed and are divided into several groups provided by FIPA [66].

In the frame of the MAS proposed, interactions conforming with the FIPA protocols “Request Interaction Protocol” and “Contract Net Interaction Protocol” are used. Apart from that, agents use additional notification messages which are not associated with any protocol. The detailed message exchange represented by sequence diagrams for request and contract net interaction are presented in Figure 4.5.

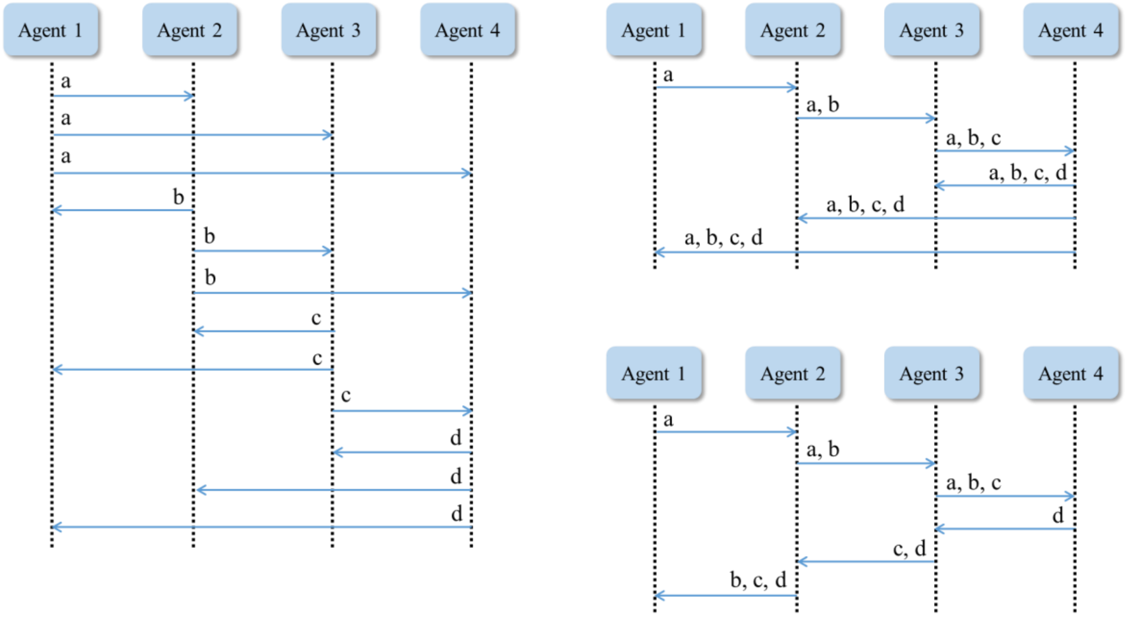

Figure 4.4 Different data exchange schemes

Exemplarily, the Contract Net Interaction Protocol represents the interaction scheme in which the Initiator is waiting for *m* proposals from other agents by initiating a call for proposals (CFP) action. It specifies the task and any conditions that the Initiator is performing during the execution of the task, depending on system functionality. Agents (participants) receiving the CFPs are viewed as potential contractors and can generate *n* responses. The acceptation of proposals results in sending appropriate notification to the Participant. Any interaction using this interaction protocol is identified by a globally unique conversation identifier assigned by the Initiator. The agents involved in the interaction must prepare all their ACL messages using this conversation identifier. Table 4.1 presents message types used in the systems proposed. They differentiate the messages exchanged and specify the intention of an agent communicating with other agents [66]. Additionally, an abbreviation is provided next to the name of the corresponding performative, which is used to describe interactions between agents in Chapters 5-7.

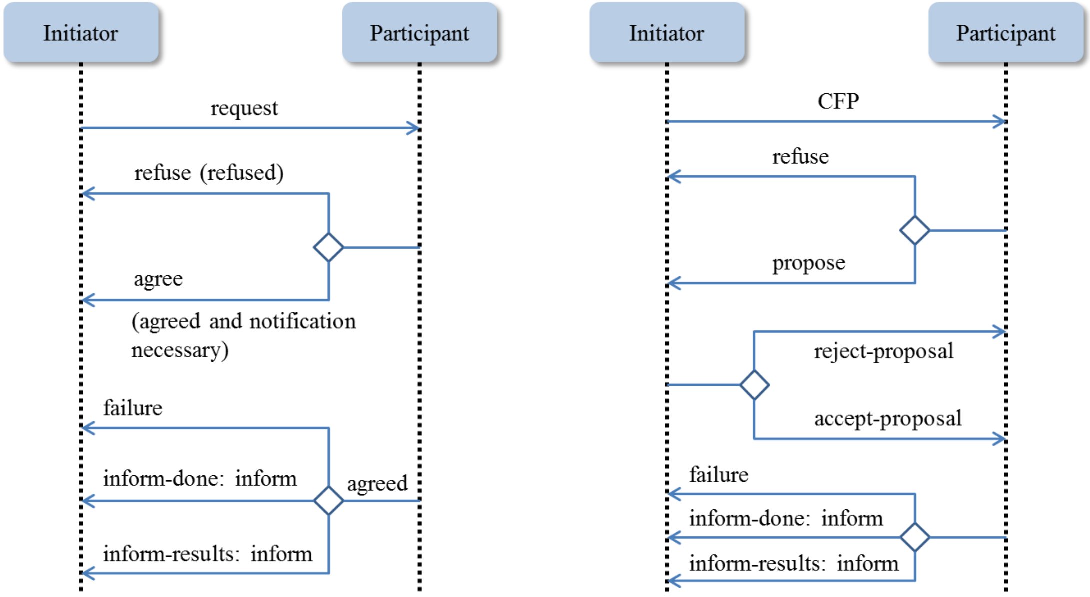

Figure 4.5 Sequence diagrams of FIPA Request Interaction Protocol (left) and Contract Net Interaction Protocol (right) [66]

An example aiming at sending CFP messages constitutes receiving the values of reactive power available that an agent could provide to support the voltage control process. Based on the assumed control algorithm, some of the proposals will be accepted by sending response *accept-proposal* and the rest will have performative *reject-proposal*.

4.3 Implementation of a multi-agent system[3]

The implementation of the system is based on the connection of two software environments (see Figure 4.6). Such an approach has been chosen to make an extensive use of full functionality and features of the programing environments proposed. Any calculations regarding the power system are performed in a MATLAB environment. This encompasses both load flow calculations and modeling more complicated power networks. The JAVA environment provides an advantage of object-programing features and multithreaded tasks execution [93].

Since features available in one type of software are difficult or even impossible to use in another, combined software operation allows one to design more advanced systems and ensure computation abilities, on the one hand, and decentralized decision-making models, on the other hand [93]. The library *matlabcontrol*, which consists of a collection of JAVA classes, is used as an interface between those two platforms. It allows the start of Matlab sessions followed by a proper definition of path resources and further work with the

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[3] This subchapter contains materials from my publications [64], [93]

environment, including calling of functions, and setting and getting variables. Two modes can be distinguished regarding the operational character of the library: Local control, where the Java programs are initiated from a Matlab session and remote controlled where the Java code calls Matlab functions. Since the interactions between the agents and organization of information flow is a prior issue in this thesis, the second operation mode enabling the calling of an appropriate optimization function has been chosen. If necessary, the appropriate functions are initiated to calculate the new operation working point of a power system.

Table 4.1 Types of message performatives used in modeled systems

Performative	Application of performatives in the approaches proposed
Inform (INF)	Notification regarding system stability (information regarding line overload or voltage instability) Information exchange between agents Sending new set points to the SA Notification regarding permission to initiate some process (e.g. data exchange) Sending generator data to the appropriate agent Notifications regarding an inability to perform the control actions desired
Request (REQ)	Requests for adjustment of control parameters
Agree (AGREE)	Agree to performing the action requested (request for additional data or set points corrections)
Refuse (REF)	Refusal to provide the data required, for example, due to insufficient power capacity or other conditions which cannot be fulfilled during the given operation step
Confirm (CONF)	Confirmation of receiving new set points Confirmation regarding acceptance of proposals
CFP (Call-for-proposals)	Calling other generators to get some data needed to perform a task required in the control action
Propose (PROP)	Proposition of parameter value, for example, the amount of active or reactive power available for control support purposes. The value received determines the task that needs to be performed by the agent sending the CFP
Accept-proposal (A.PROP)	Acceptance of selected proposals among messages received
Reject-proposal (R.PROP)	Rejection of proposals selected among messages received, depending on the process specification. If a given proposal is no longer valid, a *reject-proposal* will be sent.

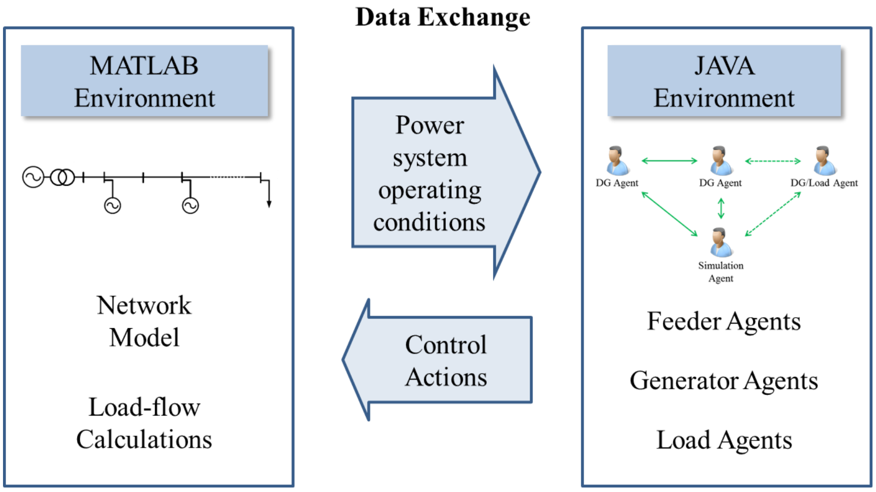


Figure 4.6 Schematic representation of environment cooperation [64]

An additional issue is the coordination between particular agents. A suitable coordination or synchronization between executions of agent tasks needs to be specified to ensure proper system operation. Such an approach in the form of the synchronization or time agent coordinating the sequence of events has not been considered, since the subsequent sequence or operation step depends on conditions that define the operation of each agent. In the case of an application of the so-called time agent, each agent might receive cyclical messages giving information about transition to the next step. That, however, could threaten the correct system operation, because passing information about the next operation point without fulfilling the required condition could cause system maloperation. An example is a situation in which an agent is waiting for messages from at least two agents. By receiving a message from a time agent about passage to the next operation step, it would miss the anticipated message from another agent. In the case of an information exchange, that would result in data incompleteness and incorrect decision-making in further steps. Therefore, the separate construction of conditions aiming at gathering the information required has been implemented in all approaches proposed. That illustrates the situation in which an agent knows, according to the messages received, when the next task should be executed. Agent interactions, however, need to be consistent to avoid cases where a program stops due to an inability to fulfill some conditions. The SA needed in systems for voltage control and congestion management is only responsible for executing load flow calculations and sending notifications regarding system instability. The SA sends no synchronization messages that could coordinate the sequence events but waits for set points sent by operative agents defining new working points. In the case of an agent-based grid restoration, in turn, the black start agent is responsible for checking system stability parameters and calculating the restoration path.

Figure 4.7 illustratively presents control schemes proposed in the frame of this dissertation. The aim of the systems proposed is to model agent interactions within particular management processes which can constitute reference models for further extension. Since the agents' computational capabilities rely on Matlab functions providing the data required, systems can be extended by modification of the functions mentioned without modifying agent types. In some cases, certain behaviors would be necessary to consider because of additional interactions required for different strategies.

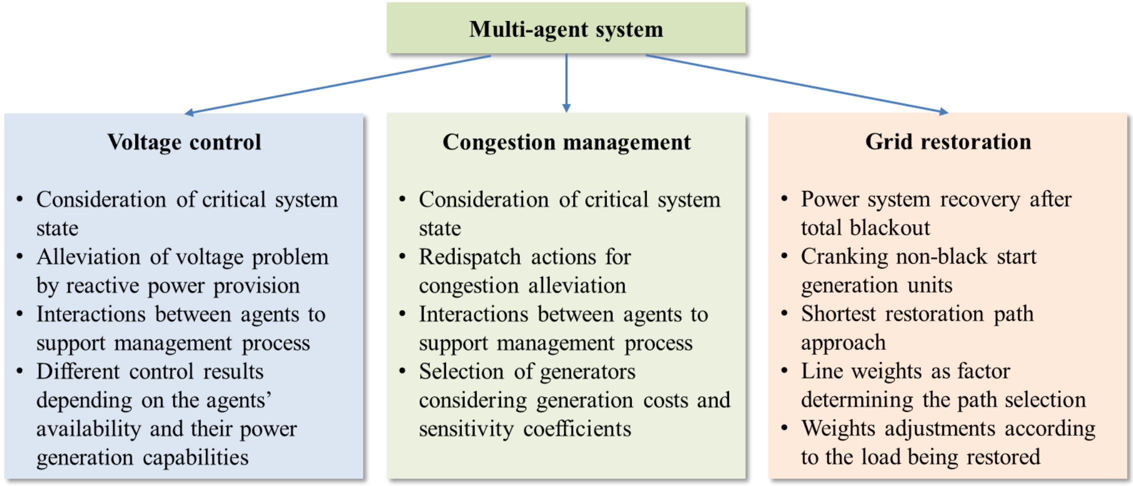


Figure 4.7 Management processes considered

5 Agent-based voltage control

5.1 General assumptions

The purpose of the agent-based reactive power dispatch proposed is to improve the voltage profile in the system. The improvement in this case brings voltage values back to the permissible ranges. Voltage values are kept at values between 0.9 and 1.1 p.u. The objective function is introduced in a linearized form through sensitivities that are yielded by linearization of the load flow equations around the nominal operating point. Control variables in the approach presented are defined as reactive power injection. The aim of the voltage control proposed is to bring system voltages back to the permissible range.

The result of the actions performed, however, will be dependent on the decision made by the agents. The minimization of reactive power provision is performed based on agent interactions and conditions assumed during the management process. In this case, however, the minimization of reactive power provision of the stable system operation has not been considered, but only system restoration to the safe operational limits. Therefore, reactive power provision will differ in each scenario. The general idea of two different control strategies is presented in Figure 5.1. On the left-hand side, the control range encompasses the range between maximum and minimum voltage value and a certain value of voltage bound in which corrective action needs to be performed. This management process is performed to optimize an already stable voltage profile. On the right-hand side, the violation of permissible voltage limits is considered and the strategy aims at a stable system operation point in which voltage values lie between $U_{\max}$ and $U_{\min}$ as the prior task. This management strategy is applied in the MAS proposed.

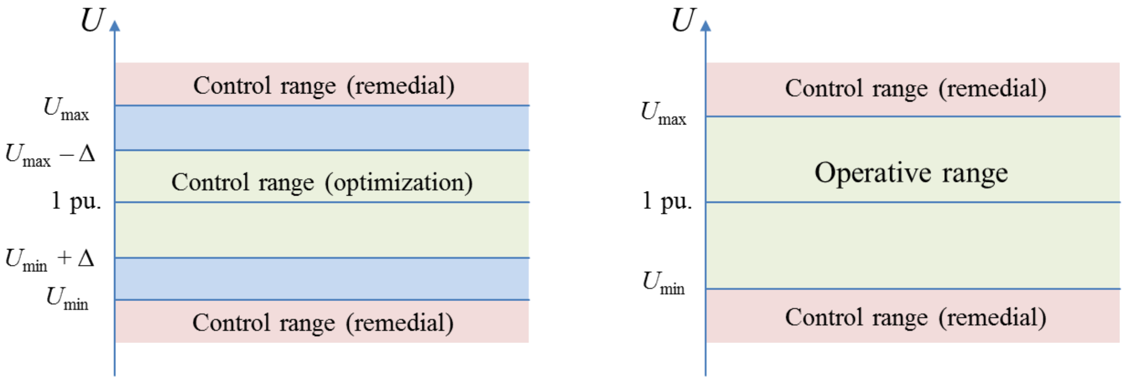


Figure 5.1 Potential control ranges in voltage control

The problem is subjected to:

$$U_{\min,k} \leq U_k \leq U_{\max,k} \tag{5.1}$$

$$Q_{\mathrm{G},\min,k} \leq Q_k \leq Q_{\mathrm{G},\max,k} \tag{5.2}$$

where:

U_k, $U_{\min,k}$ and $U_{\max,k}$ – bus voltage, minimum and maximum voltage limit, respectively,

Q_k, $Q_{\mathrm{G},\min,k}$ and $Q_{\mathrm{G},\max,k}$ – reactive power generation, and minimum and maximum capacity for generation unit, respectively.

Several assumptions have been made during the system implementation. The following points outline the main features of the MAS proposed:

- Agents solve problems in decentralized manner, which means that there is no managing agent coordinating the system operation;
- one agent is responsible for performing load flow calculations and is not involved in the control and decision process, except for sending notifications to selected agents;
- new set points are determined by generator agents through information exchange if necessary;
- agents have access to functions in Matlab which allow to calculate of the parameters required, such as active power set points or economic dispatch of active power;
- each agent can initiate only one Matlab session allowing access to the computation environment; and
- agent interactions take place in an asynchronous way (there is no coordinating agent), however, decisions are made after fulfilling appropriate conditions depending on the messages received and their content.

5.2 Jacobian matrix method

The voltage regulation in high-voltage networks is usually carried out with the help of reactive power control. The amount of reactive power needed to correct the voltage at the node can be calculated based on sensitivity coefficients that are part of the Jacobian matrix. This matrix, shown in equation (5.3), constitutes the part of the Newton-Raphson method of calculating load flow. The ratio of active and reactive power corresponds to the relevant state variables of the system (angle and voltage) to a good degree.

$$\begin{bmatrix} \Delta\boldsymbol{p} \\ \Delta\boldsymbol{q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_{\mathrm{P}\theta} & \boldsymbol{J}_{\mathrm{PU}} \\ \boldsymbol{J}_{\mathrm{Q}\theta} & \boldsymbol{J}_{\mathrm{QU}} \end{bmatrix} \cdot \begin{bmatrix} \Delta\boldsymbol{\delta} \\ \Delta\boldsymbol{u} \end{bmatrix} \tag{5.3}$$

The Jacobian matrix consists of four sub-matrices describing the connection between the relevant parameters and state variables of the system. Changes in reactive power have a significant influence on the value of the node voltage. If the active power changes are not considered, the equation (5.3) can be converted into equations (5.4) and (5.5).

$$\Delta \boldsymbol{q} = \left[\boldsymbol{J}_{\mathrm{QU}} - \boldsymbol{J}_{\mathrm{Q\theta}}\boldsymbol{J}_{\mathrm{P\theta}}^{-1}\boldsymbol{J}_{\mathrm{PU}}\right] \cdot \Delta \boldsymbol{u} = \boldsymbol{J}_{\mathrm{R}}\Delta \boldsymbol{u} \tag{5.4}$$

$$\Delta \boldsymbol{u} = \boldsymbol{J}_{\mathrm{R}}^{-\mathbf{1}}\Delta \boldsymbol{q} \tag{5.5}$$

The power change required can be determined by solving equation (5.5) with respect to $\Delta \boldsymbol{u}$ to achieve the voltage change desired.

The inversed Jacobian matrix $\boldsymbol{J}_{\mathrm{R}}^{-1}$ contains sensitivity factors describing the effects at each node as a function of the reactive power change. In this way, the reactive power required can be calculated considering the voltage difference and the highest value of the sensitivity factor for a given node. The method can be used for all topologies of the different network levels and provide very accurate calculations of reactive power. The illustrative representation of coefficients of the Jacobian matrix is presented in Table 5.1. Additionally, the colored columns indicate buses at which controllable generators are placed. They can be used to support the voltage control process. Rows in the table presented correspond to busses in the power network.

Table 5.1 Illustrative representation of the sensitivity matrix

	ΔQ_1, Bus 1	**ΔQ_2, Bus 2**	**ΔQ_3, Bus 3**
ΔU_1, Bus 1	$\alpha_{1,1}$	$\alpha_{2,1}$	$\alpha_{3,1}$
ΔU_2, Bus 2	$\alpha_{1,2}$	$\alpha_{2,2}$	$\alpha_{3,2}$
ΔU_3, Bus 3	$\alpha_{1,3}$	$\alpha_{2,3}$	$\alpha_{3,3}$

Based on the influence of a particular generator on a given bus, the change in reactive power required resulting in the change of voltage desired can be calculated using the following formula (here is an example of a change in Q required, resulting in a voltage change in bus 1):

$$\Delta Q_1 = \frac{\Delta U_1}{\alpha_{1,1}} \tag{5.6}$$

where:

ΔQ_1 – required change in reactive power,

ΔU_1 – desired voltage change in bus, and

$\alpha_{1,1}$ – sensitivity coefficient describing relation between reactive power and voltage changes in bus.

The update of reactive power value depends on previous settings and the computed change of reactive power:

$$Q_{\mathrm{DG}}(k) = Q_{\mathrm{DG}}(k-1) + \frac{\Delta U_1(k)}{\alpha_{1,1}} \tag{5.7}$$

where:

$Q_{\mathrm{DG}}(k-1)$ – values of reactive power calculated in previous iteration, and
$Q_{\mathrm{DG}}(k)$ – currently calculated value of reactive power.

The agent affected calculates the amount of reactive power required, which will result in the change of voltage desired. If the value of reactive power calculated lies outside the limits of a generator, appropriate notifications are sent to subsequent agents followed by the appropriate information flow presented in detail in the next section.

5.3 Voltage control decision process

Voltage control in the MAS proposed is performed based on the decision process presented in Table 5.2.
Each stage in this sequence corresponds to appropriate tasks, which are defined in the frame of the entire multi-agent platform. The initial state begins with receiving measurement data from generator agents (GAs).

Table 5.2 Decision-based voltage control process

Action	Remarks
Recognition	Measurement of local voltages and recognition of critical voltage violations
Announcement	Notification regarding unstable system state
Proposals	Request for voltage control support; receiving proposals from other agents in the network
Acceptation	Selection of proposals received and sending appropriate notifications
Execution	Execution of amount of reactive power accepted and checking the impact of the new working point on the power system operation

It is often impossible for practical and legal reasons to locate appropriate agents at each node of the system. Therefore, the information gathered constitutes only an approximate overview regarding the current state of the network. Limited and often uncertain data lead to challenges in optimal system control. Even in the case of voltage control, insufficient data availability imposes additional requirements regarding the robustness of the control methods applied. The occurrence of voltage disturbance causes the preparation of suitable notifications for minor agents regarding voltage compensation. The agent who recognizes the voltage problems at his node will determine whether the reactive power generation capacity available can contribute to sufficient voltage compensation. If generation limits are reached, the agent is obliged to initiate negotiation processes by sending suitable requests or proposals to subsequent agents. The responses are then reviewed regarding the amount of reactive power required. After confirmation of the proposal chosen, the new power set points for corresponding generators are set. As a next step, a verification of the new settings is performed by load flow calculation. The results give an overview regarding voltage bound violations and voltage stability of the system. Any remaining voltage violation must be resolved by repeating the whole decision process.

The agents in the system proposed can recognize potential voltage problems. If the amount of reactive power is insufficient to fully remedy the voltage, firstly, appropriate notifications are sent to neighboring agents. This encompasses proposals regarding the amount of reactive power available that could be provided during the control process. The GA responses can be accepted or rejected. After a proposal acceptation, a notification is sent to the SA regarding the new set points.

5.4 Structure of the multi-agent system

The concept of the MAS proposed is presented in Figure 5.2. The system consists of two layers. In the network layer, the power system is modeled and constitutes the platform where reference load flow calculations are performed. A Matlab environment is intended for this purpose. An agent layer serves as a decision platform where the decentralized decision-making based on available information is performed. The decision layer has been programed in a JADE framework. The information exchange is realized through the interface, enabling the connection of the two simulation environments mentioned. In the system proposed, the SA is responsible for the gathering of information from minor GAs and prepares data for the network layer.

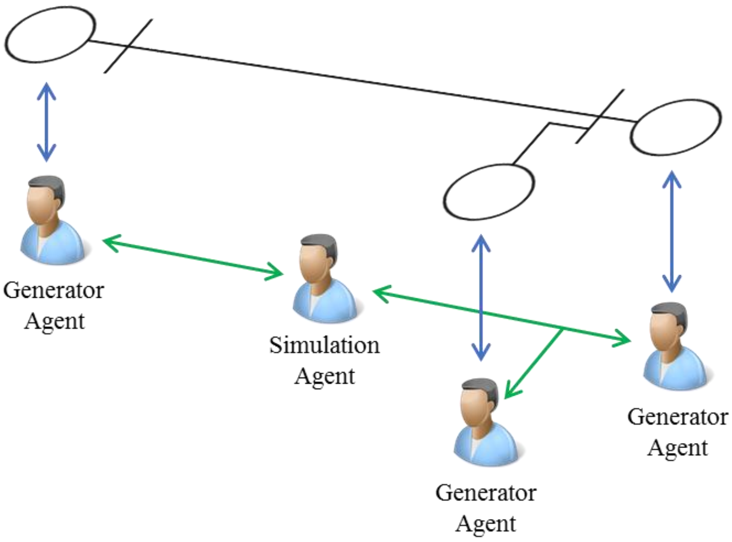


Figure 5.2 System structure proposed

5.5 Modeling of information flow

The information flow scheme plays a significant role in the operation of the MAS. Considering the multi-agent structure for the voltage control proposed, two approaches can be distinguished. In the first approach (see Figure 5.3), the SA is connected to three GAs enabling the passing of set points to the SA. The GAs are responsible for sending new set points to the SA. Regarding a more complex network, communication between the SA and each GA needs to be established. Loss of one of the communication links leads to incomplete data gathering. One of the solutions in this case would be to deploy another GA who can take over new set points from yet another GA and then pass the results to the SA. In the second approach, presented in Figure 5.4, the number of communication links with the SA is limited to communication only with GAs affected by the voltage problem. In such a configuration, new generator set points are gathered from other GAs and then passed to the SA. Here, however, an outage of an agent passing set points to the SA will result in a lack of information about the definition of the new working point. One of the possible solutions is sending data by another agent who has received an appropriate request previously. In the frame of the MAS modeled, the task range of the SA is limited and enables GAs to solve the problem in a decentralized manner.

Regarding big systems where information exchange plays an important role, the organization of information is a crucial issue. An approach based on a reduced number of receiving agents can be implemented to limit data exchange between particular agents. As an assumption, only agents with whom changes in system parameters have been determined are entitled to receive the information. The SA, who is responsible for system management, decides who should be notified about the state of the system. Depending on the current state of the system, each GA can compute their own operating point through the access to the appropriate optimization functions. An advantage of this solution is characterized by the flexibility of operational features, since the decision layer structure remains the same or can be slightly adjusted depending on the tasks performed. The interactions between agents are presented in Figure 5.5.

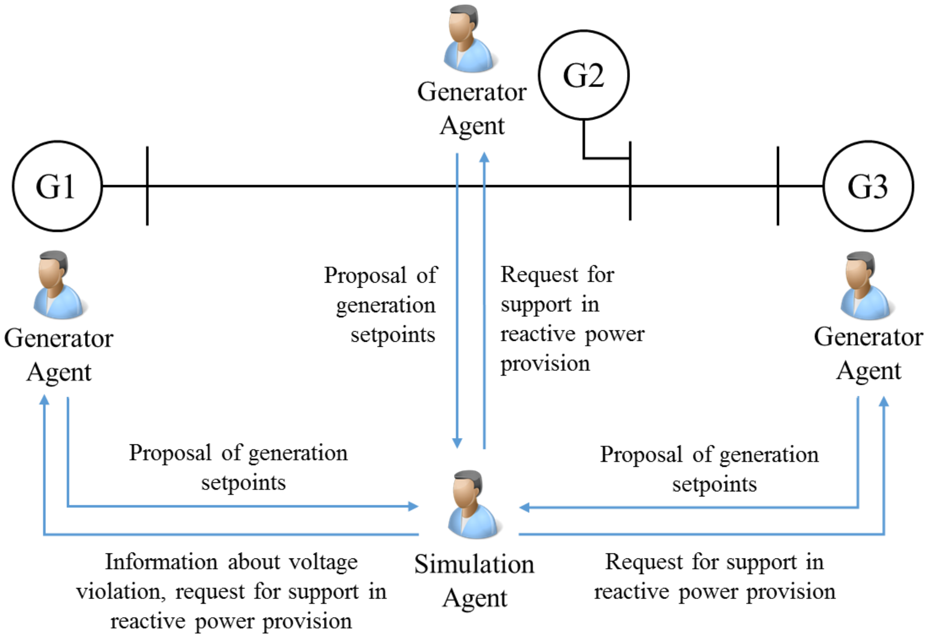


Figure 5.3 Agent interactions based on the “less decentralized” approach

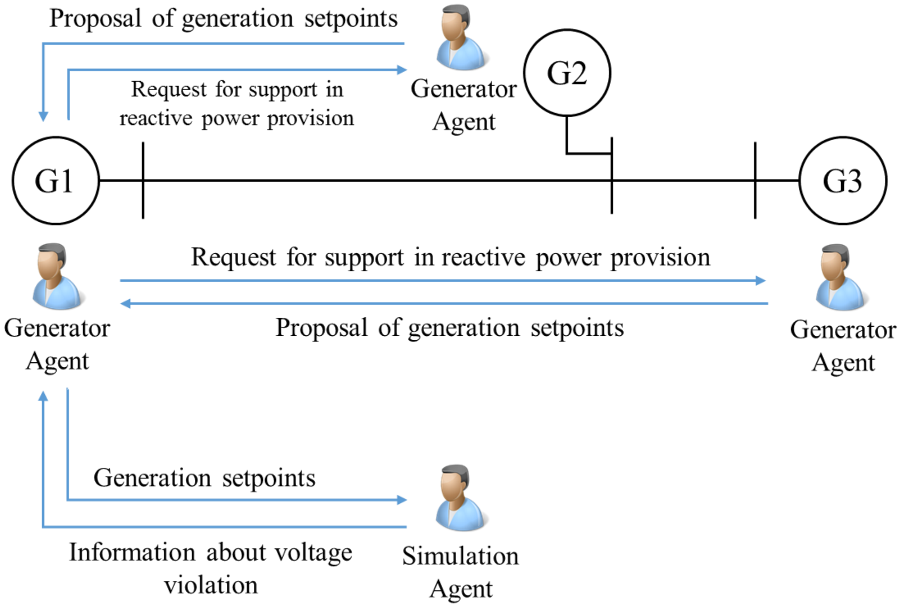


Figure 5.4 Agent interactions based on the “more decentralized” approach

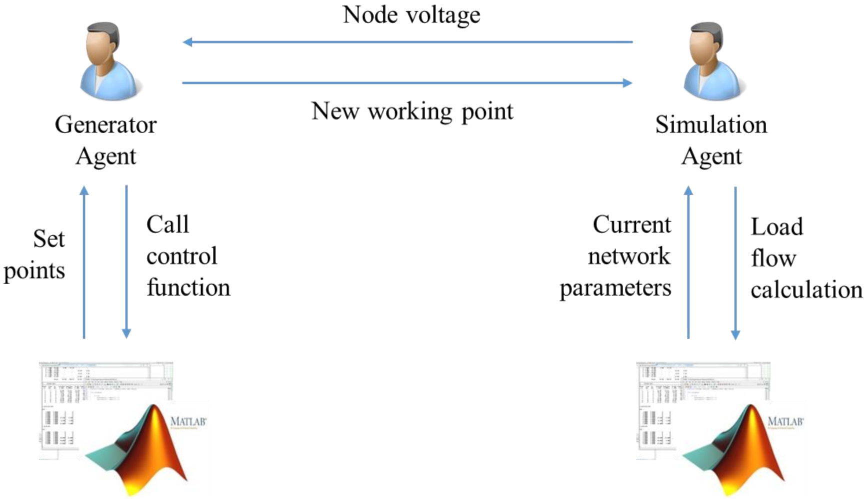


Figure 5.5 General interactions between agents in the scope of voltage control

5.6 Modeling of agent behavior

5.6.1 Simulation agent (SA)

The SA is responsible for performing load flow calculations and checking the influence of newly calculated set points on the power system. It prepares data required to update the parameters of the power system model and send appropriate notifications to the agents entitled. The control algorithm of the SA is presented in Figure 5.6.

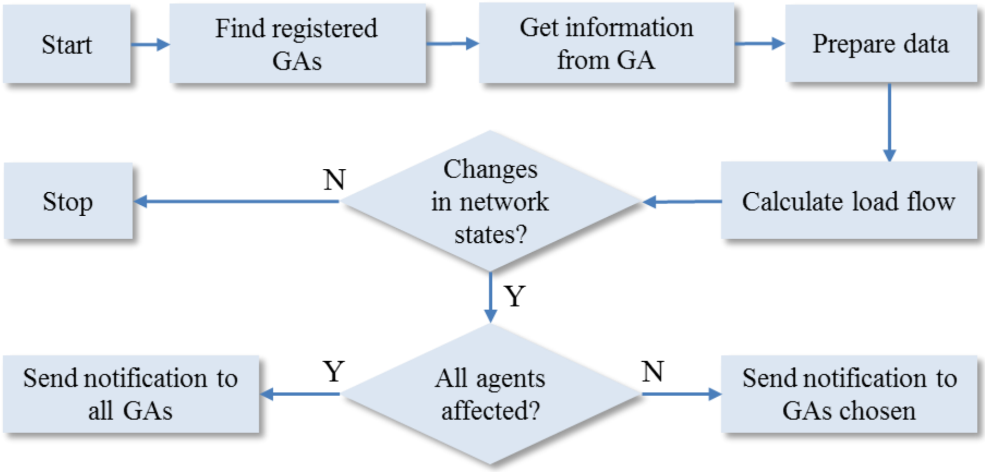


Figure 5.6 Control algorithm of the SA [64]

5.6.2 Generator Agent (GA)

The GAs are responsible for calculating the amount of generated power required as a response to the current state of the power system. A voltage limit violation leads to the activation of the tasks described above. Negotiations performed by GAs comply with Contract Net Protocol. The algorithm of the GA is presented in Figure 5.7.

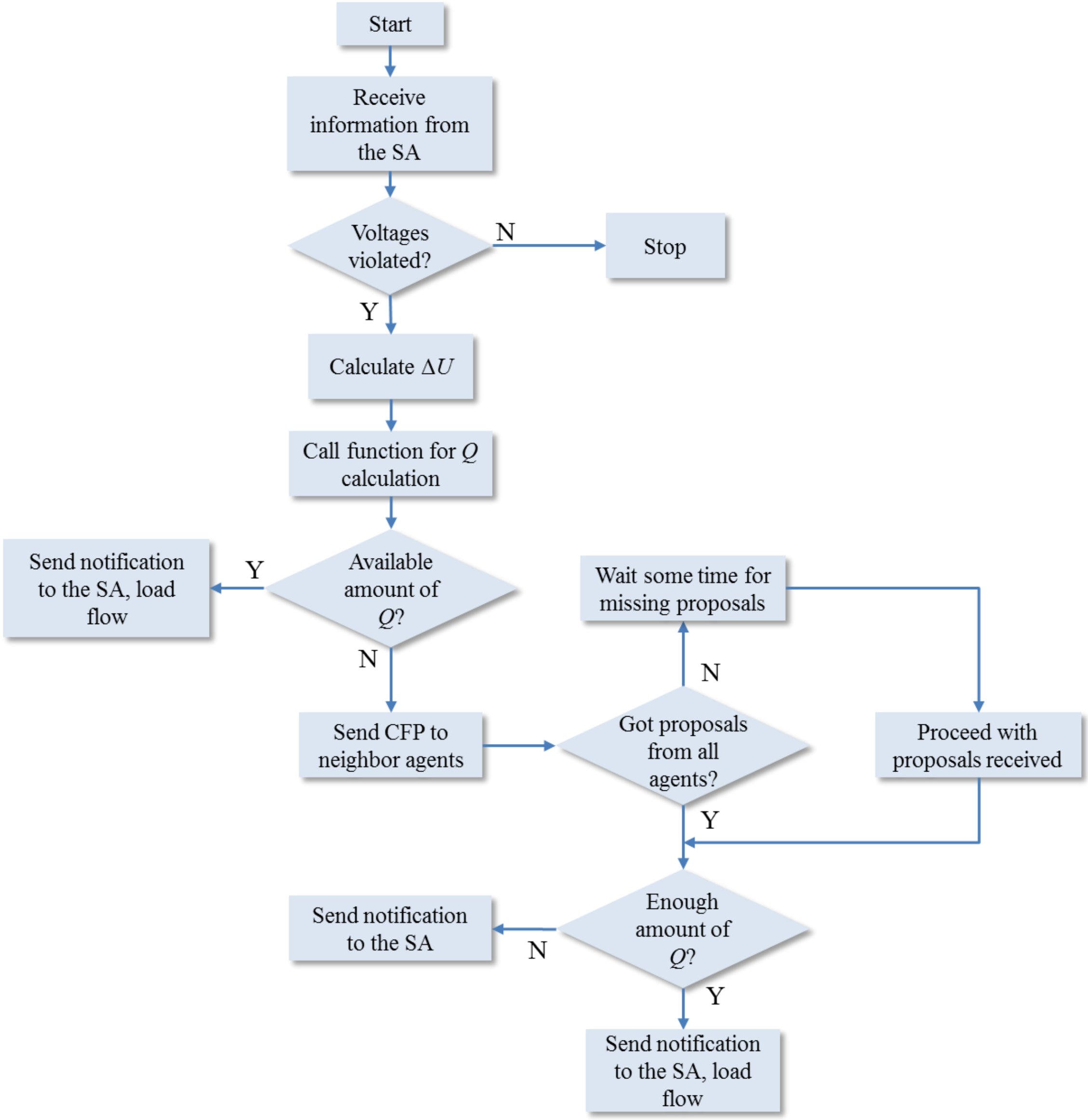


Figure 5.7 Control algorithm of the GA [64]

5.6.3 Control algorithm

The entire control algorithm is presented in Figure 5.8 and illustrates additionally the division of tasks among agents. The recognition of the problem in the approach proposed is followed by determining nodes where voltage violations are detected. Agents installed at problematic nodes try to adjust their generation of reactive power to compensate for the voltage. If the termination conditions cannot be met at the current iteration step, sensitivity factors in the Jacobian matrix are updated and the next attempt of voltage control is performed. After each iteration, load flow calculations are performed to check the influence of the new set points on the power system stability. The division of tasks into the responsibilities of requesting and supporting GAs results from interactions developed for the agents mentioned. If the GA affected cannot recover voltage to a permissible range, they will request other agents for support in voltage control. By sending appropriate calls, proposals containing amounts of reactive power are expected whose provision could bring the system to a stable operation. Depending on the strategy, supporting agents can propose sufficient reactive power, which lies in the frame of their generation capabilities. In the case of insufficient generation possibilities, the maximal available amount can be proposed, or a refusal message will be sent to the requesting agent. The receiving of proposals containing maximal available amounts of reactive power can result in the need to select more than one agent to provide the power proposed. However, before the next supporting agent is selected, a theoretical voltage change is calculated to determine whether the actual provision of reactive power has the desired impact on the voltage. If not, the influence of an additional amount of reactive power provided by the next selected agent on the voltage change is checked. If the value of the voltage desired is reached, the selection of the next generation is completed and final set points are then passed to the SA.

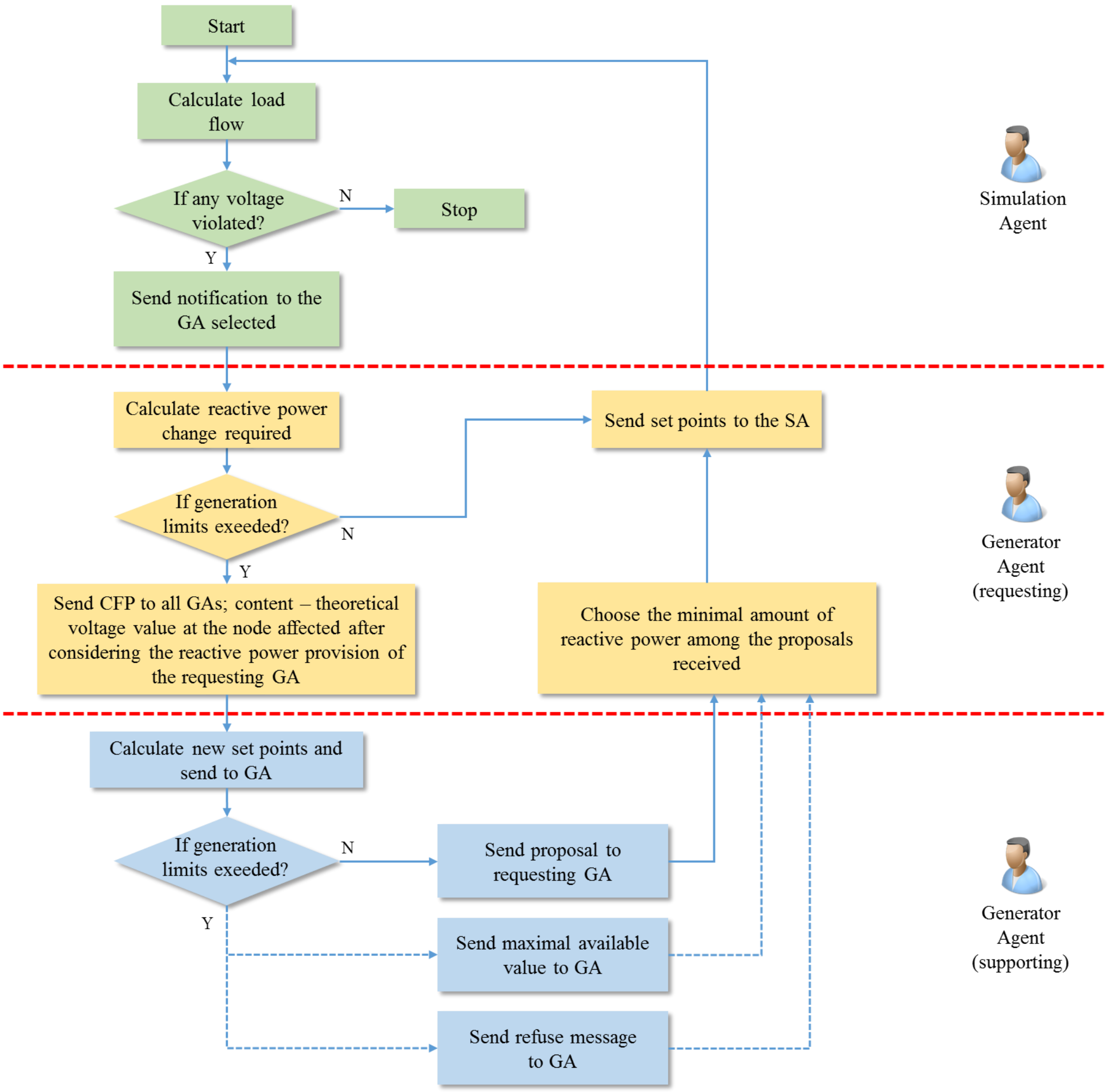


Figure 5.8 Control algorithm

5.7 Selected test cases

The adjusted 5-bus system [67], [68] has been selected for the simulations. Since four generators are available in this network, there is a possibility to perform voltage control using different generation units. The structure and system parameters were adjusted to ensure the stable load flow even during simulated voltage violations. The parameters detailed are presented in Appendix A in Table A.1. The structure of the power system proposed is presented in Figure 5.9.

Each generator in the system proposed can participate in voltage control by adjustments of reactive power, which depends on generation limitations. In this case, loads do not participate in voltage control. The system structure proposed can be applied to every network and voltage level. The basic information assigned to each GA includes the generation capacity of active and reactive power, and the bus at which an agent resides.

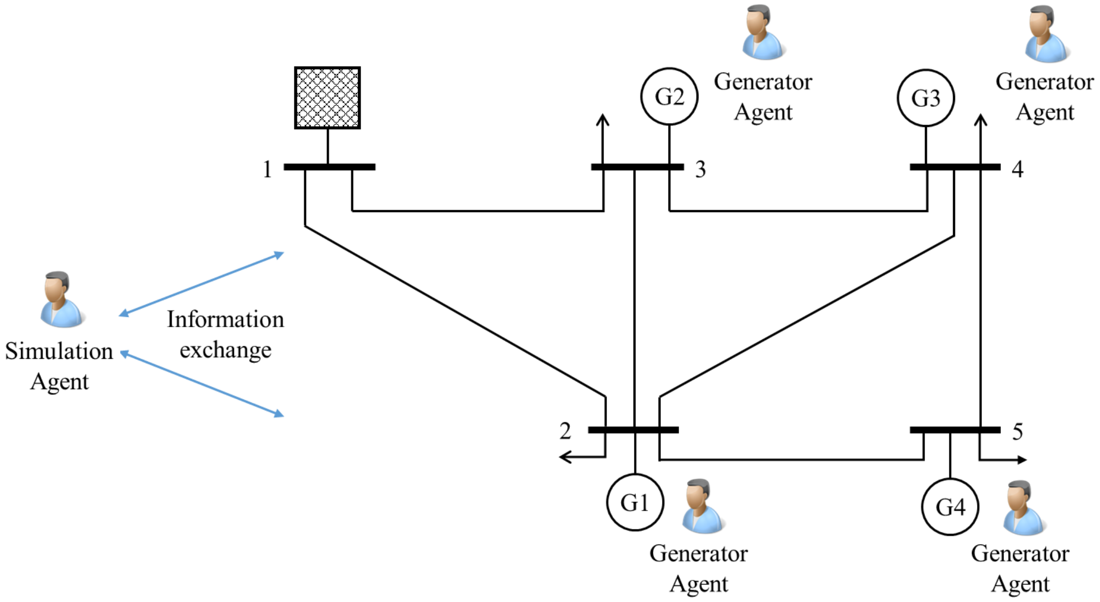


Figure 5.9 Network selected for simulations

Three scenarios are introduced to show the functionality of the system presented:

- Scenario 1: Voltage set point equals 1 p.u. For that, the amount of Q required will be calculated to achieve the voltage set point desired. Additionally, one of the generators has its reactive power provision limited, which is insufficient to recover stable system operation. In this case, another unit will support in the voltage control process.
- Scenario 2: Voltage set point equals 1 p.u. The GAs provide Q according to the limit of maximal/minimal generation. All units have a limited reactive power generation capacity, which results in the inability to reach a stable system operation in the first iteration. The voltage set point in each iteration will be decreased to allow each agent to participate in the voltage control.
- Scenario 3: In this case, in comparison to the previous scenarios, more than two generators will provide reactive power. During the control process, the theoretical voltage at the bus is calculated based on the amount of reactive power provided. If the voltage value lies within permissible ranges, set points are passed to the SA and a load flow calculation is performed.

Scenario 1

In this scenario, the voltage problem occurs at bus 4. The amount of reactive power required is calculated according to the voltage set point at 1 p.u. Table 5.3 shows the reactive power limitation assigned to each generator and Table 5.4 outlines the results of reactive power provision. Figure 5.10 presents the voltages for each node in the system. After providing reactive power, the overvoltage is alleviated and the system stability is recovered. Figure 5.11 shows the interactions between agents during the current scenario. Since generator 4 has its reactive power generation limited to ± 2 Mvar, it was insufficient to bring the voltage to the permissible level. The support of generator 3 solves the overvoltage. The resulting voltage value at bus 4 after remedial actions is 1.086 p.u.

Table 5.3 Reactive power limits

Reactive power limits in MVar			
Generator 1	**Generator 2**	**Generator 3**	**Generator 4**
± 11	± 11	± 11	± 2

Table 5.4 Set points calculated

Generator set points in MVar			
Generator 1	**Generator 2**	**Generator 3**	**Generator 4**
0	0	-10.44	-2.00

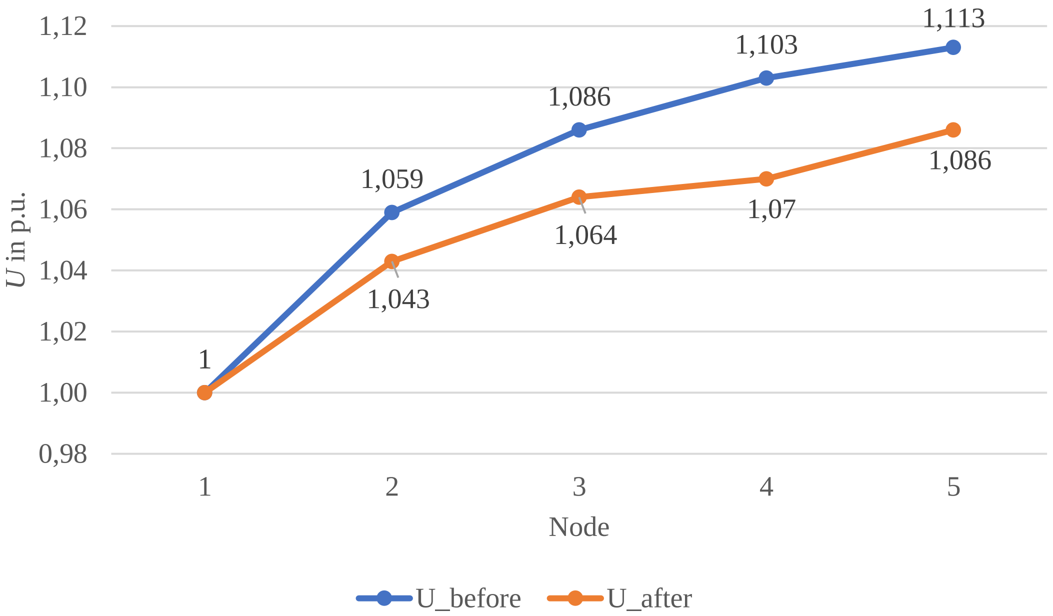


Figure 5.10 Voltage profile for scenario 1

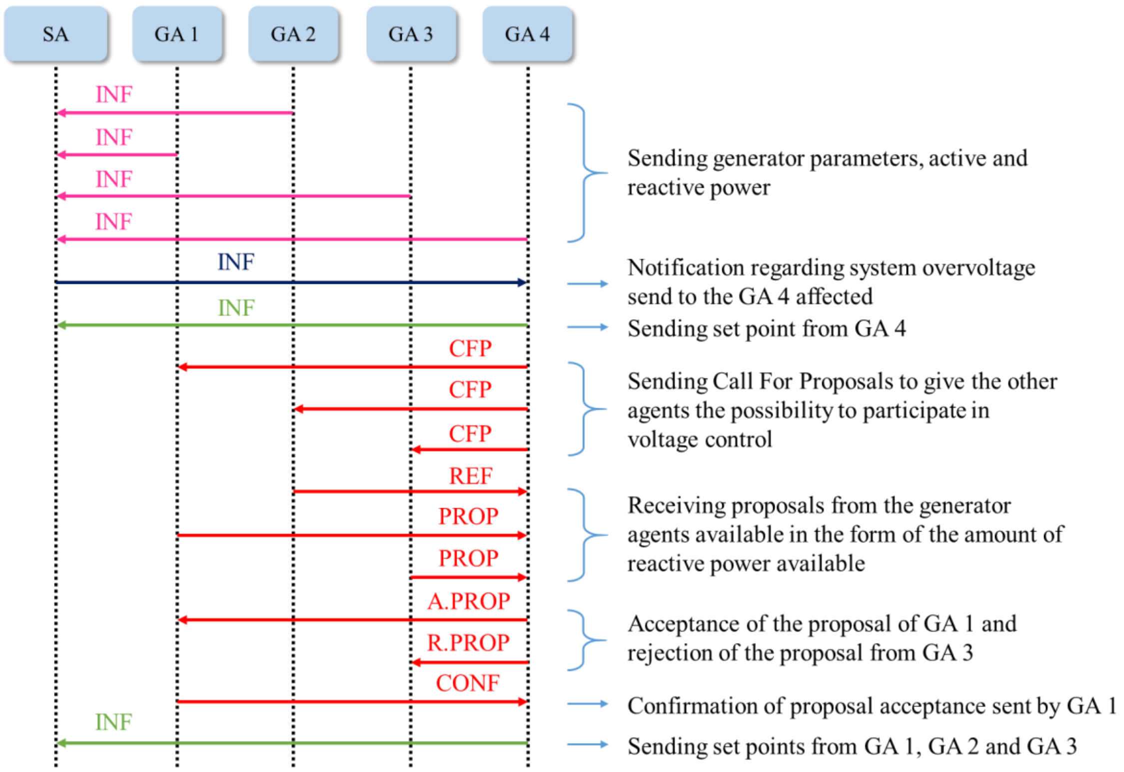


Figure 5.11 Sequence diagram for scenario 1

Scenario 2

In the second scenario, the limitation of generation possibilities has been imposed (see Table 5.5). Since the generation capabilities of generation 4 were not sufficient to recover voltage to the permissible limits, GA 4 initiated interactions with other agents providing support in voltage control. Based on sensitivity factors, the appropriate amounts of reactive power are calculated by the other agents and send as proposals to GA 4. After receiving all proposals, the minimal value of reactive power is selected. At the end, set points generated by GA 4 and GA 1 are passed to the SA to check the influence of the new working point on the network operation. Interactions between agents in the frame of this scenario are shown in Figure 5.14. The final amounts of reactive power provided by generators are shown in Table 5.6. The voltage profile obtained after the management process is presented in Figure 5.12. Additionally, Figure 5.13 shows the proposals sent by each generator in each iteration. With the increase of the voltage set point, the amount of reactive power proposed decreases. If the value of reactive power calculated is within the permissible generation range, it is sent as a proposal to the agent requiring control support.

As in the previous case, the GA affected by the voltage problem initiates interactions between agents. After sending CFP messages, the GA is expecting proposals in the form of possible reactive power provisions from other agents. The GA waits for proposals a certain amount of time. After this time is expired, the reception of messages is closed and the process of voltage control is performed further only considering the proposals received. The results obtained depend on the number of proposals received, which translates into the number of agents participating at a given point in the management process. At the beginning of the simulation, the voltage set point is 1 p.u. If the proposals are insufficient to remedy the voltage problem, the voltage set point is increased by the value of + 0.1 p.u. This results in decreasing the difference between the overvoltage value and the new voltage set point. After the notification regarding the new set point has been sent, the GA is expecting new proposals with possible amounts of reactive power. The process is repeated until at least one proposal is received.

Table 5.5 Reactive power limits

Reactive power limits in MVar			
Generator 1	**Generator 2**	**Generator 3**	**Generator 4**
± 15	± 15	± 15	± 2

Table 5.6 Set points calculated

Generator set points in MVar			
Generator 1	**Generator 2**	**Generator 3**	**Generator 4**
0	0	-13.92	-2.00

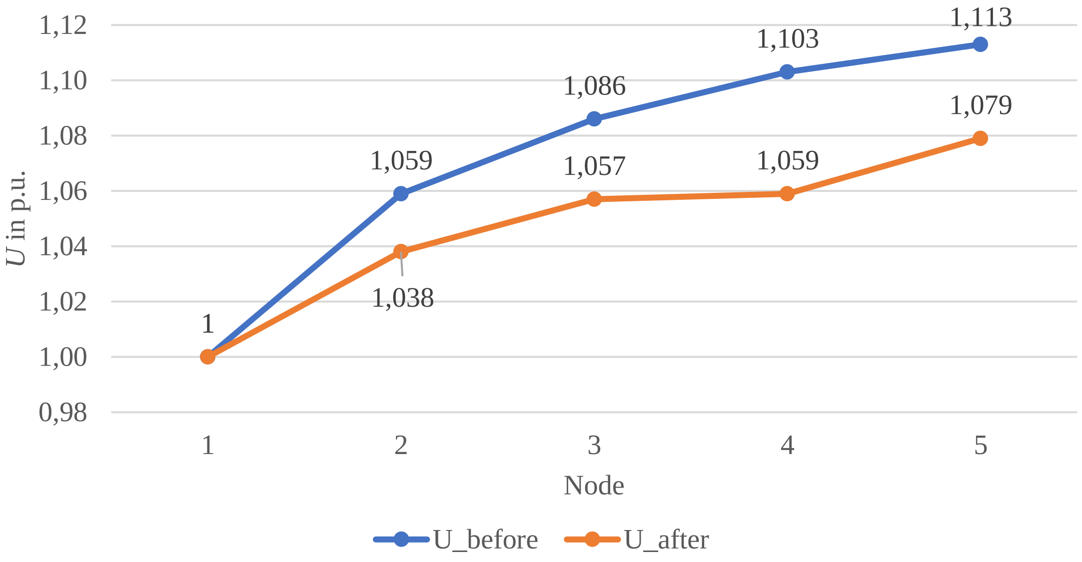


Figure 5.12 Voltage profile in the second scenario

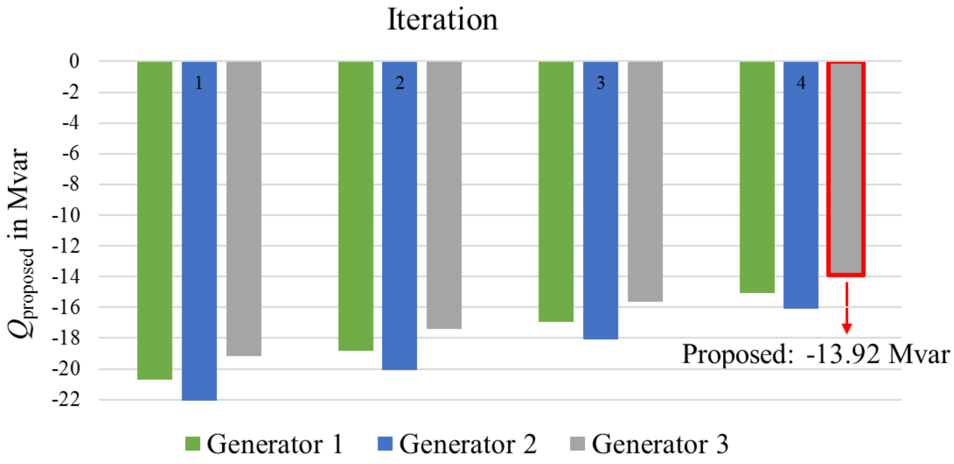


Figure 5.13 Reactive power calculated in each iteration

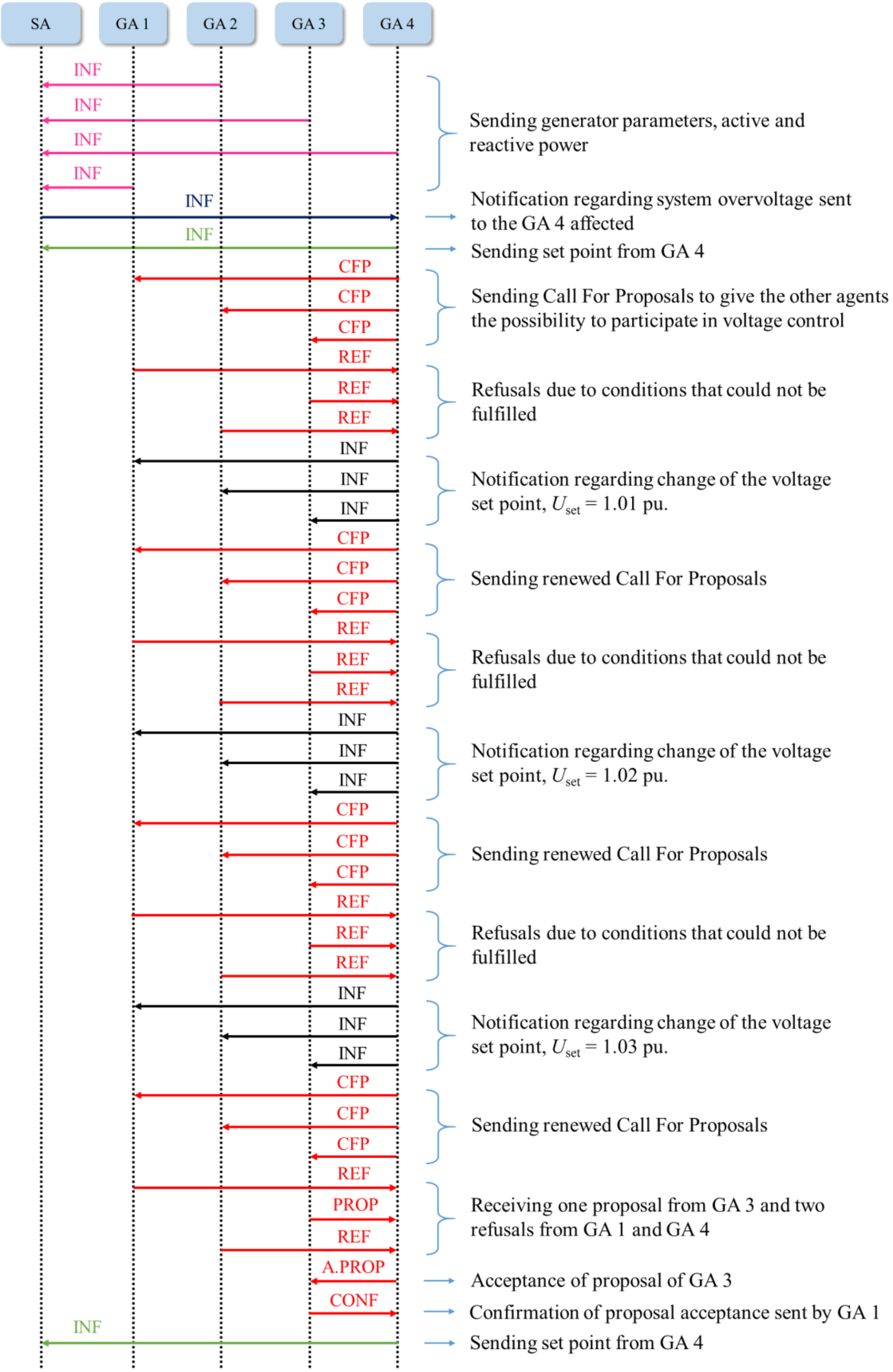


Figure 5.14 Sequence diagram for scenario 2

Scenario 3

In this scenario, all generators have a limited possibility of reactive power provision. Table 5.7 shows the initial simulation conditions assumed. Similar to previous cases, GA 4 initiates the voltage control process. Since reactive power generation capabilities of the GA 4 are limited, other GAs are called on for support in voltage control. In this case, in turn, generation limitations do not allow the selection of only one generator who can support the management process. Due to the relatively strong limitation of reactive power generation capabilities of the remaining power units, all generators are selected to provide available reactive power. The selection process chooses generators starting from the one who proposes the smallest amount of reactive power. The theoretical voltage value is calculated in each internal iteration, under the amount of reactive power available, until it lies within the range permissible. If the voltage value is between the limits assumed, agents affected by the voltage violation send confirmations to the other GA whose proposals of reactive power has been accepted. The set points accepted are presented in Table 5.8.

Table 5.7 Reactive power limits

Reactive power limits in MVar			
Generator 1	**Generator 2**	**Generator 3**	**Generator 4**
± 1	± 2	± 3	± 1

Table 5.8 Set points calculated

Generator set points in MVar			
Generator 1	**Generator 2**	**Generator 3**	**Generator 4**
-1	-2	-3	-1

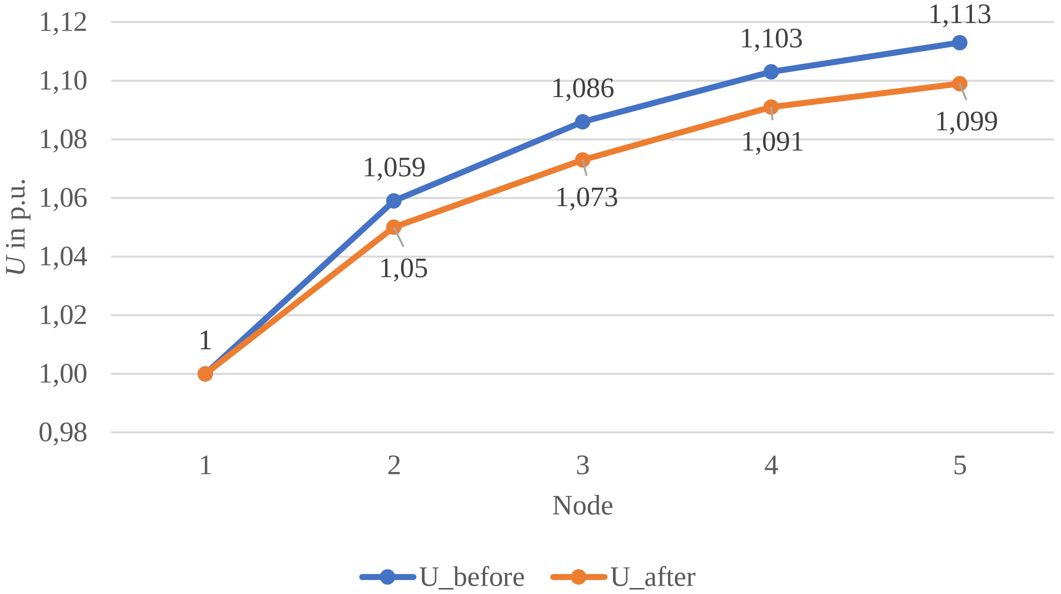


Figure 5.15 Voltage profile for scenario 3

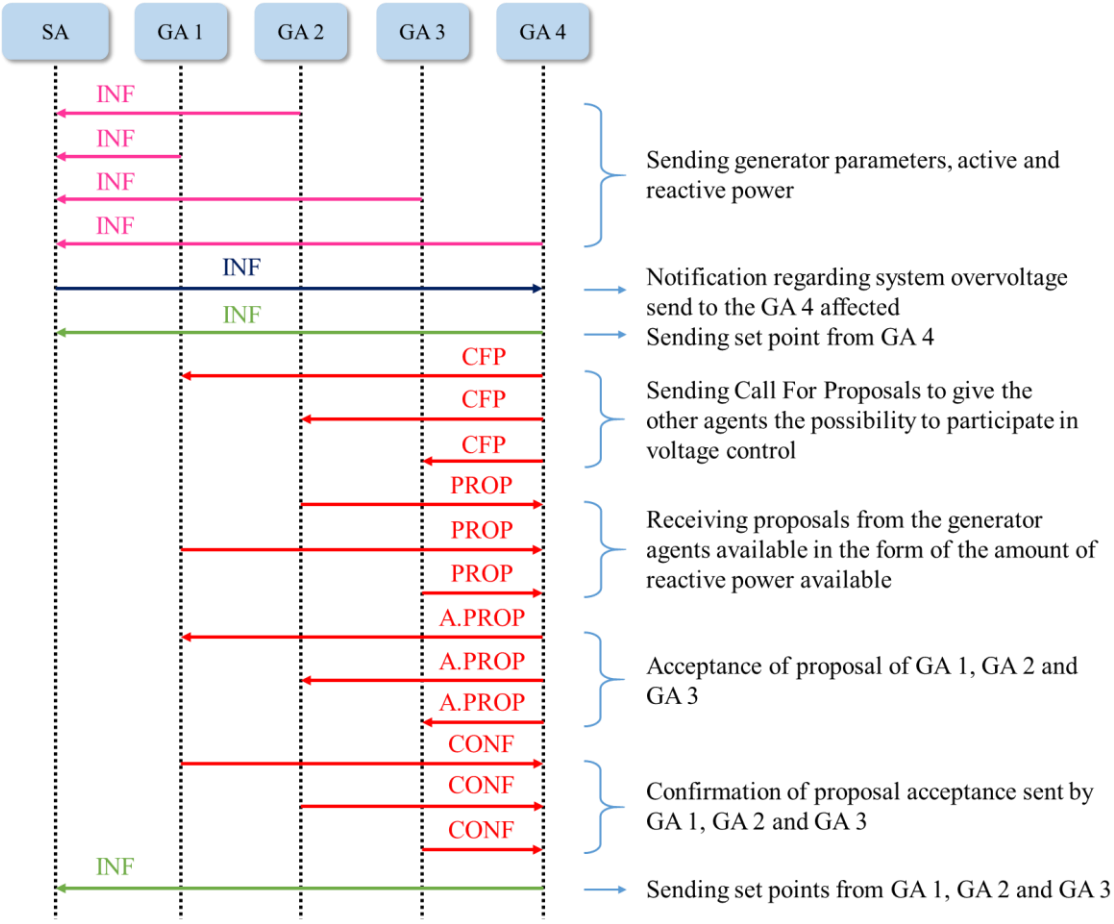


Figure 5.16 Sequence diagram for scenario 3

5.8 Treatment of potential failures

Appropriate treatment needs to be performed to ensure continuous system operation. Additional actions, including information rerouting and a renewed request for data required constitutes scheme proposals, which can be considered in such MASs where voltage control is the prior management task. Possible operation failures are presented in Table 5.9. In the possible failures enumerated, an outage of one or more GAs at the beginning of the management process can be considered. Certain requirements on the number of agents available, however, determine the successful performance of the management processes. This encompasses not only voltage control, but also different operational processes, such as redispatch or grid restoration. The certain minimal number of agents will generally be required to fulfill the tasks desired. Depending on the system complexity and functions performed, in the case of insufficient or no information exchange, the functionality of fully autonomous systems can be threatened. Figure 5.17 presents illustratively the sequence diagram of potential failures that can occur during the voltage control process proposed.

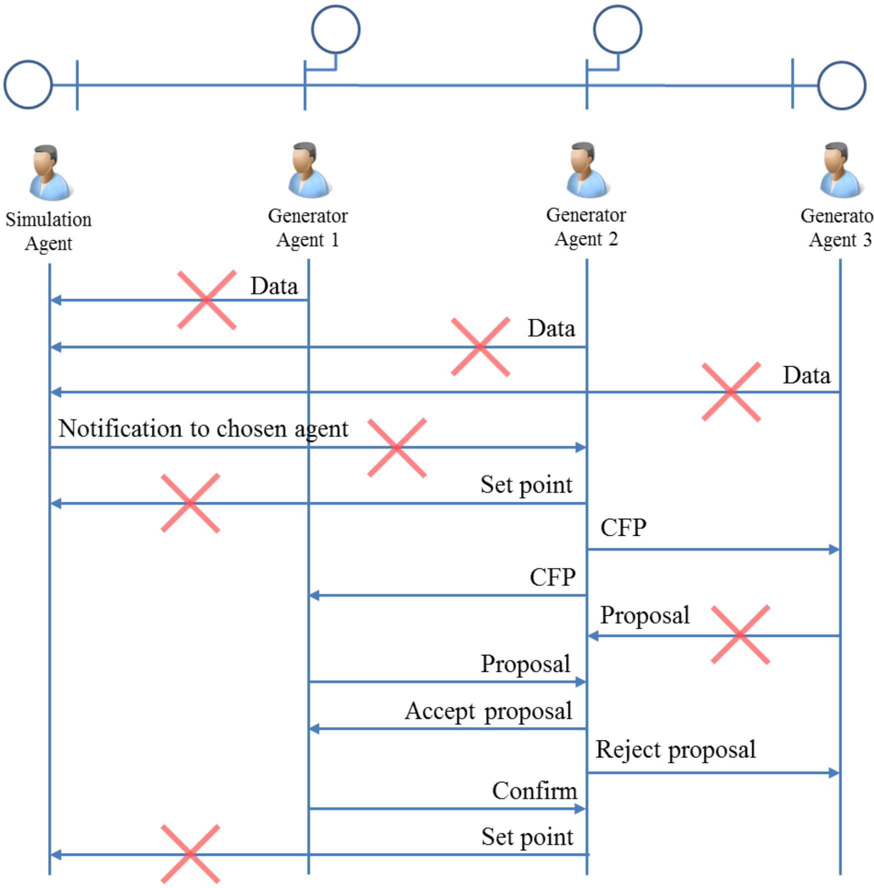


Figure 5.17 Illustration of potential failures that can occur in the voltage control process proposed

Table 5.9 Potential failures during voltage control process

Failure	**Treatment**
Failure during the passage of new set points - GA set point failure	If uncertain set points (appropriate assessment algorithm required) are received – the renewed request for providing set points is sent
	If wrong/uncertain information is still sent after a certain amount of time or number of inquiries, the receiving agent sends a notification to the other GAs
Unavailability of one GA – no response to CPF (communication or agent failure)	If at least one GA is available, an attempt to control the voltage is performed
	If there is no communication with at least one GA – the voltage control is not completed – the notification to the SA is sent
SA data misinterpretation – receiving of incorrect/uncertain set point values	If uncertain set points are received – the renewed request for providing set points is sent
	If wrong/uncertain information is still sent after a certain amount of time or number of inquiries, the SA sends a notification to other the GAs
Inability to recognize other agents in the system	By the SA: If no GA has been detected, the voltage control is interrupted (another possibility of voltage control needs to be performed, for instance, through load control)
	If at least one of the GAs has been detected, the SA performs an attempt of voltage control. In this case, negotiations among other GAs are inactive if there is only one GA available
	If reactive power is insufficient to improve the voltage situation in the system, a notification to the SA is sent with a proposal of a different control strategy
	By the GA: If only one GA is available in the system, voltage control is performed with the only GA available
	By the GA: If the communication between one or more agents cannot be established during negotiations, the control strategy is as above
	By the GA: If there is no communication with the SA, messages are sent cyclically and, after a

Failure	Treatment
	specified period of time or number of messages sent, notification is sent to the GAs available
SA failure – resulting in the inability to perform load flow calculations or misinterpretation of data received occurs	The need for a GAs organization to calculate load flow independently (distributed load flow calculation)

5.9 Incorporation of active power in voltage control

In the case of low-voltage networks, the relation between resistance and reactance allows to consider active power in voltage control. An increased share of resistance in medium and low-voltage networks in comparison to high-voltage networks provide a possibility of using a stronger relation between changes in active power and, resulting from that, changes in voltage. The concept of the control mechanism is shown in Figure 5.18 and the idea of a control scheme according to voltage infringements is presented in Table 5.10.

Table 5.10 Alternative voltage control mechanism [75]

Condition	Action
$U > U_{\text{max}}$	Decrease Q, if Q_{min} reached, then decrease P
$U < U_{\text{min}}$	Increase P, if P_{max} reached, then increase Q

Availability of active and reactive power of the generating unit is checked in the approach considered. Taking into account the economic aspects, depending on the sign of the voltage deviation, an attempt is made to maximize the generation of active power. Active power is controlled to improve the power factor in cases where an increase of the voltage is required. When there is a need to reduce the voltage, reactive power is adjusted, while maintaining the highest possible active power generation. New set points for active and reactive power are calculated based on the sensitivity coefficients and depending on the current operating point and system parameters. If the limit of generation is reached, the maximum possible value is accepted as the new set point [75].

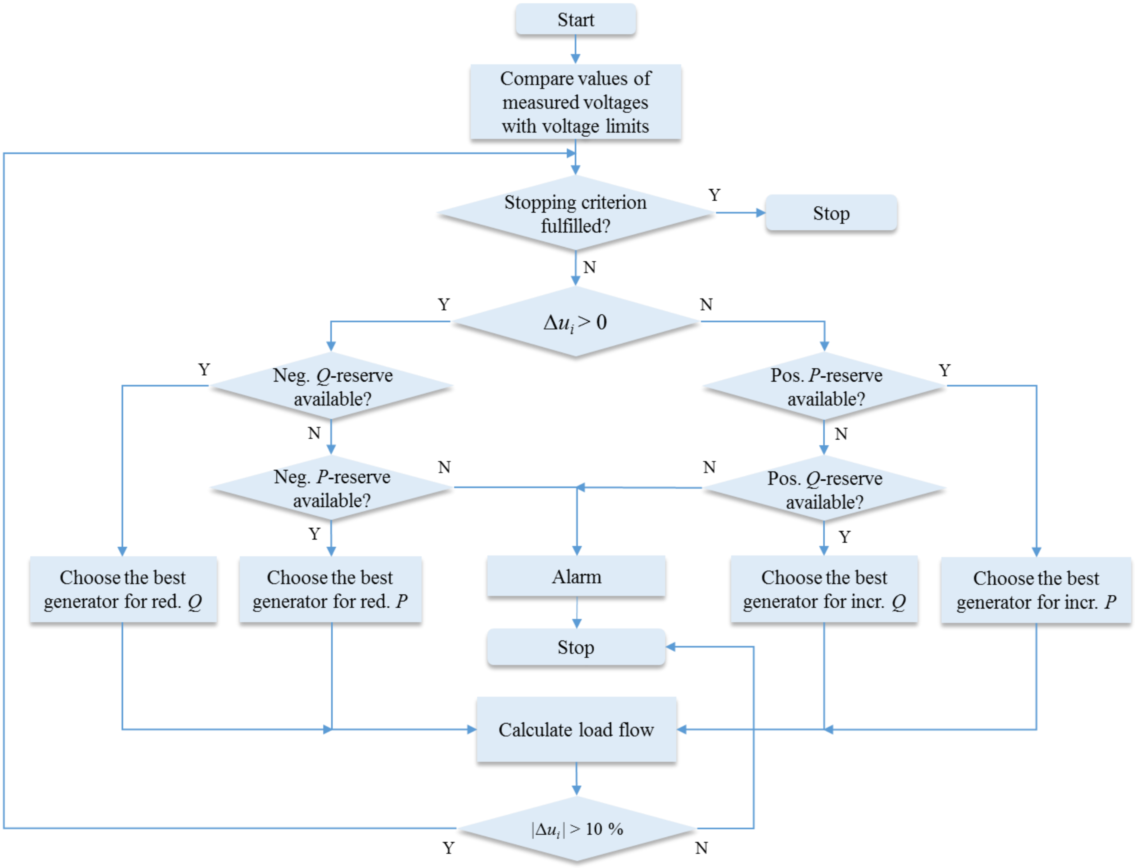


Figure 5.18 Voltage control mechanism incorporating adjustment of active power [75]

6 Agent-based congestion management

Redispatch measures are used to alleviate the congestion in the agent-based congestion management proposed. The redispatch selects power plant pairs that change their schedule over a defined time. The power generation of the power plants before the congestion (on the surplus side) is reduced and the power on the deficit side is increased. This can be illustrated by the simplified example from Figure 2.6. If the power to be transmitted is too high, the line can be relieved by the generation adjustments of power plants. The power of the generator is regulated until the (*n*-1) criterion is fulfilled again.

6.1 Sensitivity analysis

The network operator must select the most suitable power plants to realize an effective redispatch. Consequently, an appropriate calculation of the sensitivity analysis has to be carried out. Since increasing and decreasing of the generation level is considered in the process of redispatch, corresponding positive and negative sensitivity coefficients of the particular nodes must be found using the methods for sensitivity analysis chosen. The active power change P_{red} of the power plants, which must be realized to eliminate the congestion, can be determined by using sensitivity coefficients [49], [76]:

$$P_{\text{red,dec}} \cdot \eta_{\text{dec}} + P_{\text{red,inc}} \cdot \eta_{\text{inc}} = P_{\text{overload}} \tag{6.1}$$

where:

$\eta_{\text{dec},}\ \eta_{\text{inc}}$ – sensitivity coefficients corresponding to downward and upward adjustment of active power, respectively,
$P_{\text{red,dec}}$, $P_{\text{red,inc}}$ – downward and upward redispatch power and
P_{overload} – value of line overload.

When a power plant reaches its technical limit during the redispatch, the power plant with the next suitable coefficient is selected. The selection of generators will be continued until the congestion is alleviated [78]:

$$\sum P_{\text{red,dec}} \cdot \eta_{\text{dec}} + \sum P_{\text{red,inc}} \cdot \eta_{\text{inc}} = P_{\text{overload}} \tag{6.2}$$

The equation described above in the matrix formulation has the following form:

$$\begin{bmatrix} \eta_{\text{dec}} & \eta_{\text{inc}} \\ 1 & 1 \end{bmatrix} \begin{bmatrix} P_{\text{red,dec}} \\ P_{\text{red,inc}} \end{bmatrix} = \begin{bmatrix} P_{\text{overload}} \\ 0 \end{bmatrix} \tag{6.3}$$

The amount of reactive power that needs to be increased and decreased by generators should be the same:

$$P_{\mathrm{red,dec}} = -P_{\mathrm{red,inc}} \tag{6.4}$$

Since the power that needs to be reduced by one generator and is increased by another, this results in a general formula that can be used to calculate the power adjustment required:

$$P_{\mathrm{red,inc}} = \frac{P_{\mathrm{overload}}}{\eta_{\mathrm{inc}} - \eta_{\mathrm{dec}}} \tag{6.5}$$

One of the methodologies is the calculation of Power Transfer Distribution Factors representing a variation of the active power flows on the lines examined, which are the consequence of generation or load changes in a specific node of the network [77]. Another methodology related to sensitivity theory is Power Flow Decomposition (PFD) allowing the decoupling of active power components from reactive power parts. The PFD method observes the effects of, for example, switching states, load and active generation pattern, and nodal reactive power, that have a huge influence on the nodal power injection sensitivity. The way in which PFD linearizes the quadratic power flow equations does not leave any system operation points. An invertible nodal Jacobian matrix $\boldsymbol{J}_{\mathrm{KK}}$ is used in PFD [49], [78], [79].

Based on the power flow calculation, nodal currents $\underline{\boldsymbol{i}}_{\mathrm{K}}$ can be written by equation (6.6):

$$\underline{\boldsymbol{i}}_{\mathrm{K}} = \underline{\boldsymbol{Y}}_{\mathrm{KK}} \cdot \underline{\boldsymbol{u}}_{\mathrm{K}} \tag{6.6}$$

where:

$\underline{\boldsymbol{Y}}_{\mathrm{KK}}$ – bus admittance matrix and
$\underline{\boldsymbol{u}}_{\mathrm{K}}$ – nodal voltage vector.

Nodal currents can be shown as the sum of the load $\underline{\boldsymbol{i}}_{\mathrm{K,L}}$ and generator $\underline{\boldsymbol{i}}_{\mathrm{K,G}}$ currents by equation (6.7) [78]:

$$\underline{\boldsymbol{Y}}_{\mathrm{KK}} \cdot \underline{\boldsymbol{u}}_{\mathrm{K}} = \underline{\boldsymbol{i}}_{\mathrm{K}} = \underline{\boldsymbol{i}}_{\mathrm{K,L}} + \underline{\boldsymbol{i}}_{\mathrm{K,G}} = \underline{\boldsymbol{Y}}_{\mathrm{K,L}} \cdot \underline{\boldsymbol{u}}_{\mathrm{K}} + \underline{\boldsymbol{i}}_{\mathrm{K,G}} \tag{6.7}$$

Equation (6.7) can be rewritten and the nodal admittance matrix $\underline{\boldsymbol{Y}}_{\mathrm{K,L}}$ for loads can be easily subtracted from $\underline{\boldsymbol{Y}}_{\mathrm{KK}}$ by the following equation (6.8) [78]:

$$\left(\underline{\boldsymbol{Y}}_{\mathrm{KK}} - \underline{\boldsymbol{Y}}_{\mathrm{K,L}}\right) \cdot \underline{\boldsymbol{u}}_{\mathrm{K}} = \underline{\boldsymbol{i}}_{\mathrm{K,G}} \tag{6.8}$$

Therefore, the new nodal admittance matrix $\underline{\boldsymbol{Y}}_{\mathrm{KK,L}}$, which is based on generating currents, can be calculated by equation (6.9) [78]:

$$\underline{\boldsymbol{Y}}_{\mathrm{KK}} - \underline{\boldsymbol{Y}}_{\mathrm{K,L}} = \underline{\boldsymbol{Y}}_{\mathrm{KK,L}} \tag{6.9}$$

The nodal apparent power flow $\underline{\boldsymbol{s}}_{K}$ can be established by the following equation (6.10) [78]:

$$\underline{\boldsymbol{s}}_{\mathrm{K}} = 3 \cdot \underline{\boldsymbol{U}}_{\mathrm{K}} \cdot \underline{\boldsymbol{i}}_{\mathrm{K}}^{*} = 3 \cdot \underline{\boldsymbol{U}}_{\mathrm{K}} \cdot \underline{\boldsymbol{Y}}_{\mathrm{KK}}^{*} \cdot \underline{\boldsymbol{u}}_{\mathrm{K}}^{*} \tag{6.10}$$

Using Taylor series expansion, the change in the active and reactive powers can be calculated by the nodal Jacobian matrix $\boldsymbol{J}_{\mathrm{KK,L}}$, given by the equation (6.11) [78]:

$$\begin{bmatrix} \Delta \boldsymbol{p}_{\mathrm{K,G}} \\ \Delta \boldsymbol{q}_{\mathrm{K,G}} \end{bmatrix} = \boldsymbol{J}_{\mathrm{KK,L}} \cdot \begin{bmatrix} \Delta \boldsymbol{\delta}_{\mathrm{K}} \\ \Delta \boldsymbol{u}_{\mathrm{K}} \end{bmatrix} \tag{6.11}$$

$\underline{\boldsymbol{Y}}_{\mathrm{KK,L}}$ is used in the PFD method to invert the nodal Jacobian matrix $\boldsymbol{J}_{\mathrm{KK,L}}$. The change in the terminal active and reactive powers depending on the terminal voltage changes can be calculated by the following equation (6.12) [78]:

$$\begin{bmatrix} \Delta \boldsymbol{p}_{\mathrm{T}} \\ \Delta \boldsymbol{q}_{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial \Delta \boldsymbol{p}_{\mathrm{T}}}{\partial \Delta \boldsymbol{\delta}_{\mathrm{T}}^{\mathrm{T}}} & \dfrac{\partial \Delta \boldsymbol{p}_{\mathrm{T}}}{\partial \Delta \boldsymbol{u}_{\mathrm{T}}^{\mathrm{T}}} \\ \dfrac{\partial \Delta \boldsymbol{q}_{\mathrm{T}}}{\partial \Delta \boldsymbol{\delta}_{\mathrm{T}}^{\mathrm{T}}} & \dfrac{\partial \Delta \boldsymbol{q}_{\mathrm{T}}}{\partial \Delta \boldsymbol{u}_{\mathrm{T}}^{\mathrm{T}}} \end{bmatrix} \cdot \begin{bmatrix} \Delta \boldsymbol{\delta}_{\mathrm{T}} \\ \Delta \boldsymbol{u}_{\mathrm{T}} \end{bmatrix} = \boldsymbol{J}_{\mathrm{T}} \cdot \begin{bmatrix} \Delta \boldsymbol{\delta}_{\mathrm{T}} \\ \Delta \boldsymbol{u}_{\mathrm{T}} \end{bmatrix} \tag{6.12}$$

The terminal currents $\underline{\boldsymbol{i}}_{\mathrm{T}}$ can be found using a transposed topological matrix $\boldsymbol{K}_{\mathrm{KT}}^{\mathrm{T}}$ by the equation (6.13) [78]:

$$\underline{\boldsymbol{i}}_{\mathrm{T}} = \underline{\boldsymbol{Y}}_{\mathrm{T}} \cdot \underline{\boldsymbol{u}}_{\mathrm{T}} = \underline{\boldsymbol{Y}}_{\mathrm{T}} \cdot \boldsymbol{K}_{\mathrm{KT}}^{\mathrm{T}} \cdot \underline{\boldsymbol{u}}_{\mathrm{K}} \tag{6.13}$$

The terminal power changes considering equation (6.13) can be found as follows by equation (6.14) [49]:

$$\begin{bmatrix} \Delta \boldsymbol{p}_{\mathrm{T}} \\ \Delta \boldsymbol{q}_{\mathrm{T}} \end{bmatrix} = \boldsymbol{J}_{\mathrm{T}} \cdot \begin{bmatrix} \boldsymbol{K}_{\mathrm{KT}} & \\ & \boldsymbol{K}_{\mathrm{KT}} \end{bmatrix}^{\mathrm{T}} \cdot \begin{bmatrix} \Delta \boldsymbol{\delta}_{\mathrm{T}} \\ \Delta \boldsymbol{u}_{\mathrm{T}} \end{bmatrix} = \boldsymbol{J}_{\mathrm{T}} \cdot \begin{bmatrix} \boldsymbol{K}_{\mathrm{KT}} & \\ & \boldsymbol{K}_{\mathrm{KT}} \end{bmatrix}^{\mathrm{T}} \cdot \boldsymbol{J}_{\mathrm{KK,L}}^{-1} \begin{bmatrix} \Delta \boldsymbol{p}_{\mathrm{K,G}} \\ \Delta \boldsymbol{q}_{\mathrm{K,G}} \end{bmatrix} \tag{6.14}$$

The redispatch model established is used by the TSOs only to shift active power injection. The invertible Nodal Jacobian Matrix $\boldsymbol{J}_{\mathrm{KK}}$ is used with the full nodal admittance matrix $\underline{\boldsymbol{Y}}_{\mathrm{KK}}$ in PFD [78], [79].

6.2 Generation Merit Order

The redispatch power by which generation needs to be increased, also considered as positive redispatch power, is ensured by the production increase and can only be performed by generation units that are either in standby mode or are partially loaded. Thus, the upward redispatch at a specific point in time constitutes the maximum amount of power equal to the capacity of the power plant available decreased by the capacity already deployed minus the capacity reserved for frequency control. Therefore, the amount of positive redispatch power is equal to the capacities available which are neither deployed nor reserved. In turn, downward redispatch or negative redispatch power indicates a production decrease and can only be performed by generation units that are fully or partially loaded. The illustrative representation of generation ranges for coal power plant is shown in Figure 6.1.

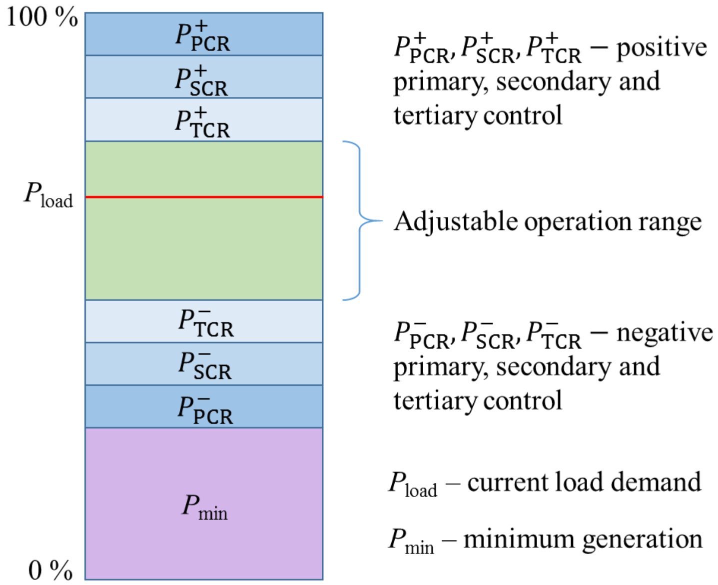


Figure 6.1 Illustration of generation ranges of a coal power plant [80]

Considering the redispatch process from a technical point of view, a possible influence and effectivity of generation adjustments on the congestion needs to be analyzed. A different location of generators in the system turns into different sensitivities or impacts of those generators on corresponding lines. An additional order of generators, which is a combination of generation actual cost and sensitivity, is considered to perform the redispatch which will be efficient from the technical and economical point of view. The new merit order merging these two factors is determined by the following formula:

$$M = \frac{C}{\eta} \tag{6.15}$$

where:

M – new merit order,
C – generation costs and
η – sensitivity factor.

Based on that, the lower the sensitivity factor of a generator, the higher the merit order value. This value will change depending on the present production costs. Table 6.2 presents costs of the power proposed by a few generators together with their sensitivity factor describing the impact of the generation change on the given line. Regarding the illustration, a certain load demand is assumed to differentiate between the positive and negative redispatch power mentioned previously. The merit order considering only costs and, additionally, generator sensitivities under consideration is presented in Figure 6.2.

Table 6.1 Example data

	Gen 1	**Gen 2**	**Gen 3**	**Gen 4**	**Gen 5**
Bid in €	10	20	30	40	50
Power in MW	20	20	20	20	20
Sens factor	0.1	0.25	0.2	0.15	0.4
New merit in €	100	80	150	266.7	125

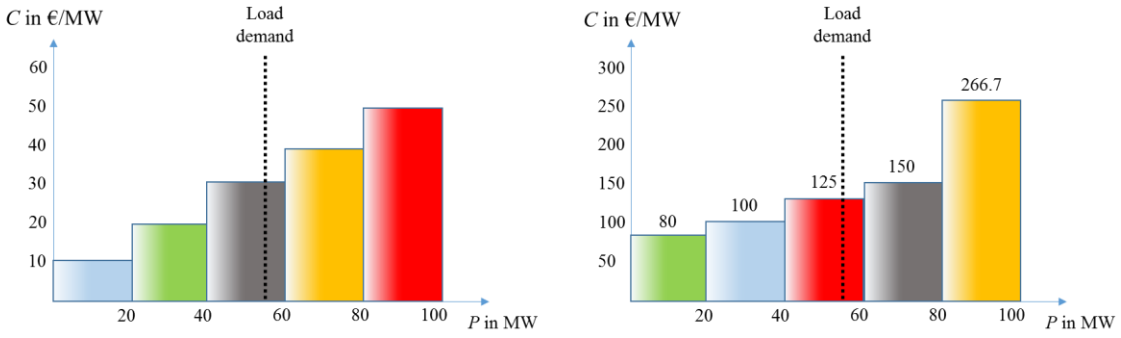


Figure 6.2 Merit order based on generation price (left) and considering sensitivity coefficients (right)

According to equation (6.15), the primary merit order is changing and represents the new ranking of generation units. Based on that, a decision can be made regarding which generator should be chosen to alleviate the congestion. Table 6.2 shows the matrix with sensitivity coefficients. Columns corresponds to generators having a certain influence on a particular line (rows).

Table 6.2 Example illustration of sensitivity matrix

	Generator 1	**Generator 2**	**Generator 3**
Line 1	$\eta_{1,1}$	$\eta_{2,1}$	$\eta_{3,1}$
Line 2	$\eta_{1,2}$	$\eta_{2,2}$	$\eta_{3,2}$
Line 3	$\eta_{1,3}$	$\eta_{2,3}$	$\eta_{3,3}$

When a generator is unavailable or a possible amount of active power provided has been deployed, a new generator needs to be found to replenish the demand for redispatch power. This, however, translates into different sensitivity coefficients, which reflect a weaker impact on the overloaded line considered. In this case, if the next generator is chosen to provide support by redispatch, its power needs to be adjusted according to its location, represented by the sensitivity factor. The correction of the active power set point proposed is based on the difference between the primary generator chosen for redispatch and subsequent generators selected according to a given merit order. Based on Table 6.2, if generator 1 cannot provide more active power resulting from its generation capacity and assuming that generator 2 has been chosen to support the redispatch process, the corrected active power provision by generator 2 is then computed using the following formula:

$$P_{\text{set,new}} = P_{\text{gen}} + P_{\text{gen}} \cdot \frac{\eta_1}{\eta_2} \tag{6.16}$$

where:

$P_{\text{set,new}}$ – corrected active power set point,
P_{gen} – initially calculated active power set point of supporting unit and
η_1, η_2 – sensitivity factor of generator 1 and 2, respectively.

The difference between sensitivity factors compensates for the location of the next generator chosen. This newly calculated power is then accepted by the corresponding GA who is responsible for the set point execution.

Several assumptions have been made during the system implementation. The following points outline the main features of the MAS proposed:

- Agents solve the problem in a decentralized manner, which means that there is no managing agent coordinating system operation;
- one agent is responsible for performing load flow calculations to check the influence of new set points on the power system and is not involved in the control and decision process;
- new set points are determined by GAs through information exchange;
- agents have access to functions in Matlab, which allow the calculation of the parameters required, such as active power set points;

- each agent can initiate only one Matlab session allowing access to the computation environment;
- agent interactions take place in asynchronous way (there is no coordinating agent), however, a decision is made after fulfilling appropriate conditions, such as the number of messages received; and
- decisions regarding the determination of set points depends on the strategy proposed (only sensitivity coefficients, only generation costs, consideration of generation costs and sensitivity coefficients). Strategies are not connected with each other and the system proposed constitutes the reference model for a possible design of a MAS.

6.3 Structure of the multi-agent system

Similar to the case of the agent-based voltage control presented previously, the system proposed consists of two layers. The functionalities of the network and the decision layer are the same. The information exchange is realized through the interface, enabling the connection of the two simulation environments mentioned. The structure of the MAS proposed is presented in Figure 6.3. The system contains three types of agents: The SA performing load flow calculation and notifying Line Agents (LiAs) about line overload, LiAs notifying generators to perform redispatch and GAs interacting with each other to find active power set points.

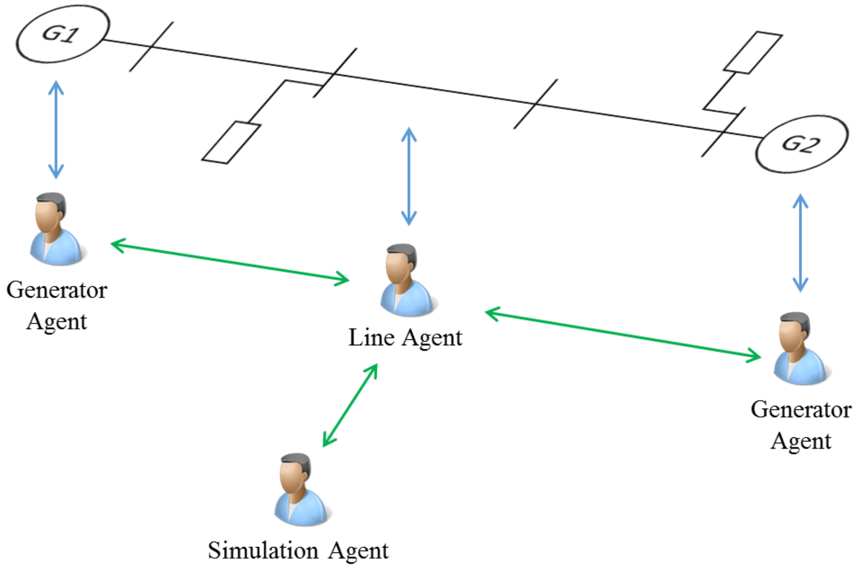


Figure 6.3 MAS structure

6.4 Modeling of information flow

Information flow in the system proposed can be modeled in different ways. The chosen approach depends on the assumptions developed. Two approaches of information can be presented since the agent-based system is intended to be autonomous and should operate in a decentralized manner. The difference between these two systems lies in information exchange between the LiA, GA and SA. The information flow schemes considered are presented in Figure 6.4 and Figure 6.5.

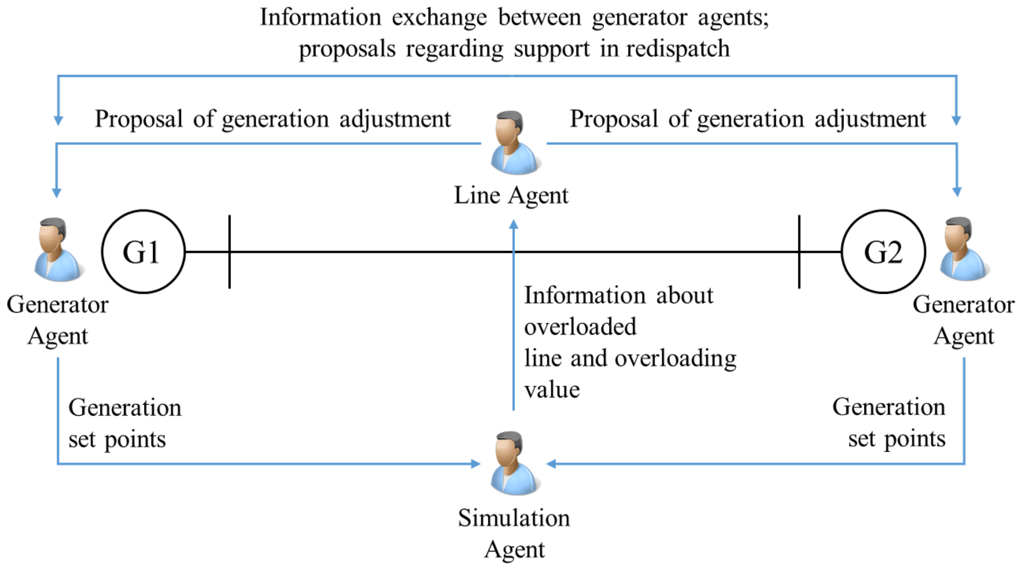


Figure 6.4 Information flow assuming a “less decentralized” approach

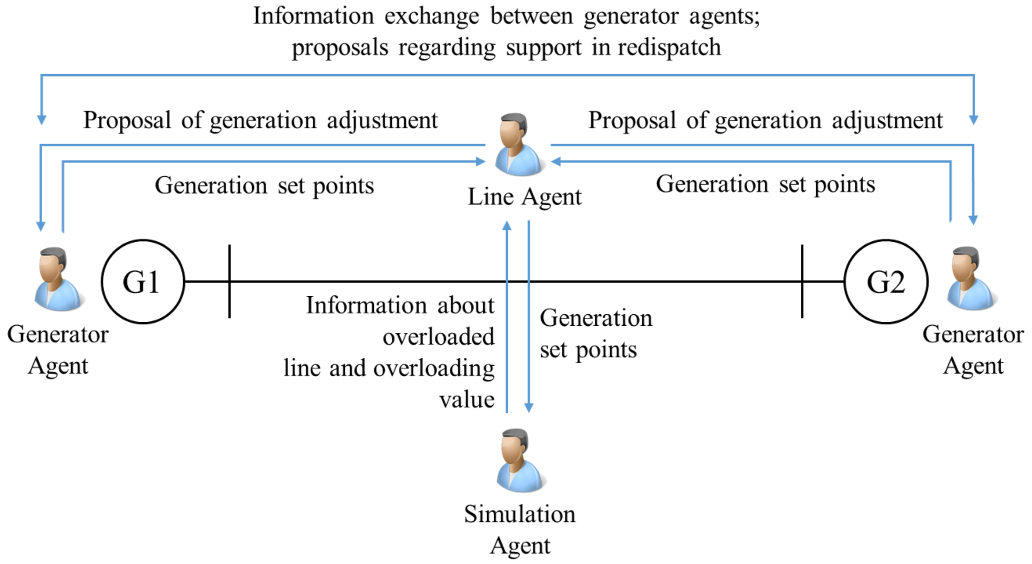


Figure 6.5 Information flow assuming a “more decentralized” approach

In the first solution, the SA is connected to three agents enabling the passing of set points to the SA. The GAs are responsible for sending new set points to the SA. Regarding more complex networks, communication between the SA and each GA needs to be established. Loss of one of the communication links leads to incomplete data gathering. One of the solutions in this case would be deploying another GA who can take over the new set point from another GA and then pass results on to the SA. In the second solution, the number of communication links with the SA is limited to communication only with the LiAs. In such a configuration, the new set points of generators are passed to the LiA and are then sent to the SA.

6.5 Technically economical optimization

After the information exchange between the GAs is completed, each GA creates an order of generation units based on the strategy assumed. Based on the merit order determined, agents who received the notification from the LiA regarding line overload selects other GAs who will be more suitable to perform the redispatch. In this case, the downward GA selects units, whose decreasing of power will contribute to the lowest costs. In turn, the upward GA chooses the unit, whose increasing of generation will be the least cost intensive. The representation of the idea mentioned is shown in Figure 6.6

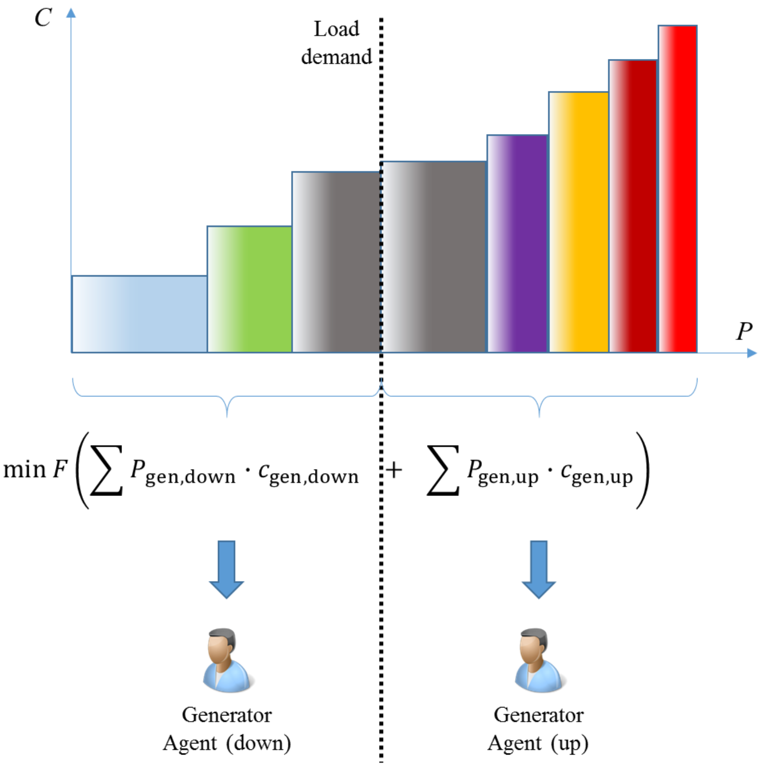


Figure 6.6 Agent interactions involved in the optimization process

The GA who is responsible for increasing or decreasing their production checks if the capacity is sufficient to cover the amount of redispatched power required. In the case where the capacity is insufficient, the GA sends a CFP message to the other GAs, which, based on the merit order, could support the redispatch process. The actual value of line overload is passed to the agent selected as part of the content of the CFP. The GAs requested send their proposals in the form of power set points, calculated from the present generation level and already corrected considering the sensitivity coefficients obtained during information exchange from the previous steps. The correction is computed based on sensitivity factors of requesting generator and support generators based on equation (6.16). The illustrative overview of the process is presented in Figure 6.7. As an example, if the calculated amount of upward redispatch power (after corrections) is higher than assumed at the beginning, downward generators will decrease their power additionally by this value. The active power balance will then be kept.

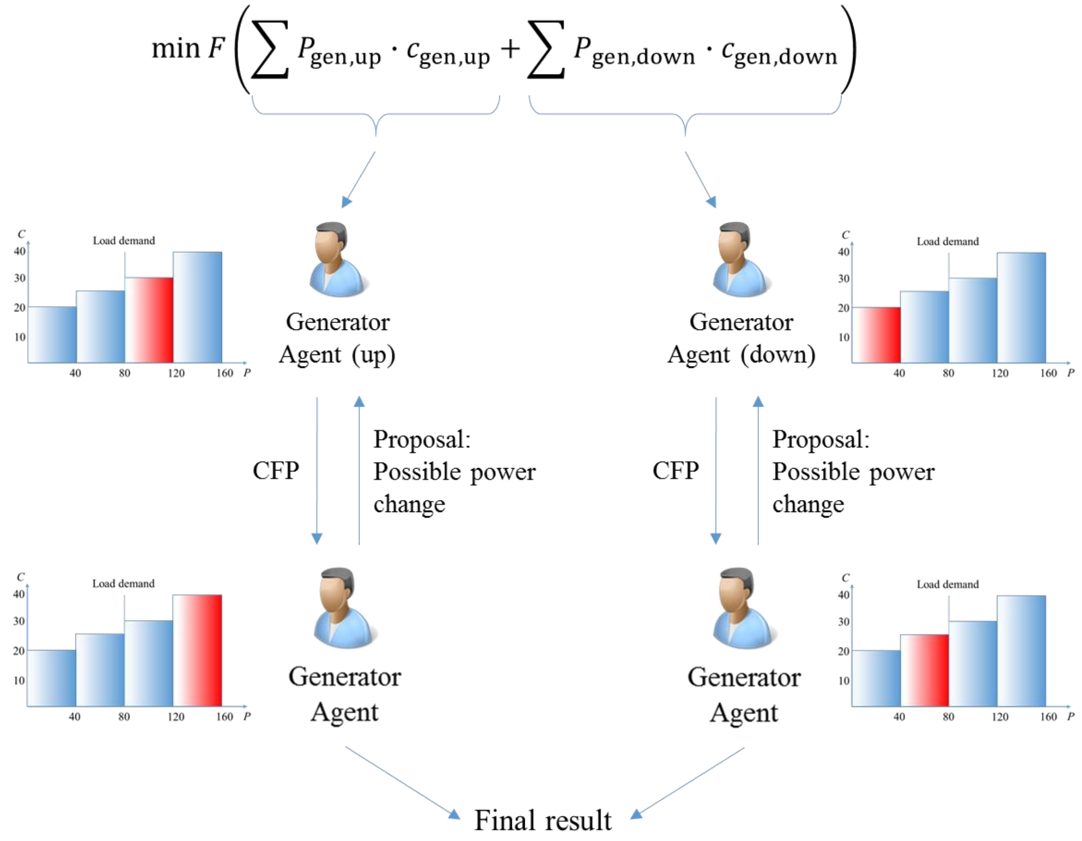


Figure 6.7 Agent interactions involved in the management process

Agents rely on cost functions, which can be modeled by using quadratic or linear functions. The quadratic function reflects the behavior of the power plant better. However, such a function can be linearized piecewise to simplify the calculation process. A quadratic cost function is normally utilized for traditional thermal power plants. For certain cases, even cubic function representation can be used to reflect the “input-output” behavior of the power plant.

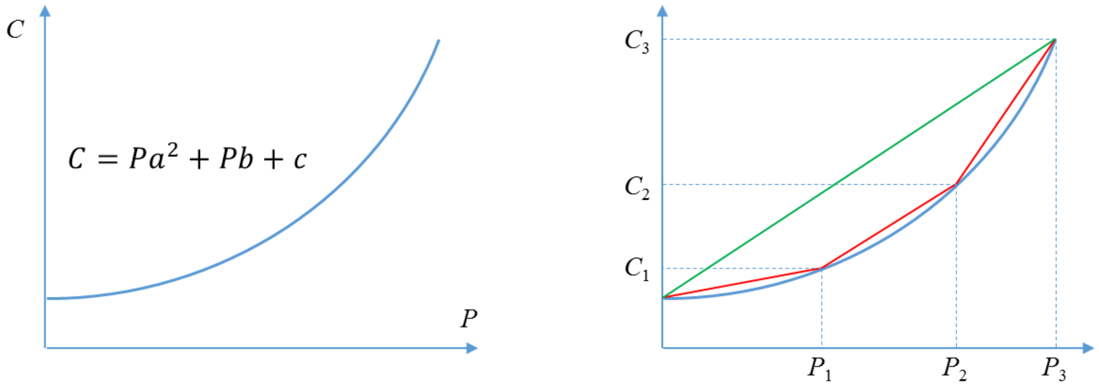


Figure 6.8 Illustrative representation of a cost function (left) and its linear approximation (right)

The agent responsible applies linear representation of the generation costs function (green line in Figure 6.8) to select generators having negative and positive redispatch potential (downward and upward generation unit sets). However, the generation cost function can be converted to a piecewise linear expression using certain numbers of variables per curve to simulate “input-output” characteristics better. The number of linear curves used indicates the degree of function approximation accuracy. In such a case, the slope of each segment is calculated as follows:

$$s_{ij} = \frac{C_{i+1} - C_i}{P_{i+1} - P_i} \tag{6.17}$$

where:

s_{ij} – i-th curve slope for generation unit j,
C_i, C_{i+1} – cost values representing linear curve boundaries and
P_i, P_{i+1} – power values defining boundaries of a given linear curve.

6.6 Modeling of agent behavior

6.6.1 Simulation Agent (SA)

Each agent operates according to its specified algorithms to perform the tasks desired. The control diagram of the SA is presented in Figure 6.9. The beginning state includes information gathering from the LiA regarding the present operating point and new set points if necessary. After load flow calculations have been completed, the level of overload of a particular line is checked. In the case of an overload being recognized, an appropriate notification is prepared and sent to the corresponding LiA. Remedial actions are performed until a stable system operation, without any overloads, is achieved.

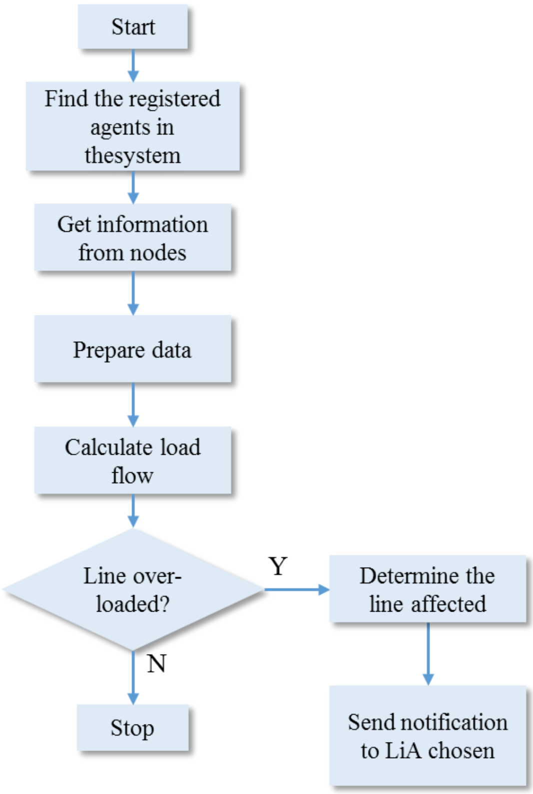


Figure 6.9 Control algorithm of the SA [58]

6.6.2 Line Agent (LiA)

Figure 6.10 presents the control algorithm for the LiA. After receiving the notification from the SA, the LiA sends notifications to two arbitrarily selected GAs. They decide if they will continue the redispatch process or other, more suitable generators need to be selected to perform the actions desired. The LiA sends the amount of the line overload to the GAs in a message content.

6.6.3 Generator Agent (GA)

The control diagram of the GA is presented in Figure 6.12. Its tasks start by receiving the notification from the LiA regarding the line overload. The GAs then exchange information, including sensitivity coefficients. Depending on the strategy selected, the GA will decide if it will continue redispatch or another, more suitable generator needs to be selected to provide services. If the generation limits of a given generator are reached, subsequent GAs are searched until the demand for active power is covered. If the number of generators available for redispatch is insufficient, congestion management cannot be completed. The detailed listing of data exchanged is shown in Figure 6.11. It encompasses not only generation costs, but also the sensitivity coefficients needed to create a merit order for each unit.

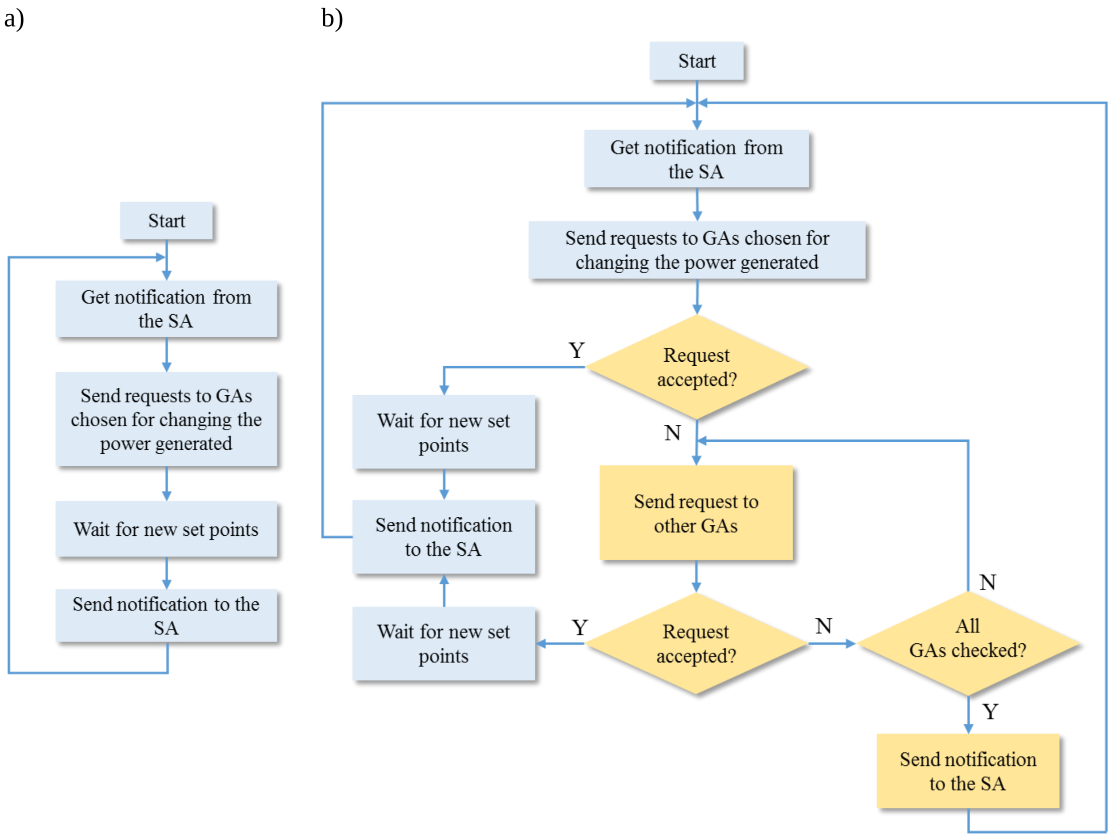
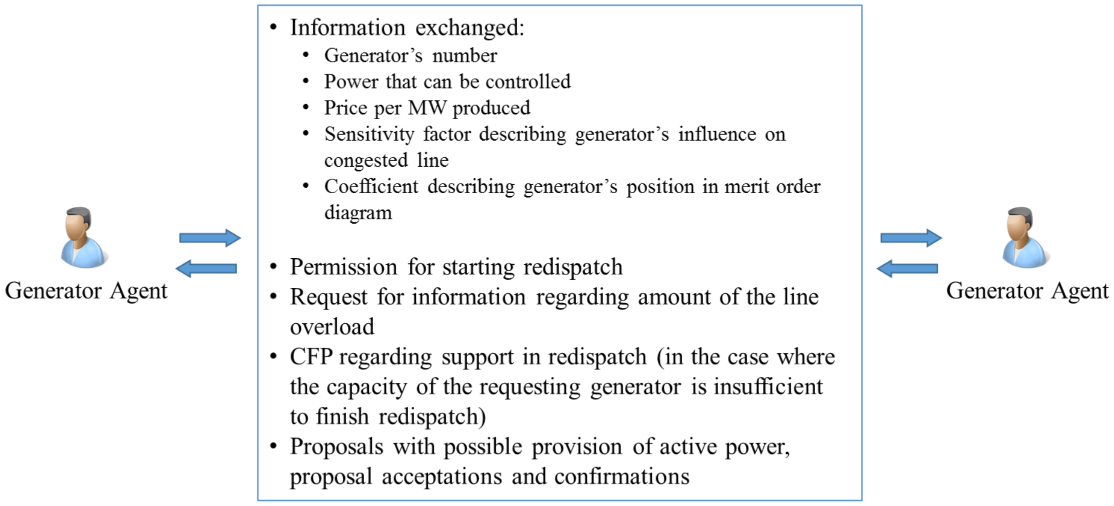


Figure 6.10 Control algorithms for the LiA: a) without and b) with consideration of the agent’s availability [58]



- Information exchanged:
  - Generator’s number
  - Power that can be controlled
  - Price per MW produced
  - Sensitivity factor describing generator’s influence on congested line
  - Coefficient describing generator’s position in merit order diagram
- Permission for starting redispatch
- Request for information regarding amount of the line overload
- CFP regarding support in redispatch (in the case where the capacity of the requesting generator is insufficient to finish redispatch)
- Proposals with possible provision of active power, proposal acceptations and confirmations

Figure 6.11 Information exchanged by GAs

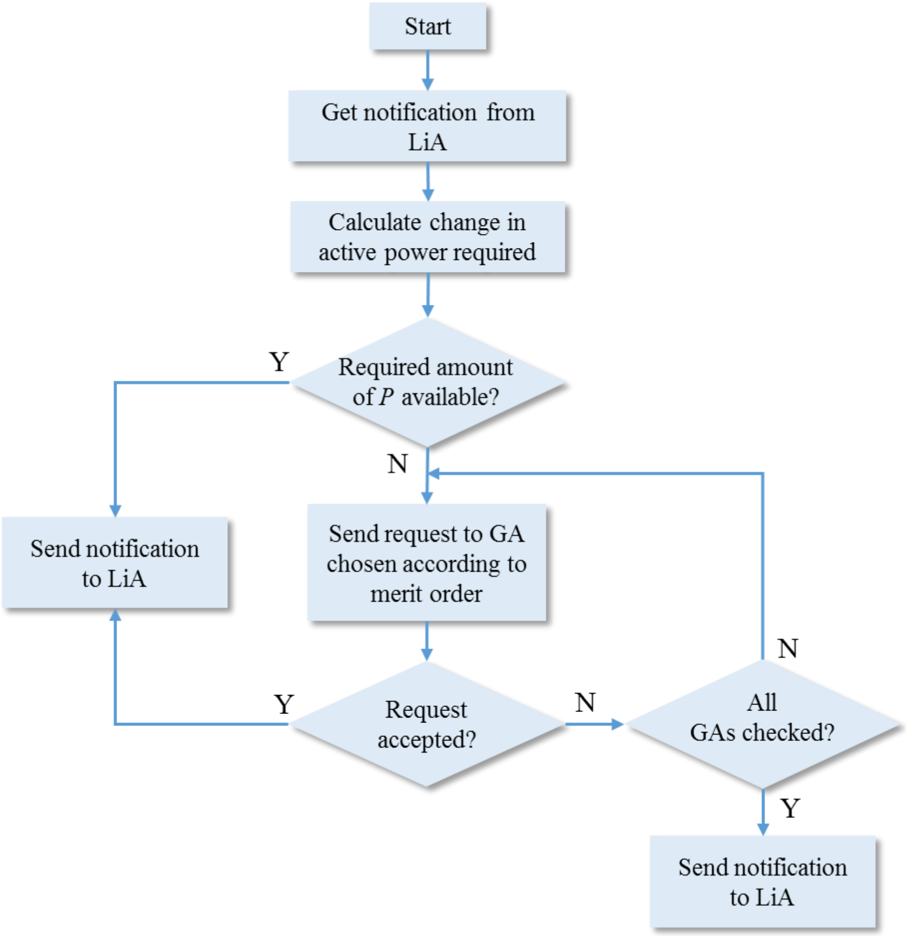


Figure 6.12 Control algorithm of the GA [58]

6.7 Control algorithm

The entire control algorithm is presented in Figure 6.13. Specific parts of the control scheme for each agent can be distinguished since three different types of agents cooperate with each other in the system proposed to achieve the goals desired. In the case of line overload, appropriate notifications including information about overload value are sent to a particular LiA. At this point, the LiA passes the information about the line overload to two arbitrarily selected GAs. The GAs, however, through the information exchange, decide whether they will continue redispatch or other, more suitable generators need to be found to start the management process. If the capacity of a given generator reaches its limits, the corresponding GA sends messages to other agents who can support the redispatch process. In the case of sufficient generator capacities, a remedial action can be completed, otherwise the redispatch is not finished and the LiA and the SA must be notified of that fact.

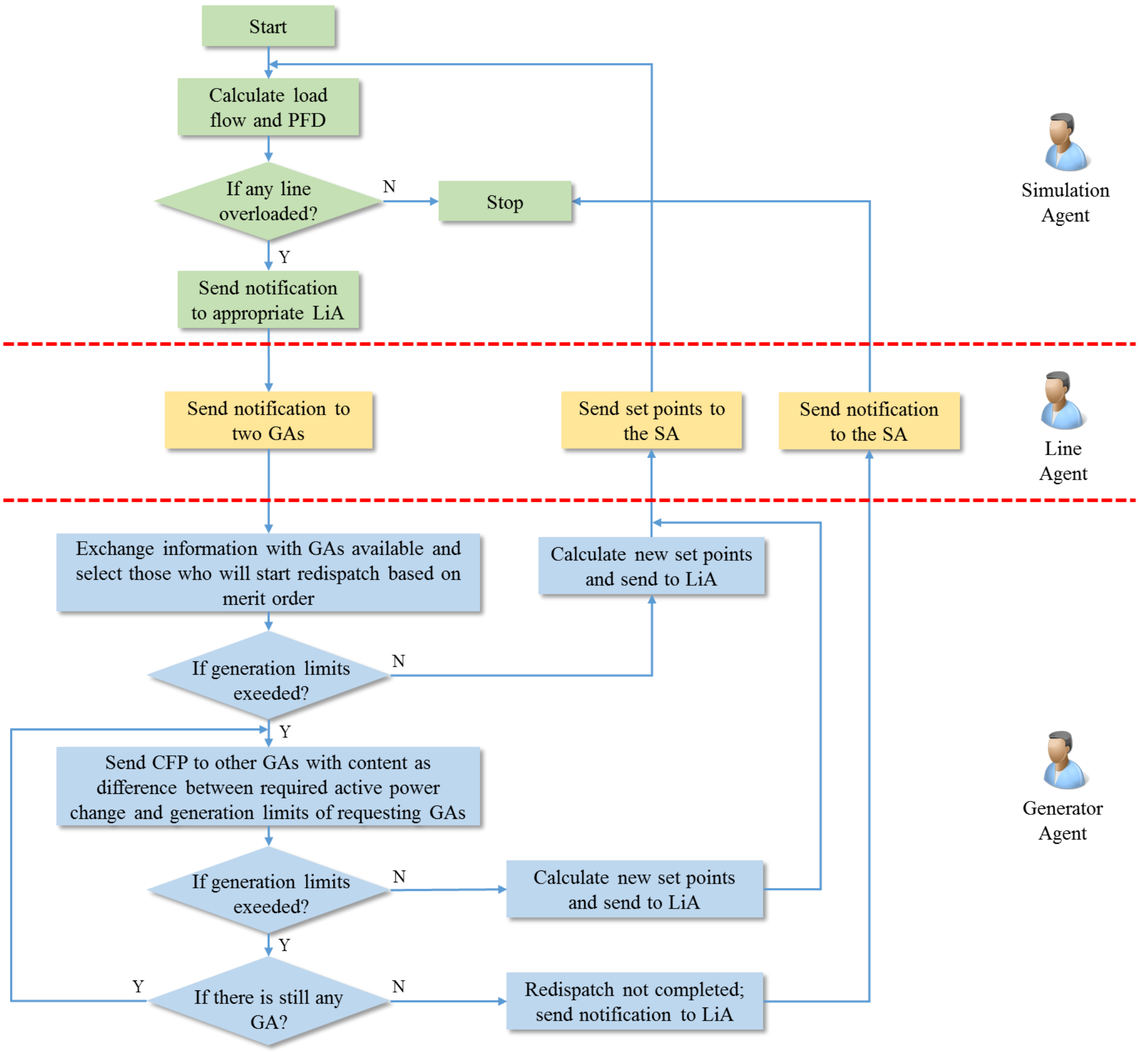


Figure 6.13 Entire control algorithm with general tasks division per agent type

6.8 Selected test cases

Simulations were performed on the power system structure selected seen in Figure 6.14. There is one agent at each bus who can react based on the situation in the system. The SA is responsible for gathering set points from other agents and calculating the load flow. The SA also decides which LiA should be informed in case of line overload. The LiA receives the amount of the line overload in a message content. Based on that, the LiA selects two GAs to initiate the redispatch. These GAs, however, will decide whether they will continue the redispatch or delegate it to more suitable GAs. Three cases will be presented in the frame of the simulation performed. At the beginning, the operation of the system regarding technical redispatch will be considered. In this case, the selection of generation units does not depend on generation costs but only on sensitivity coefficients. Subsequent scenarios encompass congestion management in which generation costs are considered.

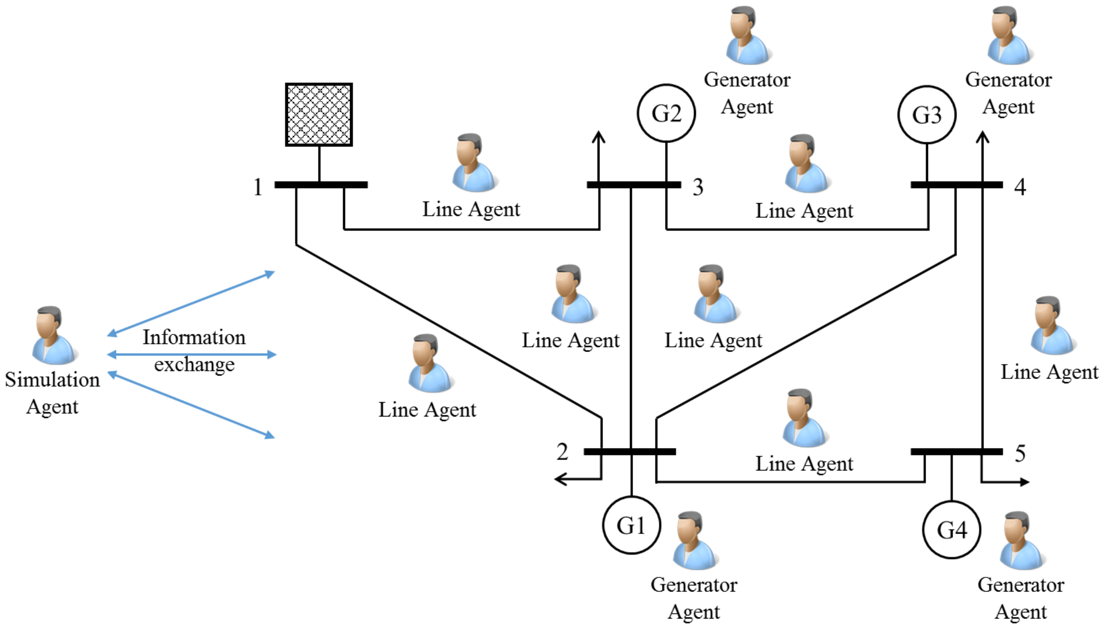


Figure 6.14 MAS used for redispatch purposes

The simulation considering costs includes cases with traditional and changed merit order described in the previous subchapter. For simulation purposes, parameters such as generation level and prices have been assumed and do not reflect the real values. The results obtained in all cases do not correspond to real costs which would occur in a real network operation and present the system performance by using different redispatch approaches. Parameters regarding line limits and generator settings corresponding to the reference scenario are presented in Appendix A, Table A.2 and A.3, respectively.

Scenario 1

In this scenario, the redispatch process is performed based only on sensitivity factors. After the recognition of the line overload, an appropriate LiA selects two generators to alleviate the congestion. At this point, no merit order has been considered. Table 6.4 presents the number of the overloaded line, utilization share before and after congestion alleviation together with redispatch power and total redispatch costs. Table 6.5 shows the generators selected for redispatch and the corresponding adjustments of active power. For simulation purposes, the data shown in Table 6.3 has been assumed. Sensitivity coefficients correspond to line 5.

Table 6.3 Generator data

	Generator 1	Generator 2	Generator 3	Generator 4
Costs in €/MW	120	90	20	25
Power available	40	40	40	40
Coefficients	0.710	0.593	0.499	-0.027

Table 6.4 Results summary for scenario 1

Line no.	Line utilization before remedial actions in %	Line utilization after remedial actions in %	Redispatch power in MW	Redispatch costs in €
5	108.07	100.00	2.61	378.45

Table 6.5 Generator set points in MW before and after congestion

Scenario	Generator 1	Generator 2	Generator 3	Generator 4
Before	40	40	40	40
After	42.61	40	40	37.39

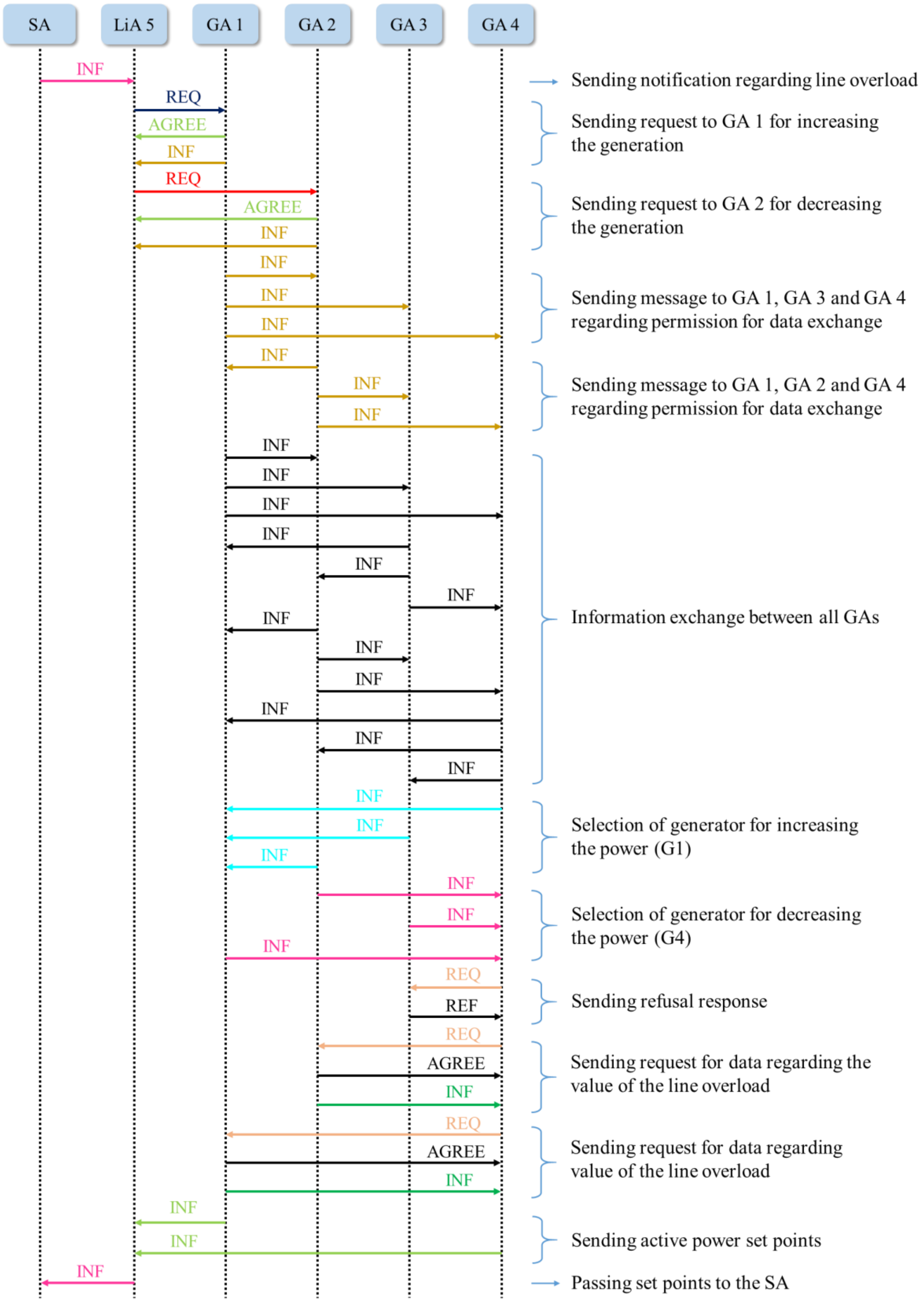


Figure 6.15 Sequence diagram for scenario 1 (first iteration)

Scenario 2

This scenario considers redispatch based on the merit order determined only by generation costs. The power generation data, including generated power and its costs, are provided in Table 6.6. The values of sensitivity coefficients provided correspond to line 5. The merit order is shown in Figure 6.16. Table 6.7 presents the results summary for the scenario considered.

Assuming a load demand at the level of 80 MW, the division between generators that need to increase and decrease their generation can be noticed. The total redispatch power is 17.17 MW. The generation of the generator G2 needed to be increased by this amount. In turn, the generation of G3 needed to be reduced by the same amount. The line utilization after remedial action is 100 %. The agent interactions illustrating sequential execution of tasks are presented in Figure 6.17. Additionally, the simulation results for the limited generation of generator G3 to the value P_{min} = 35 MW are presented in Table 6.9 and Table 6.10. Since that was insufficient to cover the necessary amount of active power needed to alleviate the congestion, the next unit has been selected to complete the missing amount of active power. In this case, generator G4 decreased its generation by 2.57 MW. The total redispatch power is 7.57 MW. The generation of G2 needed to be increased by the same amount. Agent interactions for this scenario are presented in Appendix B in Figure B.1.

Table 6.6 Generator data

	Generator 1	**Generator 2**	**Generator 3**	**Generator 4**
Costs in €/MW	120	90	20	25
Power available	40	40	40	40
Coefficients	0.710	0.593	0.499	-0.027

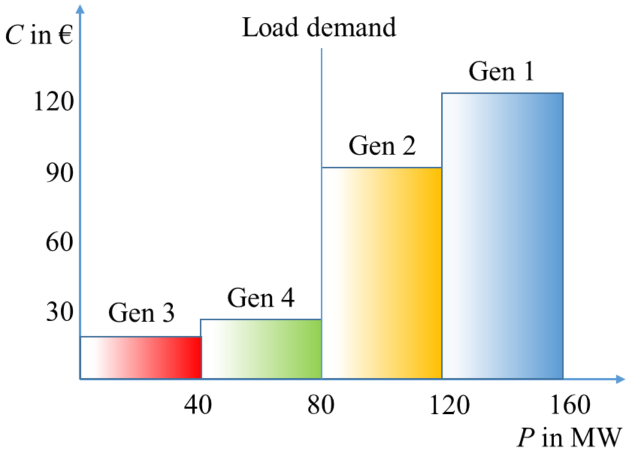


Figure 6.16 Merit order considering only generation costs

Table 6.7 Results summary for scenario 2

Line no.	Line utilization before remedial actions in %	Line utilization after remedial actions in %	Redispatch power in MW	Redispatch costs in €
5	108.07	100.00	17.17	1888.70

Table 6.8 Generator set points in MW before and after congestion

Scenario	Generator 1	Generator 2	Generator 3	Generator 4
Before	40	40	40	40
After	40	57.17	22.83	40

Table 6.9 Results summary for scenario 2 (for limited generation of G3)

Line no.	Line utilization before remedial actions in %	Line utilization after remedial actions in %	Redispatch power in MW	Redispatch costs in €
5	108.07	98.95	7.57	845.55

Table 6.10 Generator set points in MW before and after congestion (for limited generation of G3)

Scenario	Generator 1	Generator 2	Generator 3	Generator 4
Before	40	40	40	40
After	40	47.57	35	37.43

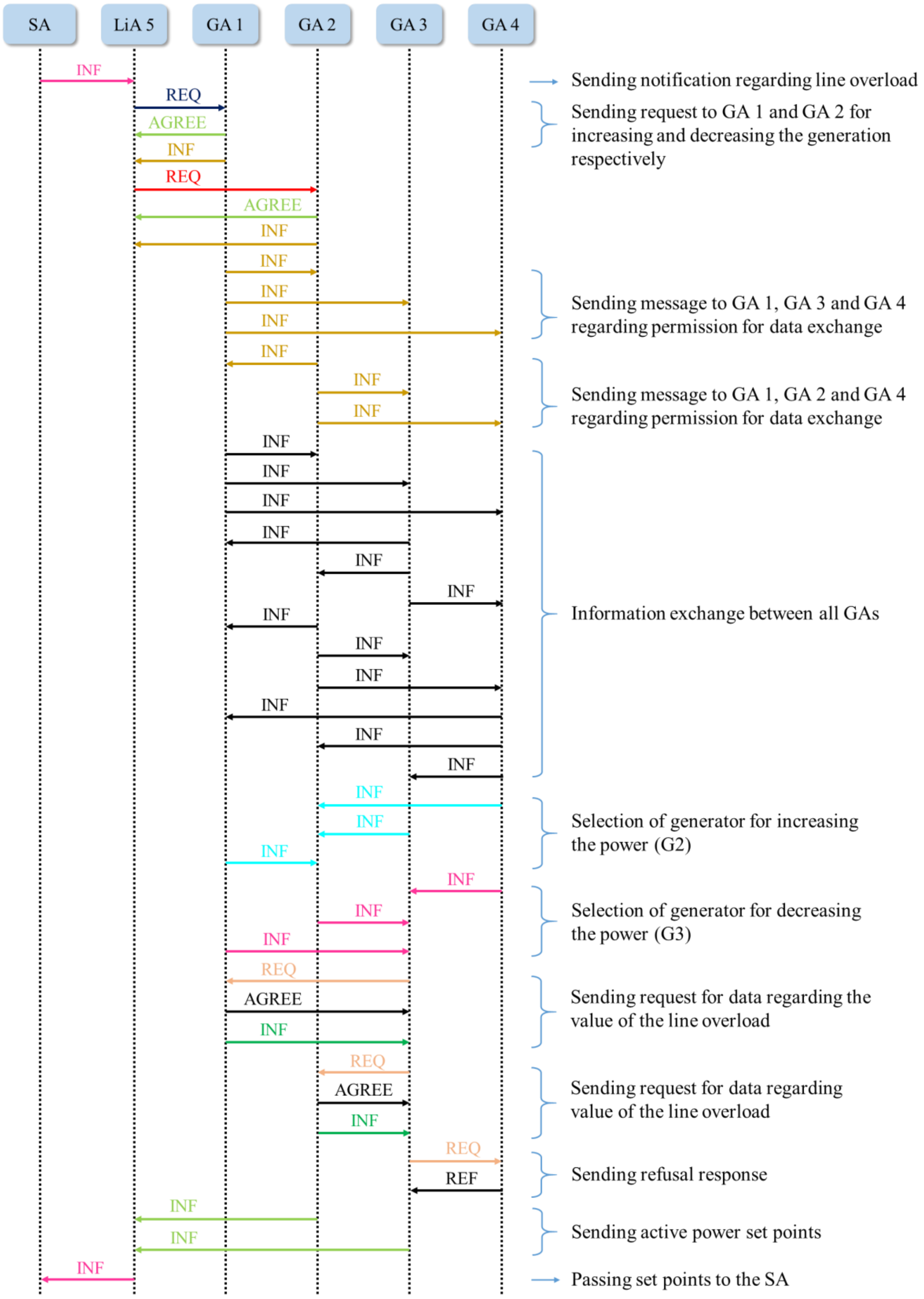


Figure 6.17 Agent interactions for scenario 2 (first iteration)

Scenario 3

In this scenario, the changed merit order determined by the generation costs and sensitivity factors is considered. The order of generators has changed in this case compared with the merit order given in the previous scenario, which is the result of considering the sensitivity coefficients. The power generation data, including generated power and its costs, are provided in Table 6.11. The changed merit order of generators is shown in Figure 6.18 and corresponds to the value of the sensitivity coefficients considered. The results summary and generator set points are presented in Table 6.12 and Table 6.13, respectively. The sequence diagram of actions performed by agents is shown in Figure 6.19.

Table 6.11 Generation data

	Generator 1	Generator 2	Generator 3	Generator 4
Costs in €/MW	120	90	20	25
Coefficients	0.710	0.593	0.499	-0.027
New merit order	169.01	152.03	40.08	-925.93

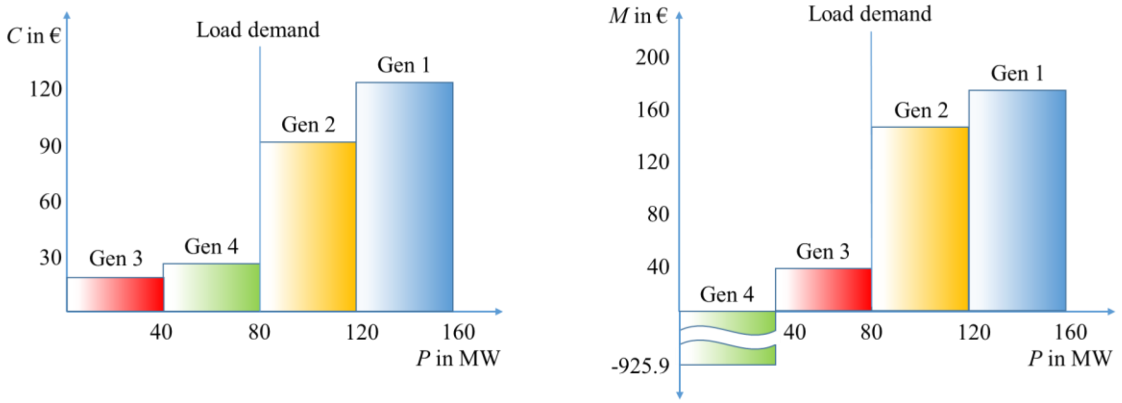


Figure 6.18 Merit order considering only generation costs (left) and additional sensitivity factors (right)

Table 6.12 Results summary for scenario 3

Line no.	Line utilization before remedial actions in %	Line utilization after remedial actions in %	Redispatch power in MW	Redispatch costs in €
5	108.07	100.00	3.06	351.90

Table 6.13 Generator set points in MW before and after congestion

Scenario	Generator 1	Generator 2	Generator 3	Generator 4
Before	40	40	40	40
After	40	43.06	40	36.94

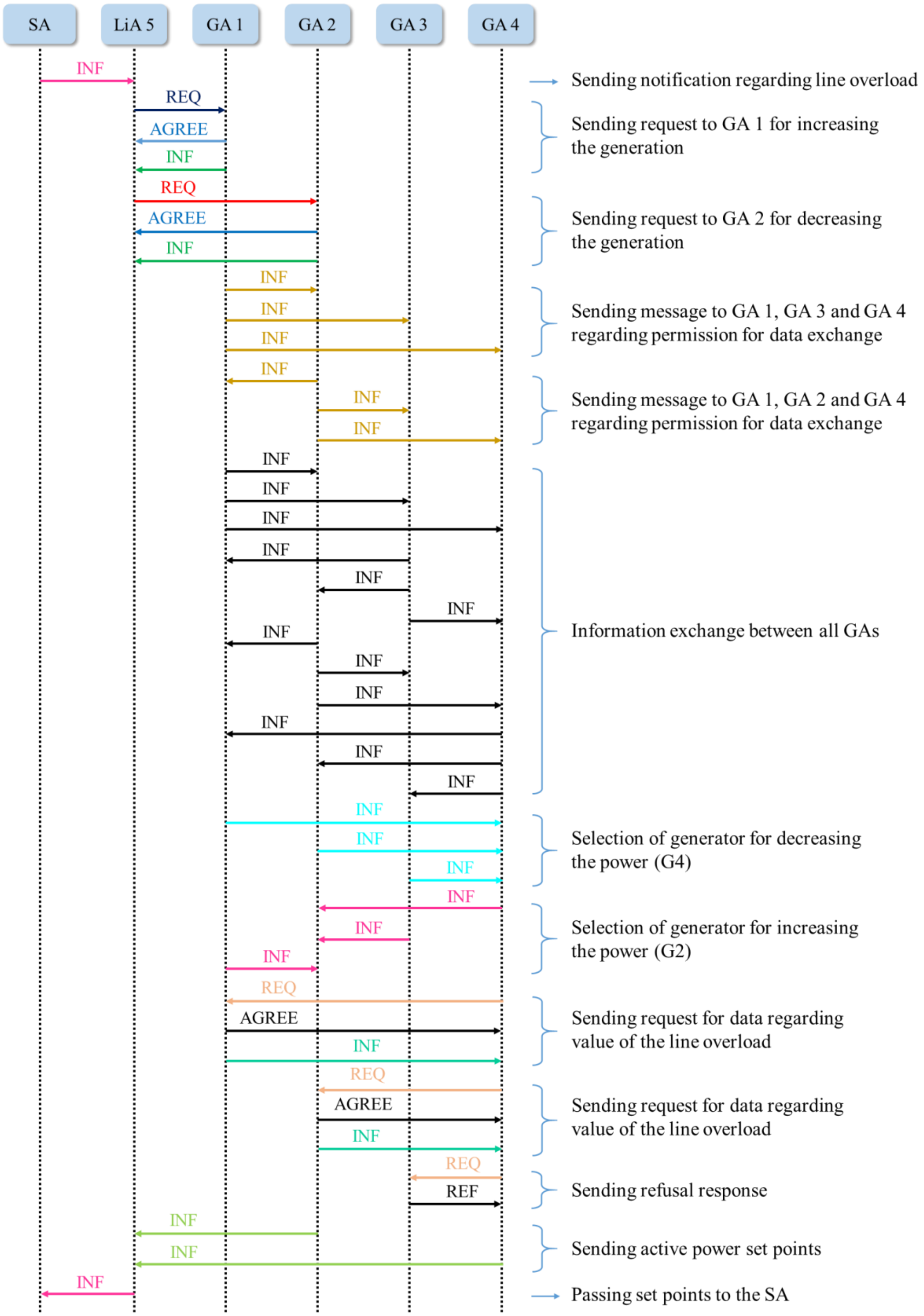


Figure 6.19 Agent interactions for scenario 3 (first iteration)

The results obtained show that the new order of generators used for potential redispatch translates into a different selection of generators used in redispatch. The redispatch costs in this case will be changed as well. Since the new merit order considers the location of power plants, generation costs regarding each unit are calculated correspondingly. Furthermore, with the increasing location of generators, a higher amount of energy needs to be transmitted by this unit. The results obtained for different strategies are presented in Table 6.14.

Table 6.14 Results for different strategies

Strategy	**Redispatch power in MW**	**Redispatch costs in €**
Only sensitivity coefficients	2.61	378.45
Old merit order (only generation costs considered)	17.17	1888.70
Old merit order (only generation costs considered and limited generation of G3)	7.57	845.55
New merit order (sensitivity factors and costs considered)	3.06	351.90

The first strategy, being a part of network-related measures according to the §13.1 of the German Energy Act (EnWG [81]), allows redispatching only from a technical point of view by choosing generators based on their sensitivity coefficients. That, however, can contribute to higher costs. The next two approaches incorporate generation costs of the units considered, since economical aspects play a significant role in the management of the power system. The second strategy, considering only generation costs, is ineffective and contributes to relatively higher redispatch costs. The application of sensitivity coefficients in the new merit order creates the possibility of the redispatch, which is effective from a technical and economical point of view. Considering aspects such as the price of the generation and the influence of the unit on a given line, it gives an additional option for the selection of generators and their ranking, which will depend on location and costs. This means that the farther away the generator is located (lower the sensitivity factor), the higher the costs for delivering energy to a given place or for triggering a specific reaction of the system. In this case, the merit order will differ from the one based only on the generation costs.

The proposed strategies, however, are not interconnected. Only one methodology can be selected at the beginning of the congestion management. The extension of the system constitutes merging several strategies depending on the results obtained. The merit order based only on generation costs contributes to higher costs in comparison to the merit order, in which sensitivity coefficients are incorporated as well. The results provided, however, show an advantage of the new merit order approach considering assumed generation data.

6.9 Treatment of potential failures

Remedial or management actions which will help to continue the further operation through the redundancy available in the system to keep the system working robustly and reliably need to be introduced. Potential operation failures are presented in Table 6.15. Additional actions, including information rerouting and renewed requests for data, constitute communication scheme proposals which can be considered in such MASs where recovering system stability is the prior task. The table below, however, presents only proposals of situations which can cause a disturbances to the system operation. Similar to the case of the agent-based voltage control presented previously, certain requirements regarding the number of agents available, however, determine the successful performance of the management processes.

Table 6.15 Potential failures in the system

Failure	Treatment
Failure during transporting new set points – DG dispatch agent set point failure	If uncertain set points are received – send a renewed request to provide set points If the wrong information is still sent after a certain amount of time or number of inquiries, the receiving agent sends a notification to the other GAs
Unavailability of one of the GAs – no response to CPF (communication failure or agent failure)	If at least two GA are available, an attempt at redispatch is performed If there is no communication with at least two GAs – redispatch is not completed – the notification to the SA is sent
SA data misinterpretation – receipt of incorrect/uncertain set point values	If uncertain set points are received – send the renewed request for providing set points If the wrong information is still sent after a certain amount of time or number of inquiries, the SA sends a notification to the other GAs

Failure	Treatment
Inability to recognize other agents in the system	By the SA: If no GA has been detected, redispatch is interrupted (another possibility of congestion management needs to be considered) By the SA: If at least two of the GAs have been detected, an attempt at redispatch is performed. Negotiations among others GA are inactive if there is only one GA available If the amount of active power is insufficient to improve the stability of the system, a notification to the SA is sent with a proposal of different control strategy (e.g. through load control) By the GA: If, during negotiations, the communication between one or more agents cannot be established, the control strategy is as above By the GA: If there is no communication with the SA, messages are sent cyclically and time expires or the number of checking messages sent reaches a certain number, notification is sent to the GAs available
SA failure – resulting in the inability to perform load flow calculations or receive uncertain information	The need for a GA organization to calculate load flow independently (in the proposed approach not considered)

7 Agent-based grid restoration

The outage of the whole system will be considered in the approach proposed and, depending on the parameters of the system, various restoration strategies may be assigned. The task assignment during the system restoration is decentralized. Moreover, possible information flow and agent organization in power restoration will be presented. The information share is limited and only those agents who need to perform the next step of the operation are notified. This happens in the case of information subscriptions, which takes place only at selected agents and are associated with the next management step. The types of agents have been selected in such a way to allow later extension of the power restoration system with additional functionality, such as voltage control or congestion management described in the preceding chapters. In this case, it is not necessary to create new agents and adjust the entire agent structure, but to supplement the existing agent's tasks with the functions mentioned previously.

The issue of power system restoration covers many aspects, mentioned already in Chapter 2.4. In this approach, the focus lies on the rebuilding of a single system island by searching for the shortest restoration path. Having developed the power restoration strategy, the functionality can be adapted to other islands of the system. The algorithm will work in the same manner and the results will match the structure and parameters of the network. The following subchapter introduces different algorithms dealing with the problem of the shortest path in a graph theory.

7.1 Shortest path algorithms

The problem of searching for the shortest path is utilized here since the restoration process encompasses determining the sequence of components that need to be energized. The proposed graph theory-based method represents the network in the form of a graph which is used to determine the restoration sequence strategy. Various types of algorithms can be used for the determination of the shortest path and may include [103]:

- Dijkstra's algorithm
- Bellman-Ford algorithm
- A*(star) search algorithm
- Floyd-Warshall algorithm
- Johnson's algorithm

Table 7.1 presents the comparison of possible algorithms used to search for the shortest path. Dijkstra's algorithm will be applied for the restoration procedure proposed.

Since assumptions of the methodology selected do not consider negative weights and negative cycles, it is sufficient to model edges and nodes, which correspond to power lines parameters (which have a positive value) and busses of the power system modeled.

Each algorithm is characterized by a certain computational complexity. In the description provided, parameters *v* and *e* correspond to the number of vertices (nodes) and edges (links), respectively, in the graph considered.

Table 7.1 Comparison of possible algorithms used to search for the shortest path [98], [99], [100], [101], [103]

Parameter	**Dijkstra's algorithm**	**Bellman-Ford algorithm**	**A* search algorithm**	**Floyd-Warshall algorithm**	**Johnson's algorithm**
Function	Solves the shortest path with a single source.	Solves the shortest path for negative edge weights.	Solves the shortest path using a heuristic approach.	Solves all pair shortest paths.	Solves the shortest path problem for all pairs.
Time complexity	O $(\lvert v^2\rvert)$	O $(\lvert v\rvert\lvert e\rvert)$	O $(\lvert v\rvert+\lvert e\rvert)$	O (v^3)	O $(\lvert v^2\rvert\log\lvert v\rvert + \lvert v\rvert\lvert e\rvert)$
Negative weights	No	Yes	No	Yes	Yes
Negative cycles	No	Yes	No	No	No

7.2 Structure of the multi-agent system

The following agent types have been introduced in the frame of the MAS for grid restoration proposed. They perform the tasks desired to exchange information and manage the system within the grid restoration process. The basic structure of the MAS considered together with all types of agents available in the system is presented in Figure 7.1.

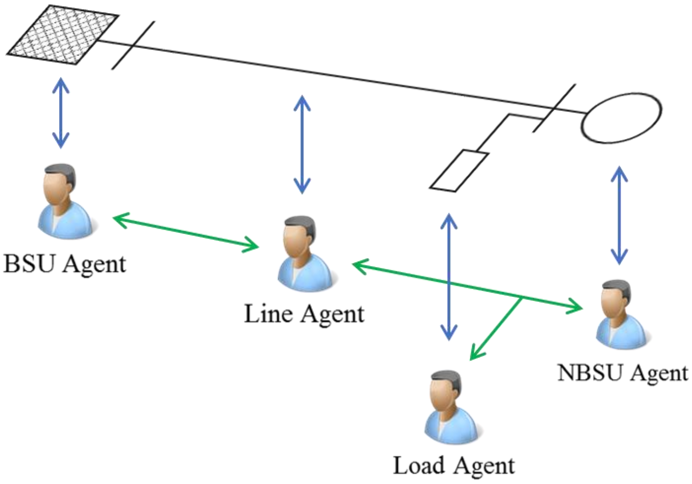


Figure 7.1 Structure of a MAS for grid restoration

7.3 Modeling of agent behavior

7.3.1 Black start unit agent (BSUA)

The black start unit agent is considered as a self-starting generator providing cranking power to the non-black start generators. The agent related to this black start generator sends relevant notifications, followed by recognition of other agents in the system, such as NBSAs and LiAs. The BSUA has the following tasks:

- Provides cranking power to non-black start generation,
- Receives requests regarding determination of restoration paths and
- Determines the shortest path between source and target.

The BSUA in this case is responsible for the calculation of the restoration path to components, which are non-black start units (NBSUs) and loads in the approach proposed. After a path is determined, the request for readiness for restoration is sent to the first component in the path. The block diagram of the BSUA algorithm is presented in Figure 7.3. After the restoration path has been determined, the BSUA sends requests regarding readiness to subsequent agents determined through the indexes contained in the restoration vector. An agent who has received the request for providing readiness to restoration passes the request to the next agent defined. The last agent in the restoration vector can be a load agent (LoA) or a NBSA. In the backward direction, the messages containing status of readiness to restoration are sent. Starting from load or NBSA, appropriate notifications are passed until the BSUA receives status information from all agents in the path. The concept of information exchange is shown in Figure 7.2 and illustrative interactions between the agents chosen are shown in Figure 7.4.

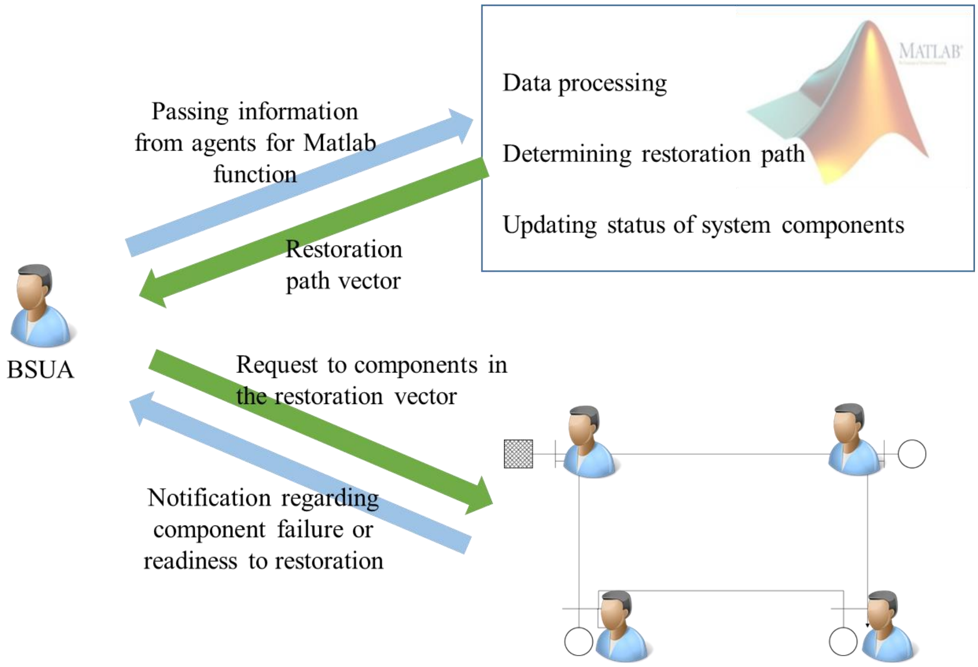


Figure 7.2 Information flow between BSUA, Matlab functions and other network agents

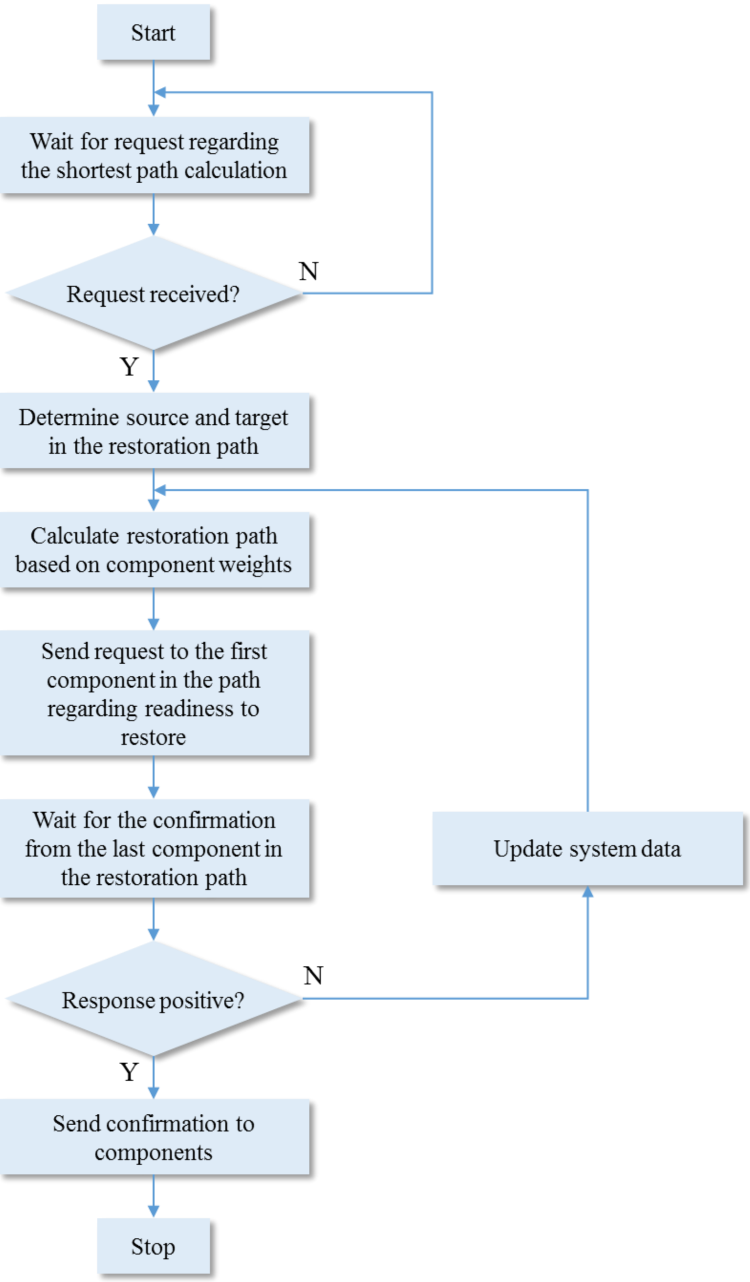


Figure 7.3 Block diagram of the BSUA algorithm

Figure 7.4 shows an example of sending the message requesting readiness for restoration. The BSUA selects the path and the notification regarding the restoration readiness is sent to the first component in the path. The message is then passed to the next component in the path. The confirmation is sent from the last component in the path through all agents that participate in sending *ready* messages. If one of the agents submits a rejection for the restoration process due to certain interruptions or failures, the BSUA will find another path and the message chain will be repeated.

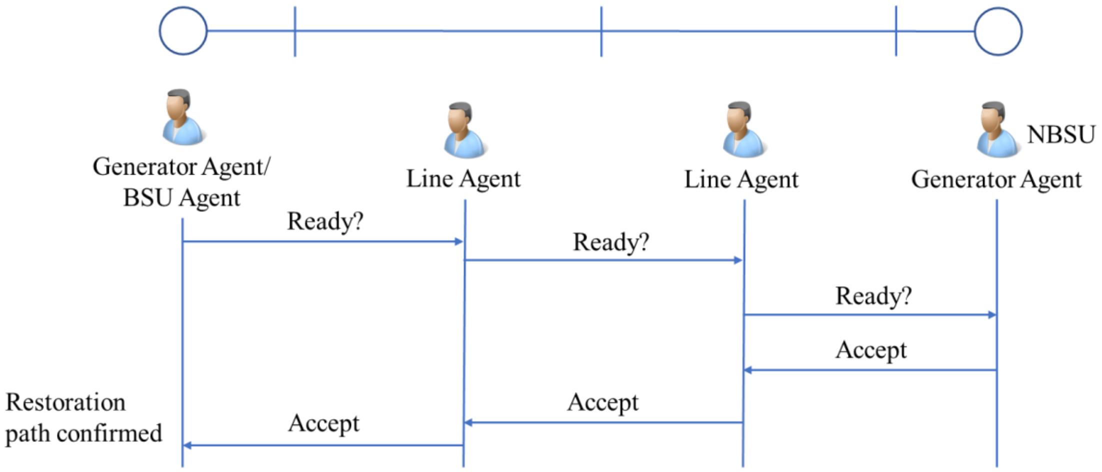


Figure 7.4 Sending message to components regarding readiness for restoration

7.3.2 Non-black start unit agent (NBSA)

The NBSA is characterized by the inability to self-start after the power outage. Information, such as maximum power, minimal time needed to restart the generator or the node at which the non-black start unit is located, is provided to other NBSAs at the beginning of the restoration process. To send appropriate notifications, the NBSA must register other agents it will later communicate in its memory. The NBSAs send information to each other about the content of the minimum necessary time needed to rebuild the power supply and then check which starting time is smallest. Once the shortest time has been determined, an agent sends a notification to the agent who has the shortest time to begin the process of network restoration. The NBSA fulfills the following tasks:

- Sends request to BSUA to determine the shortest path;
- selects the NBSA who should be restored first;
- checks whether the load to be restored resides in the same node as the NBSU, if not, the request to BSUA to determine the restoration path to this load is sent;
- checks restoration status of loads in the system and decides which one should be energized next; and
- sends information updates regarding loads already restored to other NBSAs.

The algorithm given follows the execution of NBSA tasks (see Figure 7.5). At the first stage of the grid restoration, the NBSA sends the message including their generation parameters to other agents from the same group. After information from all necessary agents has been received, the agents choose one non-black start generator to initiate the restoration process. The agent who has received starting permission checks what loads in the system need to be energized. The load with the highest priority will be restored first. Depending on the localization of the load in the network, the non-black start units residing at the same node will restore it, or a restoration path to this load will be determined. As a next step, the notification is sent to other NBSAs with content including the status of the loads restored.

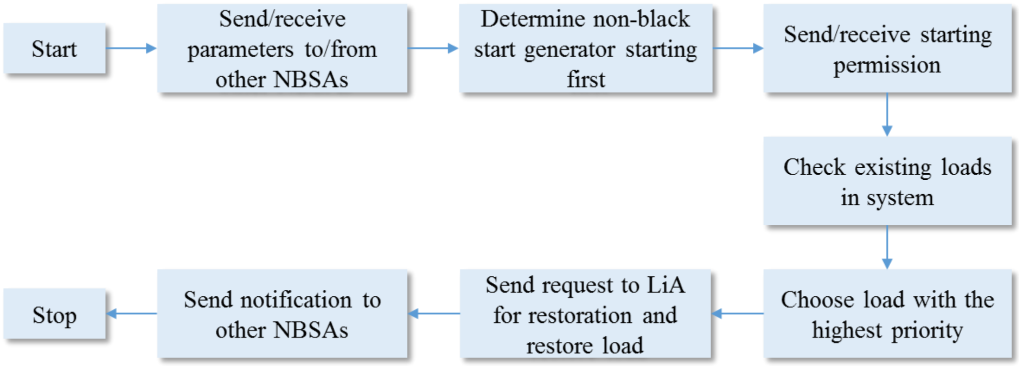


Figure 7.5 Block diagram of the NBSA algorithm

At the beginning of the restoration process, NBSAs need to decide which non-black start generator should initiate the entire procedure. One of the parameters that characterizes the operation of NBSUs is the minimal starting time at which a generator can still start after the power outage without the necessity of time-consuming preparation and warming up the unit. Figure 7.6 presents the interaction between NBSAs exchanging information regarding starting time. In this case, the agent whose generator has the minimal starting time receives *permission start* notification and the restoration process is initiated.

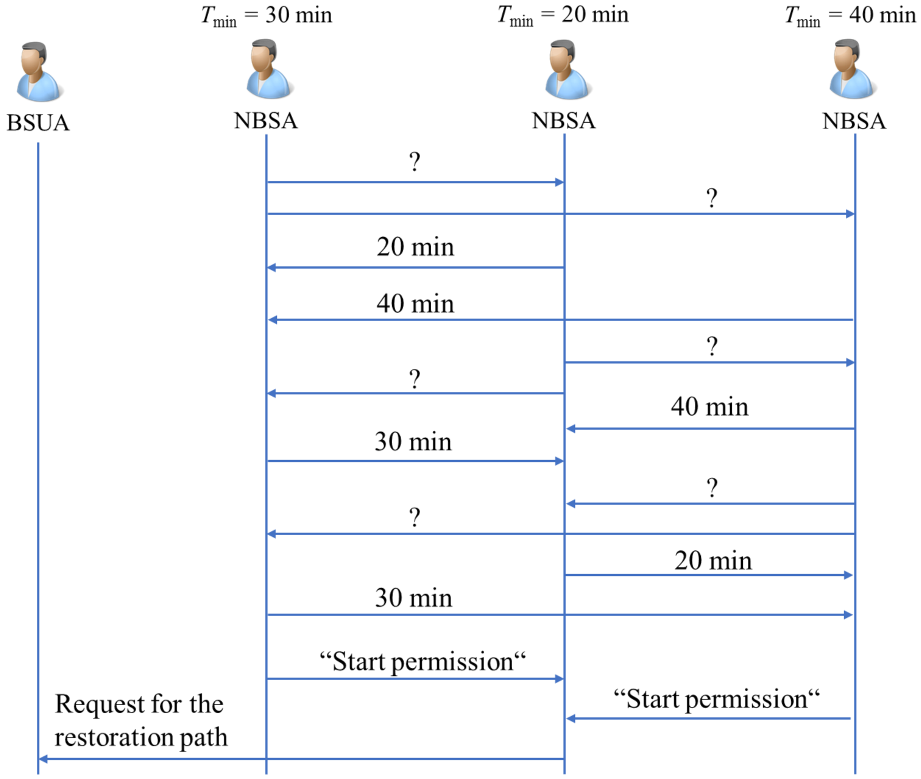


Figure 7.6 Exchange of starting times between NBSAs

7.3.3 Line agent (LiA)

The LiA has been considered due to the algorithm for calculating the shortest path. Since the algorithm utilizes weights to calculate the shortest path, line parameters, such as restoration time, resistance, reactance and capacitance, can be treated as potential weights. In this case, however, selection of the restoration path would not be performed considering the amount and dynamic behavior of loads in the system. Therefore, instead of using traditional parameters such as weights in the approach presented, an adjustment of an alternative line weights will be introduced and described in the further section. The weights are adjusted appropriately depending on the readiness of components for restoration.

The LiA fulfills the following tasks:

- Sends line parameters to BSUAs (at the beginning of the restoration process),
- determines readiness for restoration, and
- passes requests regarding readiness for restoration to subsequent agents in the restoration path.

The block diagram of the LiA is presented in Figure 7.7. The LiA’s tasks encompass sending messages to the BSUAs with content including line parameters and waiting for queries regarding readiness for restoration. After the query/request is received, the LiA can decide whether the line should be connected to the system or not. At this point, the simulation of line failures can be performed by means of sending a negative response. If the BSUA receives such a *failure message* from the LiA, another restoration path including other lines needs to be found.

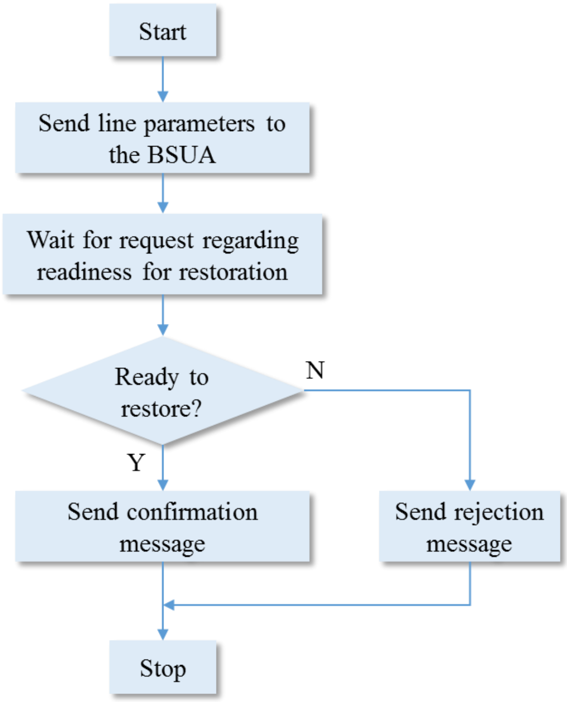


Figure 7.7 Block diagram of the LiA algorithm

7.3.4 Load Agent (LoA)

In this approach, the tasks of the LoA include provision of load demand data and preparation of responses regarding requests for restoration and readiness for restoration. If a system outage occurs, the LoA sends information to the NBSA regarding their demand and priority. The restoration time and dynamic models of loads are not taken into consideration. The LoA has the following tasks:

- Receives notification regarding readiness for load restoration – if load needs to be restored, it constitutes the last component in the restoration path;
- receives requests for partial load restoration from NBSAs; and
- sends confirmation or refusals of restoration readiness.

The block diagram of the LoA is presented in Figure 7.8. Since the LoA's behavior includes several tasks which are executed simultaneously, on the one hand, it sends load parameters to the NBSA and waits for restoration service and, on the other hand, waits for queries regarding readiness for restoration sent by the BSUA.

Figure 7.9 presents the situation in which two loads need to be supplied. Since the load with priority 2 resides at the same bus as the non-black start generator, it could be restored from this unit, avoiding the energization of additional lines. However, considering the load priorities indicating an agent’s own interests, the proper request is passed. In this case, the load with priority 2 sends the request to the second load to change the priority to be restored from the NBSU. Since a rejection message has been received, first load “1” will be restored and then load “2.” This must be followed by an energization of an additional line. With the remaining power of 4 MW, the second load can be partially restored.

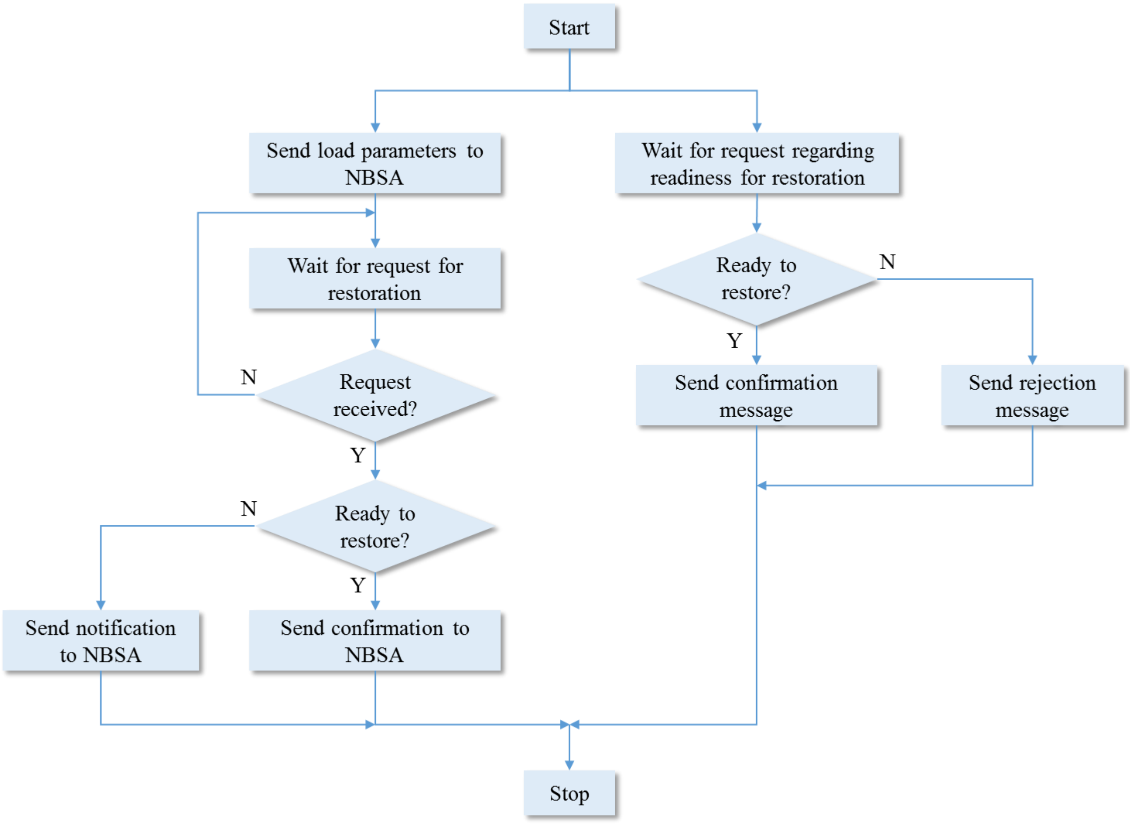


Figure 7.8 Block diagram of the LoA algorithm

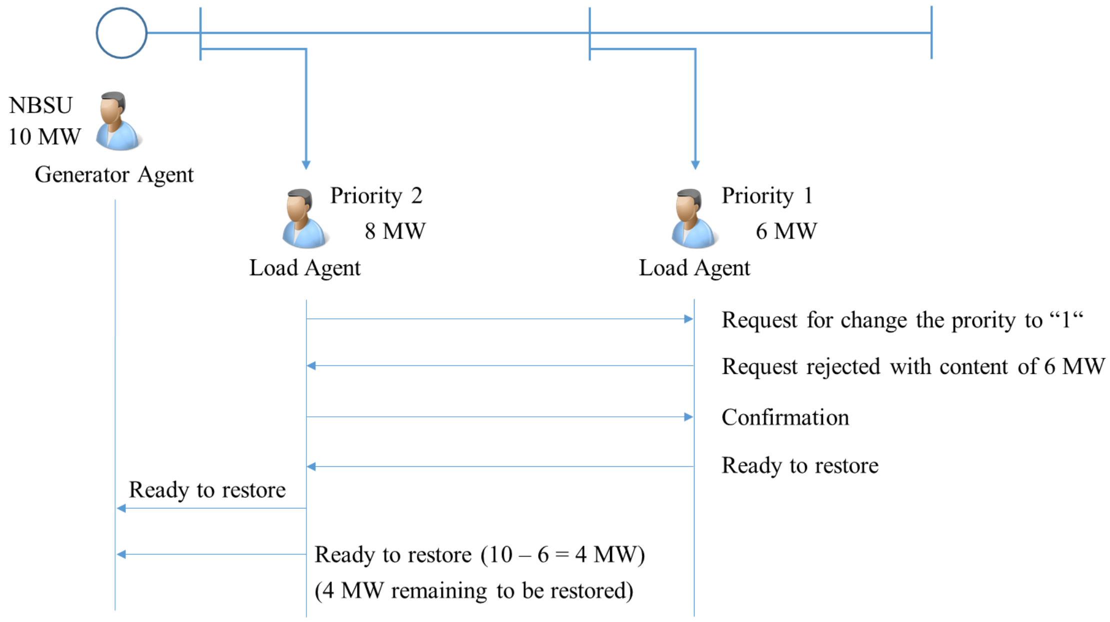


Figure 7.9 LoA interactions in the case of a request for load priority change

The interactions above present the situation in which LoAs have exact knowledge about their demands at the time of integration with the power system. However, considering the dynamic nature resulting from the start-up of cooled devices and load diversity, an increased load demand at the restoration moment can be expected. For the purpose of the approach proposed, load demand required in negotiations needs to be assumed. Figure 7.10 illustrates an example of the active power intake for a residential area at the moment of restoration.

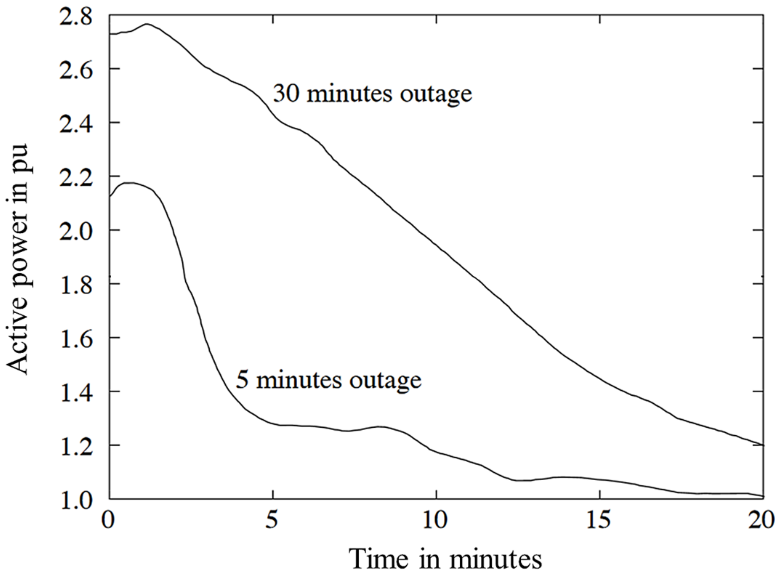


Figure 7.10 Example of load demand under different outage periods [102]

To make accurate assumptions, precise dynamic load behaviors are required, which are not always available and even not considered in such models. In this approach, the approximation at the time of load restoration is carried out through percentage estimation of the load demand. In this case, the load demand expected will be greater than at the moment of power outage. After a load is connected to the network, the effect of the assumed demand on the system operation can be assessed through simulations. If the estimated load demand results in network instability, remedial control actions are required. The challenge constitutes agent interactions in the restoration process in which the accurate load demand is not known.

The balance between generated and consumed power must be kept in the process of grid restoration. In the case when generated power is insufficient to fully restore the load desired, it needs to be partially restored. Otherwise, the next generation unit is searched to provide support in power provision. The power imbalance in the investigations proposed is represented by the congestion on given lines. Increased line overload is eliminated by the connection of additional generation units. If load flow calculations do not prove any congestion, the next restoration path is determined. Here, however, the order in which components should be connected to the system is not considered. A possible solution is to perform simulations of all possible switching combinations and then determine the order of path execution.

Figure 7.11 shows the example of the restoration of one load together with the illustrative representation of line utilization. Since the selected load at the beginning of the restoration is supplied only by the one generation unit, it contributes to line overloading (upper left figure). Some remedial actions are required because the system in this state is unstable. In this case, the starting of the next generator selected will provide additional power to cover the load demand. Some congestion can still occur as certain transmission limitations are imposed on the line (upper right figure). Energizing of the subsequent unit supports the full restoration of the load. After line congestion is alleviated (bottom figure), other paths required to restore the second load can be calculated.

7.4 Agent interactions

Interactions between specific agents are presented in Figure 7.12. The interconnection between agents ensures information exchange during the restoration process. The necessary information – e.g. load data – is vital to recognize which load needs to be restored first. The interactions presented constitute the possible communication scheme that can be performed in the frame of grid restoration. More sophisticated interactions would be required if the management concept considers more factors, including the additional dynamic behaviors of components. Moreover, agents available in the system might be required to perform distributed load flow calculations instead of relying on the one specific agent.

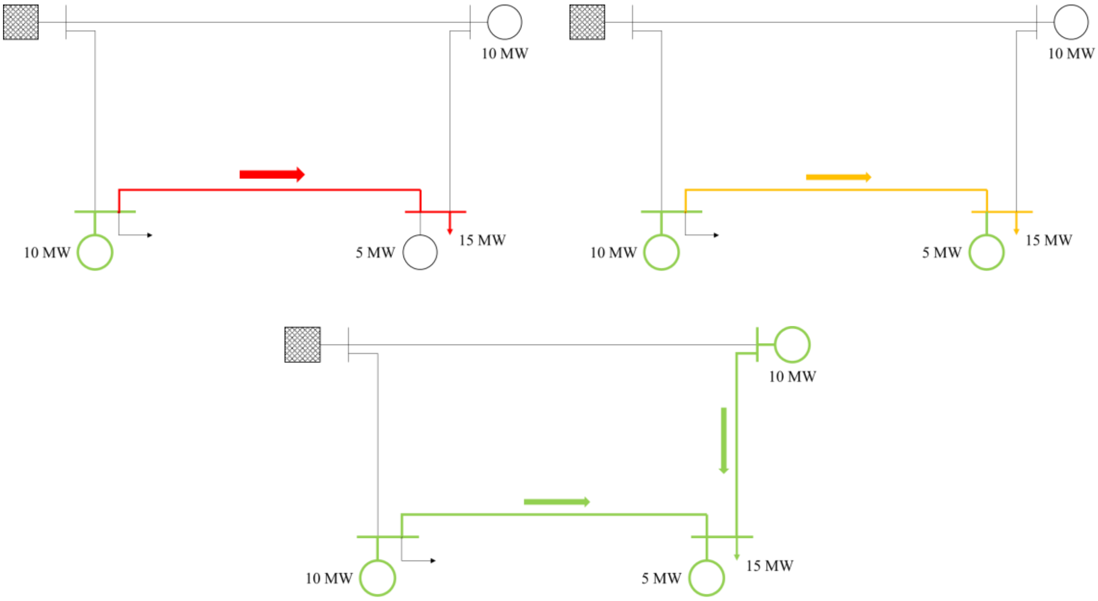


Figure 7.11 Power provision to the load selected and corresponding line overload

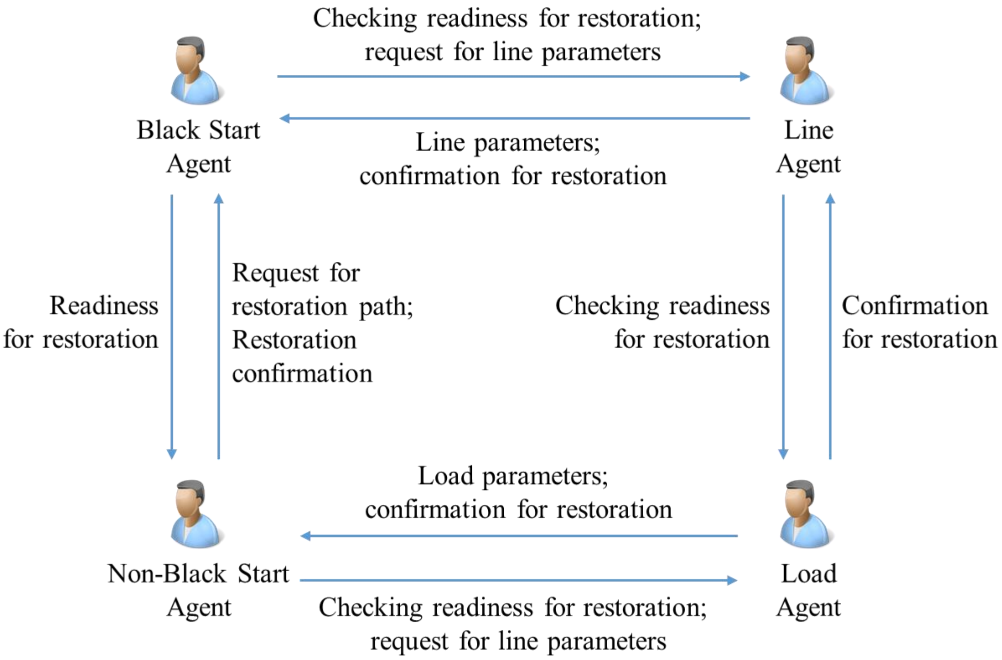


Figure 7.12 Agent interactions in the system

Additionally, since there are more NBSAs interacting with each other, the additional information exchange is shown in Figure 7.13. Since the tasks fulfilled by those agents are the same, the order of NBSAs sending corresponding requests and notifications depends on the restoration step and the selection of the non-black start initiating the whole restoration process.

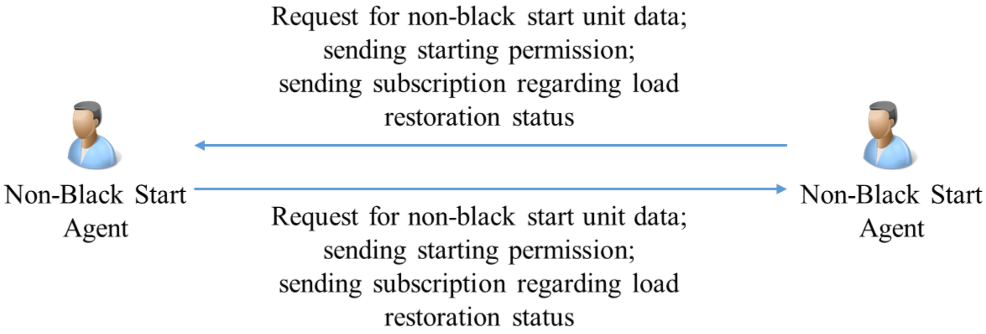


Figure 7.13 Interactions between NBSAs

7.5 Control algorithm

The algorithm responsible for load restoration is shown in Figure 7.14. The operation starts with the collection of information from loads in the system. They include data such as load demand at the time of the blackout, priority of the load, the node in which it is located and the status of the recovery if the load has been partially energized in the previous step of system restoration. Upon receiving the data, the load with the highest priority is searched for. The capacity of the non-black start generator is then compared to the load demand. If the non-black start can restore the load, it will check if it is at the same bus as the NBSU. If not, a request is sent to the BSUA to determine the path to the load. After receiving a confirmation of readiness for the components included in the restoration path, the load is energized and a notification is sent to the remaining NBSAs regarding the status of the loads restored. In the case of the insufficient power of the generator, the request for the possibility of partial load restoration is prepared. After a positive response, the notification procedure is the same as for the full power restoration. The difference is the content of the subscription, in which the restoration status must be marked appropriately. This is necessary in subsequent steps of the system restoration. At the moment of available power from another NBSU, which load needs complete restoration and which are fully connected to the network are checked.

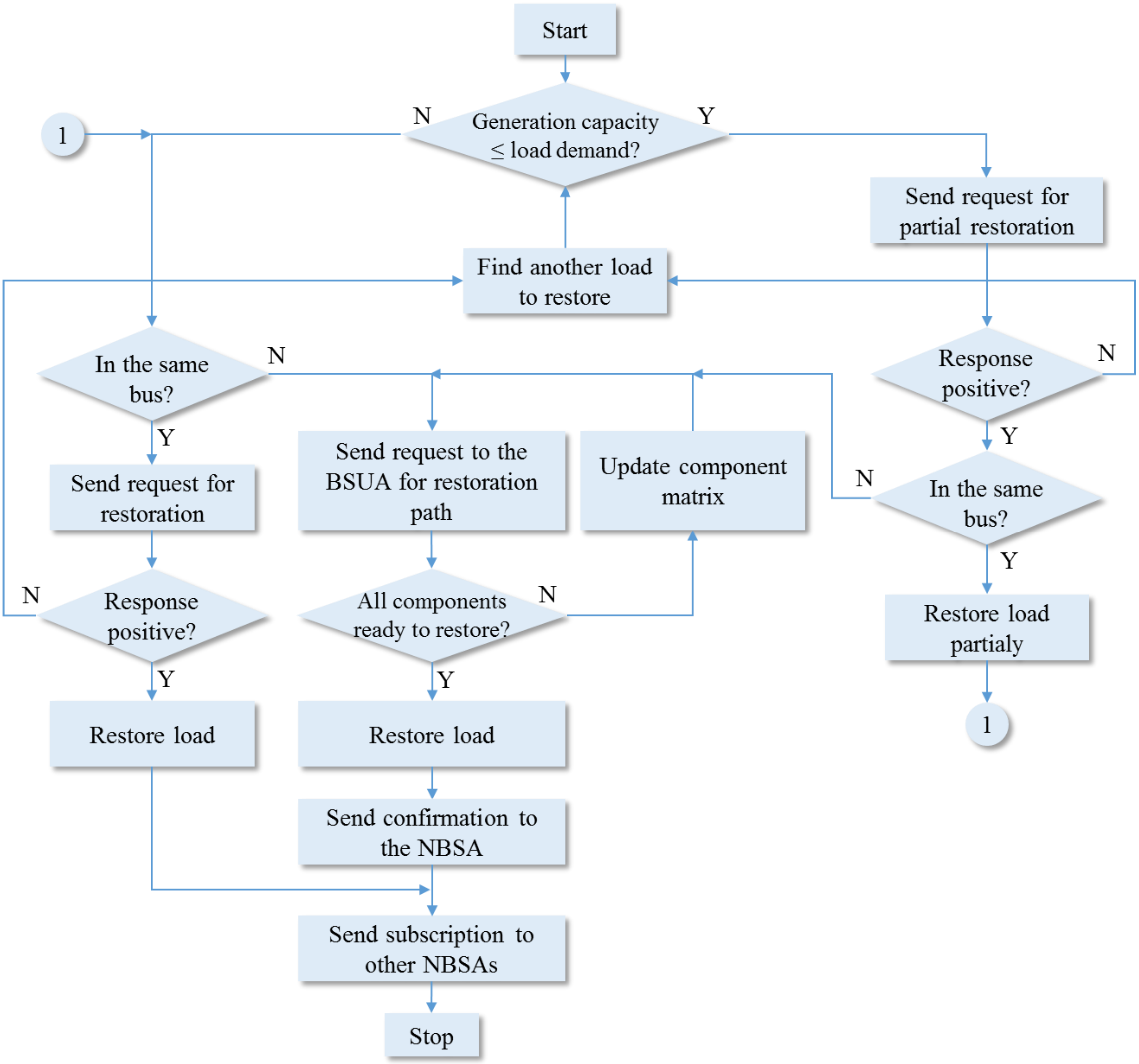


Figure 7.14 Block diagram of the load restoration algorithm

7.6 Selection of weights

The selection of weights needed for the shortest path algorithm can be realized based on different assumptions. One of them can be line impedances. Since each line in the system is characterized by certain values of reactance and resistance, this can be deployed as weights for the shortest path algorithm. Considering concerns which are present during the restoration process, application of the reactance as weights would help to find the path which results in the smallest voltage transients or overvoltages. This, however, might not be considered as a crucial decision factor due to the very small transient duration periods. Comparing the period of the whole restoration procedure, often lasting several hours, consideration of millisecond phenomena seems to be unjustified.

The weights adjustment in the restoration scheme proposed is based on element confirmations included in the restoration path. At the beginning of the restoration, each line has the same weight value equal to 1. After the path has been selected and confirmed by components, line weights are decreased by the value of 0.1. That gives the priority of choosing the same components in the next path, since the sum of weight will be smaller. Once the path has been confirmed, the values of weights are decreased. The value of 0.1 is chosen arbitrarily and is used to show the adjustment principle. If one of the components refuses readiness for restoration, its weight increases its value by 1. The number of switching operations can be lowered by choosing the same restoration path to energize different components. The remaining components can be restored if the power system is robust enough for possible disturbances since the grid restoration aims at picking up the main power system structure. The weight adjustment can be represented in the following form:

$$w(n,i) = \begin{cases} w_{n,i} = 1, & n = 1 \\ w_{n,i} = w_{n-1,i} - 0.1, & n > 1 \cap \forall y_i = 1 \\ w_{n,i} = w_{n-1,i} + 1, & n > 1 \cap \exists y_i = 0 \end{cases} \tag{7.1}$$

where:

$w_{n,i}$ – weight of i-th component in the current path in the n-th iteration and
y_i – status of component restoration readiness: $y = 1$ – ready; $y = 0$ – not ready.

The block diagram of the adjustment procedure proposed is presented in Figure 7.15. After path selection, load flow calculations are performed to check system stability in case of practical path execution.

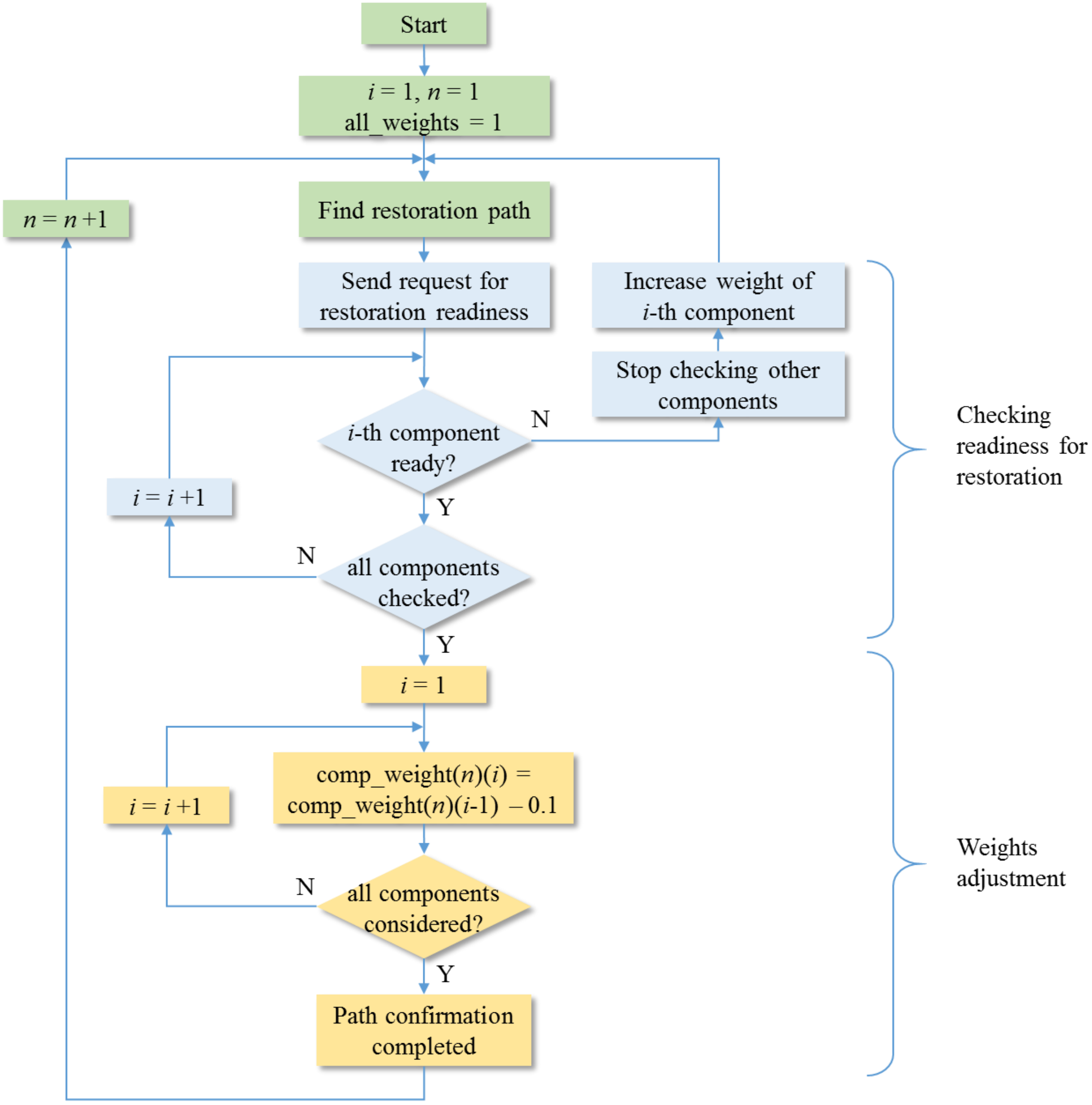


Figure 7.15 Block diagram of the algorithm for path confirmation and weights adjustment

Figure 7.16 shows the network considered together with agents subordinated to each network component as an example of the concept. This structure will be considered to present agent interactions during the grid restoration.

Several assumptions are made during the visualization of the weight adjustment concept. The NBSUs are energized in the following order: NBSU 1, NBSU 2 and NBSU 3. Load 1 has priority “2” and Load 2 has priority “1” which means that Load 2 will be restored first. During the restoration, it is assumed that the load demand of available loads exceeds their rated values, which translates into a necessity of performing additional actions to meet the load demand.

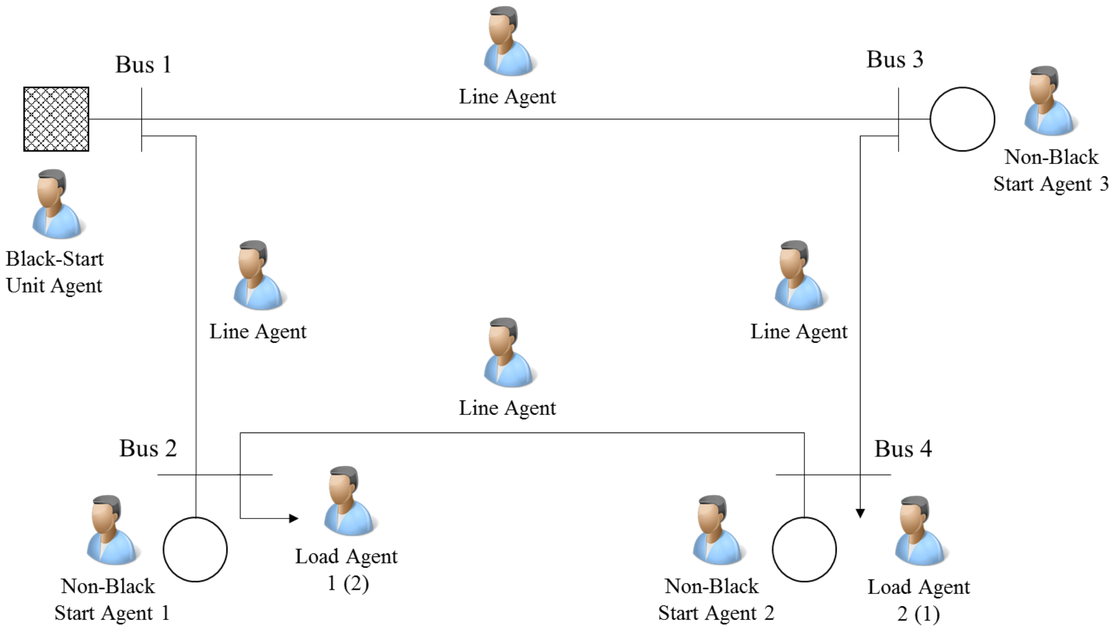


Figure 7.16 System structure

In the first step, the path from black-start unit (BSU) to NBSU 1 needs to be found to provide cranking power. Since there are two possible paths available to complete this step (represented by blue and green path in Figure 7.17), the one which has the least number of lines is selected, which also translates into a smaller number of switching operations. After the path to restore NBSU 1 is selected, the weighting of the corresponding line is decreased by 0.1, starting from 1. This value is chosen arbitrarily and serves to illustrate the principle of the weight adjustments proposed during the restoration. The current weight value of line 1 is now 0.9 (see Figure 7.18).

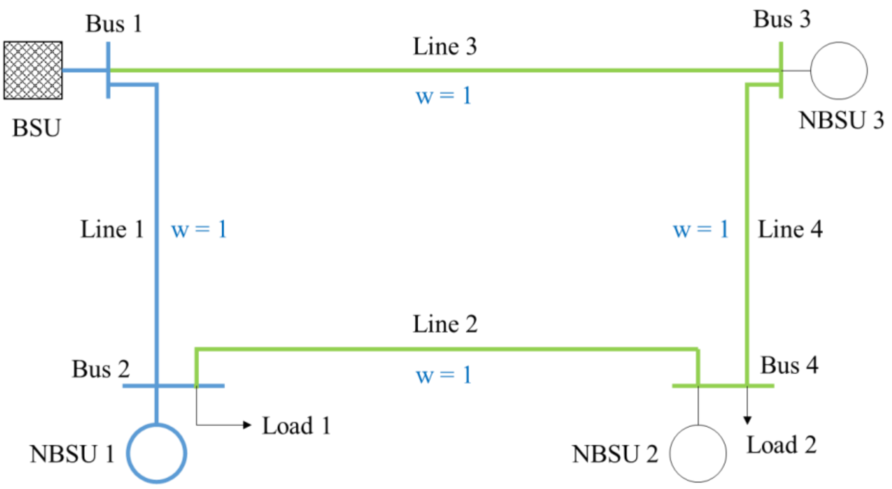


Figure 7.17 Selection of path to energize NBSU 1

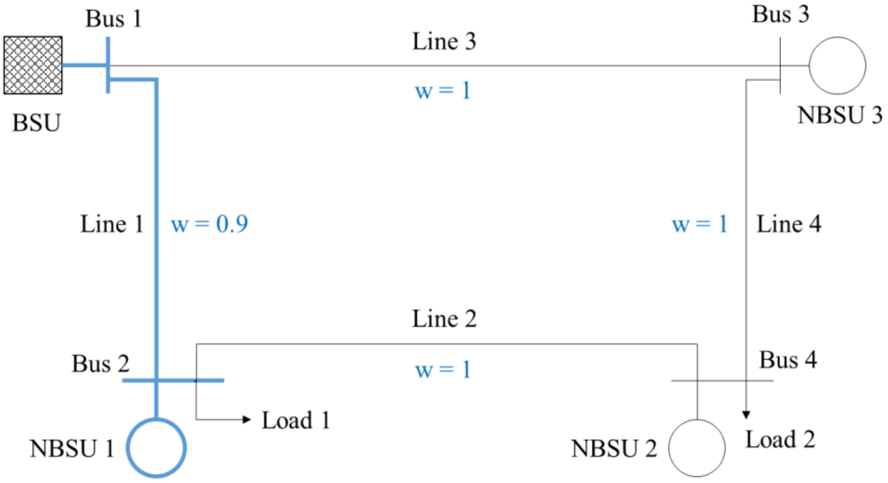


Figure 7.18 Weight adjustment after energization of NBSU 1

In order to keep the balance between the generated and consumed power, after NBS1 has been restored, the load having the highest priority is found and this constitutes the factor for the determination of the order of loads to be restored. There are two possibilities to energize load 2 from NBSU 1 (see Figure 7.19). Based on the current weight values, the path which has the least sum of weights is selected to energize the load. In this case, the path containing line 2 will be used to provide power to load 2. After the path is selected, the weight is adjusted by decreasing its values by 0.1. The resulting representation of weights in network is presented in Figure 7.20.

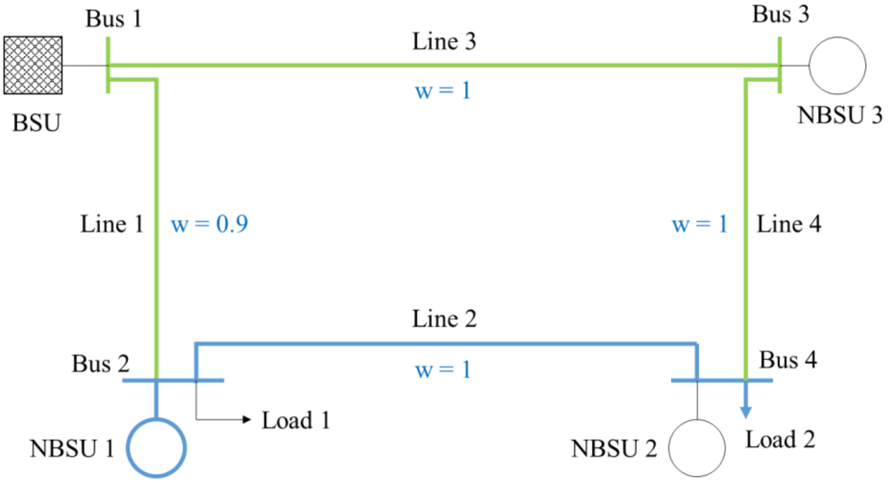


Figure 7.19 Selection of path to restore load 2

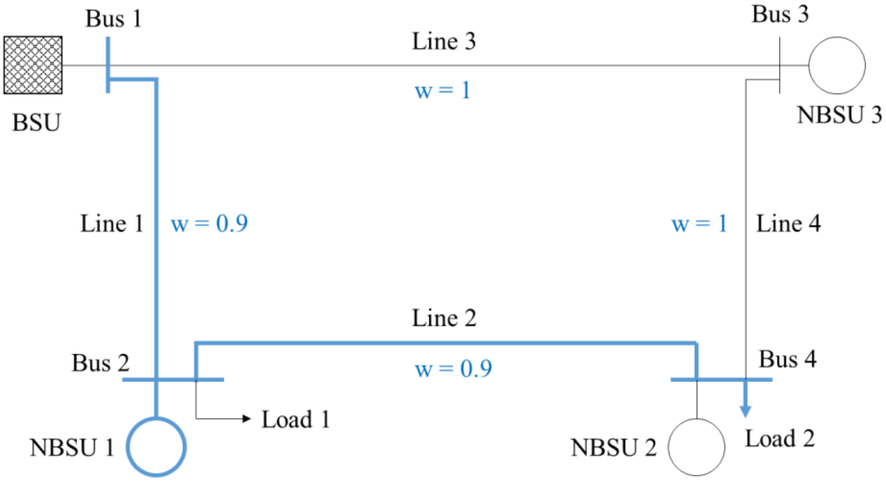


Figure 7.20 Weight adjustment after restoration of load 2

In this example, it is assumed that agents corresponding to NBSUs do not know the exact load demand at the beginning of the restoration. It is assumed that the load demand is much greater than the capacity of NBSU 1. Other generators need to be energized to increase power generation capability in the system to meet the load demand. According to the minimal critical time, generation unit NBSU 2 has been selected to be energized. Since there are two paths with the same amount of lines (see Figure 7.21), the decision regarding path selection is made based on sum of weights in each path. In this case, the path including lines 1 and 2 will be used to energize NBSU 2. The weights after adjustment are presented in Figure 7.22.

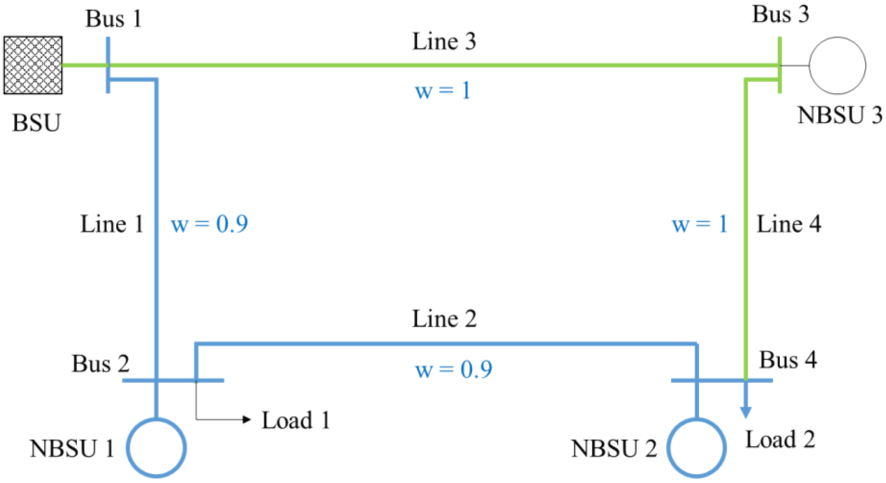


Figure 7.21 Selection of path to energize NBSU 2

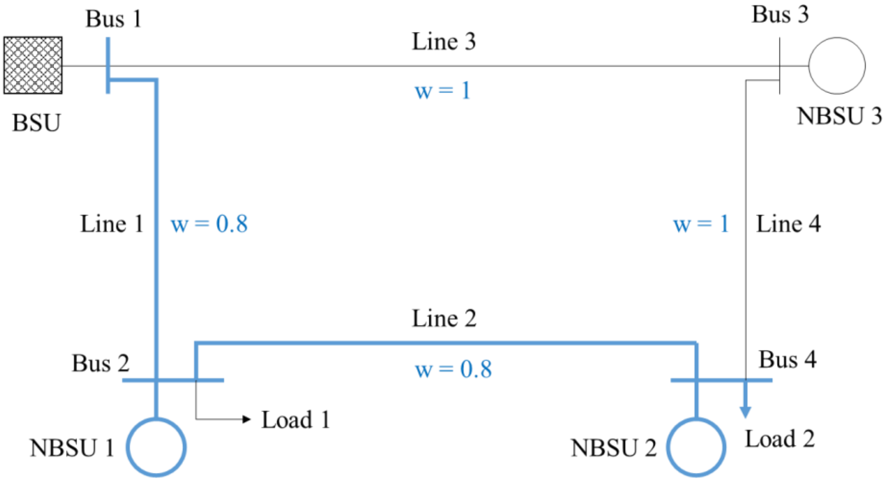


Figure 7.22 Weights adjustment after energization of NBSU 2

Assuming that the power provided to load 2 is still insufficient, which results from system instability derived from load flow calculation, the third generator NBSU 3 will be energized through line 3, which constitutes the path having the least sum and number of lines among other available possibilities (see Figure 7.23 and Figure 7.24).

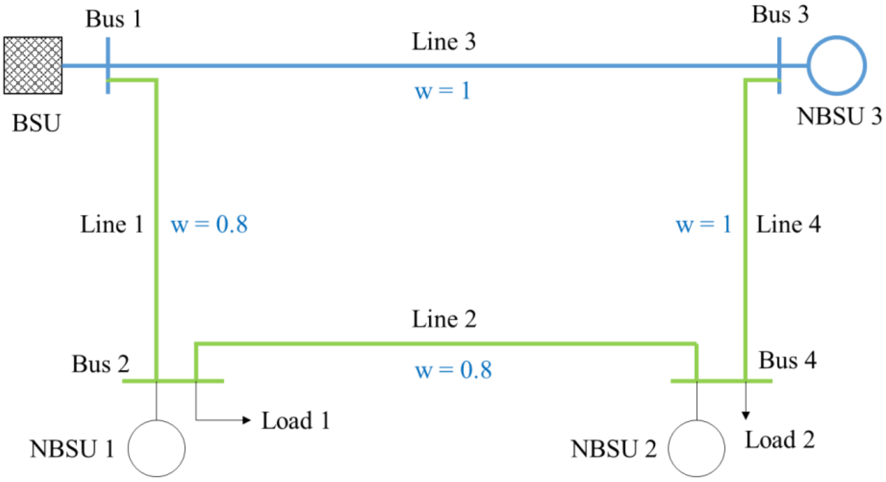


Figure 7.23 Selection of path to energize NBSU 3

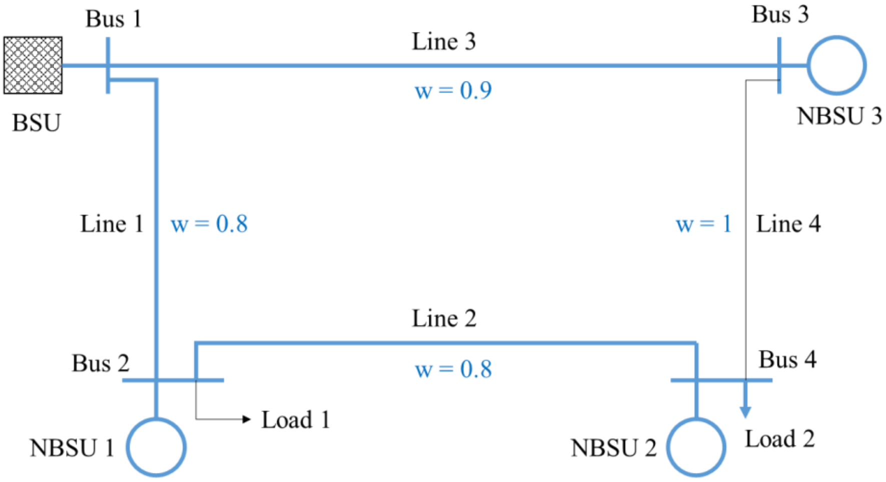


Figure 7.24 Weights adjustment after energization of NBSU 3

After NBSU 3 is restored, power to load 2 is provided using line 4 (see Figure 7.25), which has been selected based on the same principle presented previously. In the case of the restoration of load 2, the final weight representation is shown in Figure 7.26.

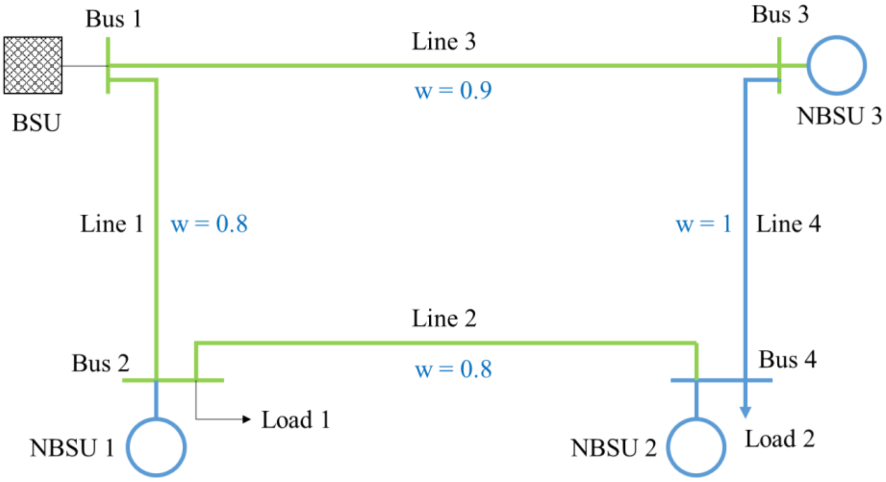


Figure 7.25 Selection of path to provide additional power to load 2

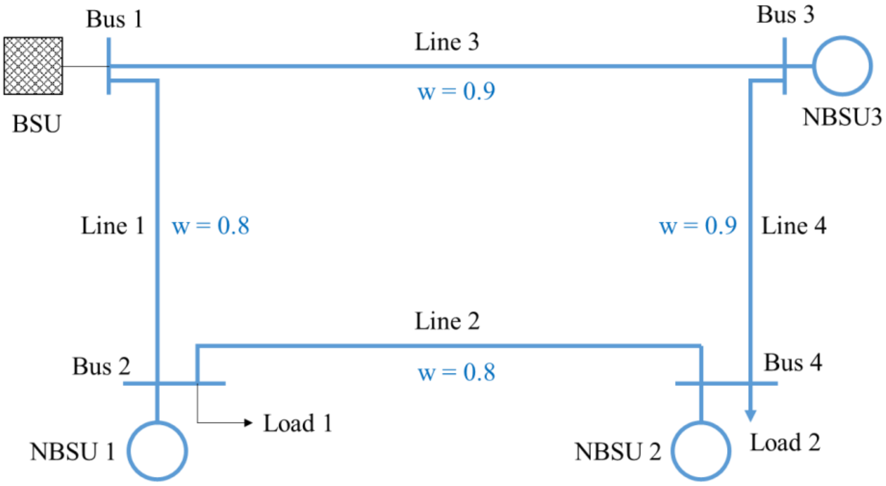


Figure 7.26 Weights adjustment after full restoration of load 2

Since all the lines in the system have been connected, the execution of restoration of load 1 will be proven by load flow calculations.

After a certain time, normally lasting several hours, the load demand of load 2 will decrease and reach its rated value due to dynamic properties of load during restoration. Since load 2 resides in the same bus as NBSU 2, its partial demand will be covered by the capacity available of NBSU 2. The rest of its demand needs to be covered by the two other generations units, NBSU 1 and NBSU 3.

The load demand of load 1 at the beginning of the restoration can be much greater in comparison to its nominal value. Since load 1 is located at the same node as NBS1, this generation unit will start the restoration process. If the load flow calculation proves system instability after connecting the whole load at bus 2, another strategy needs to be applied. The partial restoration can be executed here. It is possible to restore the total load partially since loads in a real power system are connected to the main bus through several terminals. However, because the initial load demand is unknown, the success of partial restoration can be proven in advance by load flow calculations. The next sections of the load can be restored depending on the power generation capability and system robustness to possible power imbalances. The selection of specific load parts to be restored depends, however, on internal decisions and load division schemes.

7.7 Selected test cases

The illustrative power system presented in Figure 7.16 has been selected to validate the assumed functionality. It consists of a grid island in which one black start generator is available and can provide cranking power to other NBSUs. Two loads with priorities 1 and 2 are located at buses 3 and 2, respectively. The voltage level was not considered, since this parameter is not necessary to prove system functionality under the assumptions provided. The aim of this scenario is to provide a restoration sequence with the shortest possible restoration time. Communication channels are assumed to exist between each two components and buses directly connected by a power line, whether this line is energized or not.

The BSU can provide cranking power to NBSU 1, NBSU 2 and NBSU 3. Those units have a power capacity of 10, 5 and 10 MW, respectively. Load 1 and Load 2, in turn, considering the increased demand at the beginning of the restoration process, have demands of 15 and 20 MW with priorities 2 and 1, respectively. The load with priority 1 will be restored first.

The objective is to maximize power output – and therefore load coverage – in each specified restoration step. At the same time, during power restoration, in order to keep balance between generated and consumed power, loads are energized after each step involving restoration of non-black start units.

Objective functions in this case encompass maximizing the amount of load restored considering the load priority

$$\max \sum_{i}^{N_{\mathrm{L}}} L_i \cdot y_i \tag{7.2}$$

where:

N_{L} – number of loads in the system,
L_i – load in bus i,
y_i – status of load restored

and minimizing of restoration time T_{res}

$$\min T_{\mathrm{res}} \tag{7.3}$$

Table 7.2 and Table 7.3 present the line utilization and bus voltages, respectively, during the grid restoration performed. Figures from Figure 7.27 to Figure 7.32 shows selected restoration steps indicating changes in the system. In turn, Figure 7.33 and Figure 7.34 present interactions between agents. The full interactions conforming to the FIPA Request Protocol, mentioned in Subchapter 4.2, are not shown here since the request messages sent to specific agents are accepted in all cases. In this scenario, partial restoration is considered to present agent interactions. In order to perform partial load restoration, it is assumed that NBSAs know the initial load demand at the beginning of the restoration. It is very difficult to estimate initial load demand in the real network operation, due to dynamic load behaviors. The scenario presented, however, is a good example of agent interactions and behaviors that could be applied in grid restoration. The consideration of additional stability issues of the power system restoration, presented in Chapter 2.4.6, translates into a need to extend agent tasks and functions.

Table 7.2 Line utilization during the partial load restoration

Restoration step	**Line utilization in %**				**Remarks**
	Line 1	**Line 2**	**Line 3**	**Line 4**	
Step 1	54.9	0	0	0	Restoration NBSU 1
Step 2	0.8	84.2	0	0	Full restoration of Load 2 (10 MW)
Step 3	27.2	41.9	0	0	Restoration NBSU 2
Step 4	0.4	41.9	0	0	Partial restoration of Load 1 (5 MW)
Step 5	0.4	41.9	0	82.5	Restoration NBSU 3
Step 6	21.1	10.5	52.2	30.5	Complete restoration Load 1 (15 MW)

Table 7.3 Bus voltages during the partial load restoration

Restoration step	**System voltages in p.u.**			
	Bus 1 (slack node)	**Bus 2**	**Bus 3**	**Bus 4**
Step 1	1.0000	1.0152	-	-
Step 2	1.0000	1.0123	1.0057	-
Step 3	1.0000	1.0176	1.0163	-
Step 4	1.0000	1.0126	1.0112	-
Step 5	1.0000	1.0126	1.0112	1.0143
Step 6	1.0000	1.0073	1.0105	1.0133

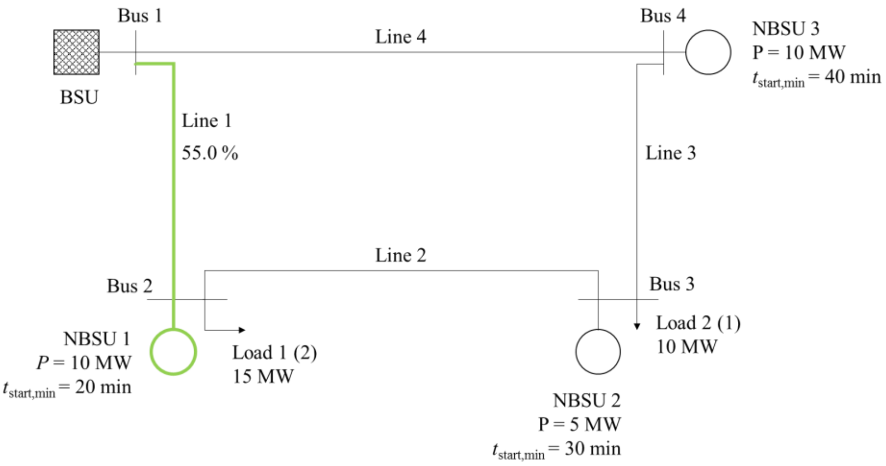


Figure 7.27 Step 1: Energizing of NBSU 1

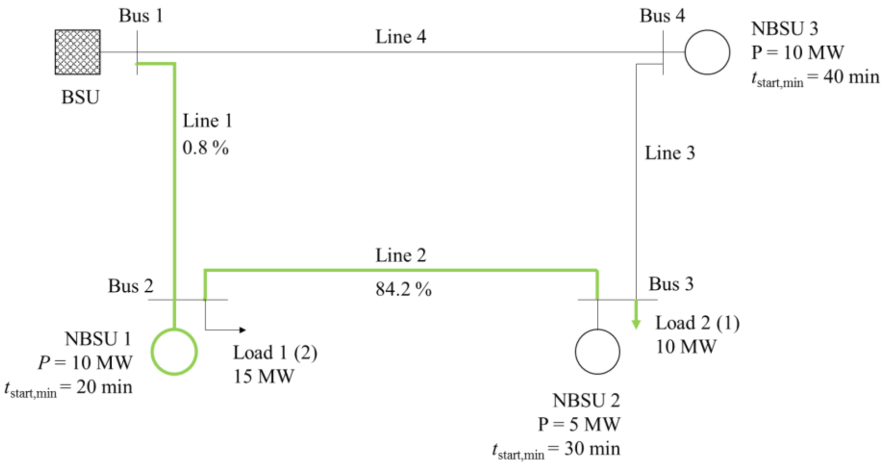


Figure 7.28 Step 2: Full restoration of Load 2

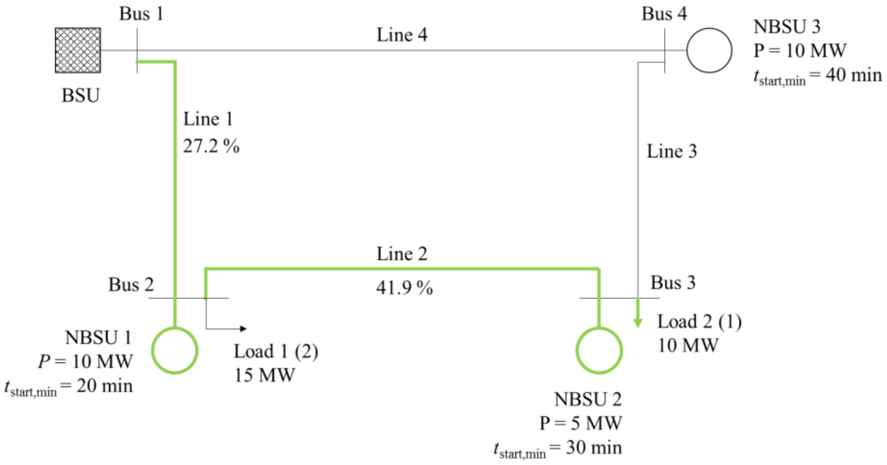


Figure 7.29 Step 3: Restoration of NBSU 2

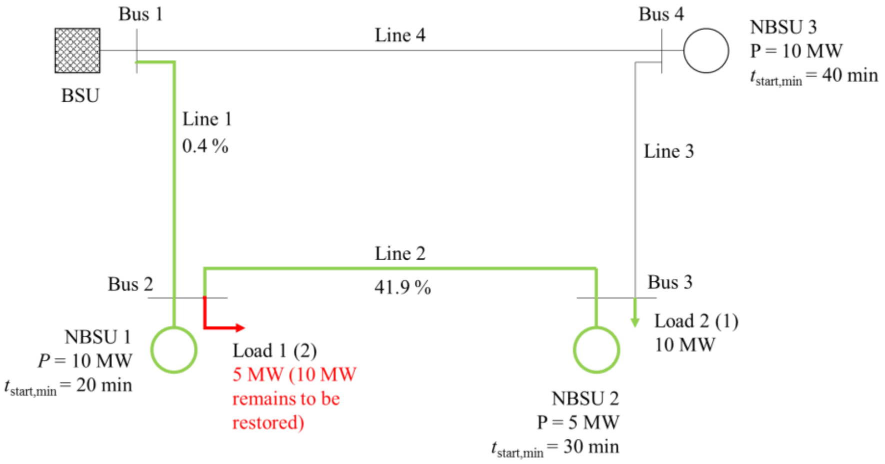


Figure 7.30 Step 4: Partial restoration of Load 1

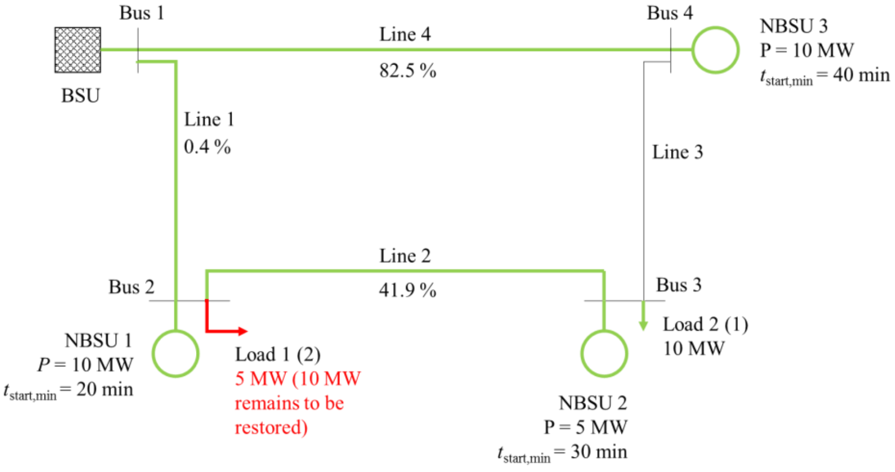


Figure 7.31 Step 5: Restoration of NBSU 3

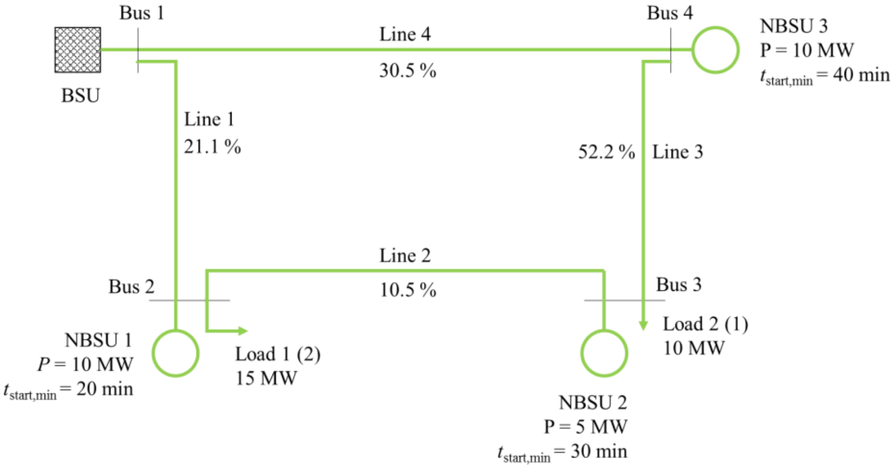


Figure 7.32 Step 6: Full restoration of Load 1

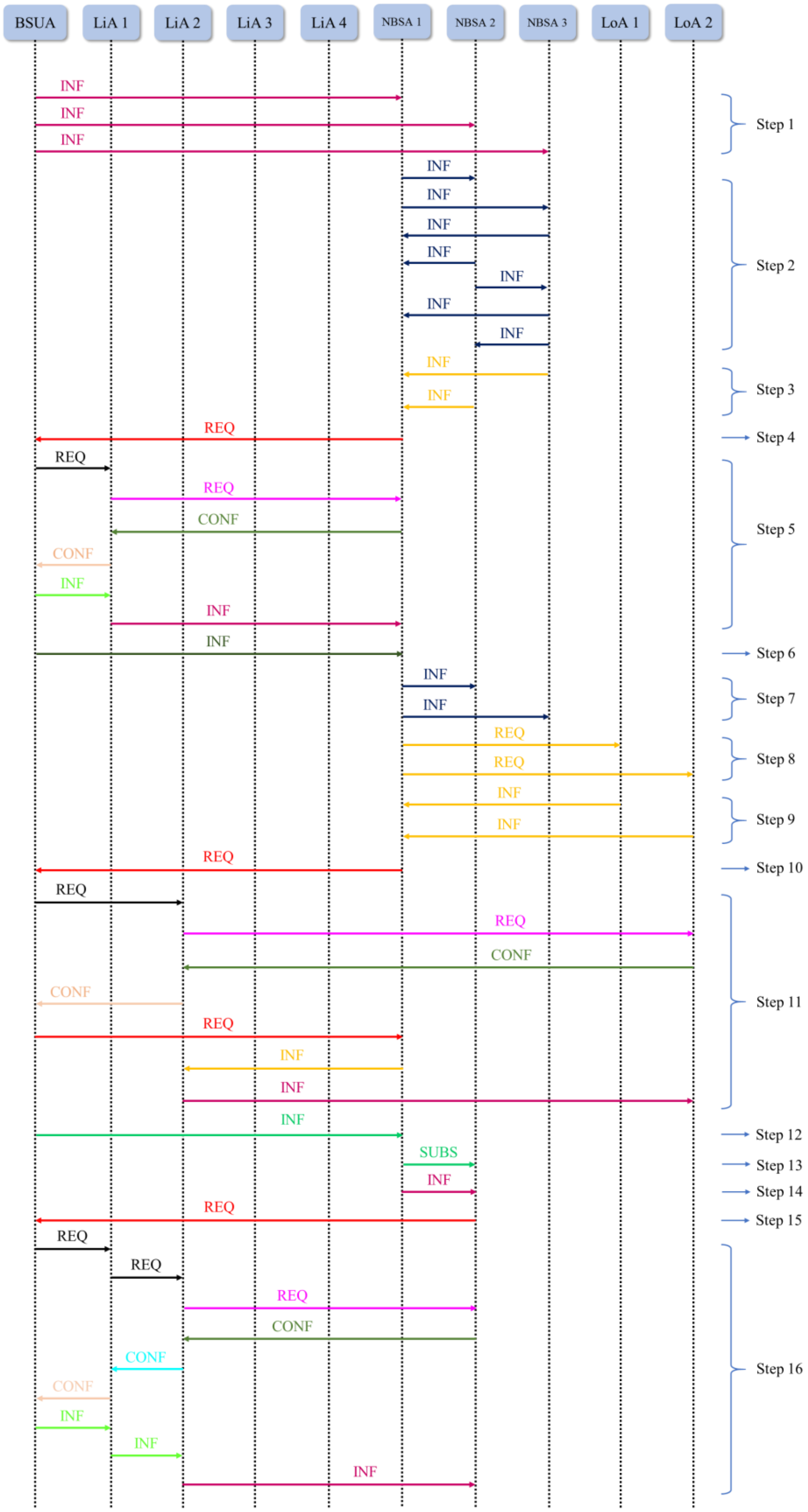


Figure 7.33 Agent interactions in grid restoration

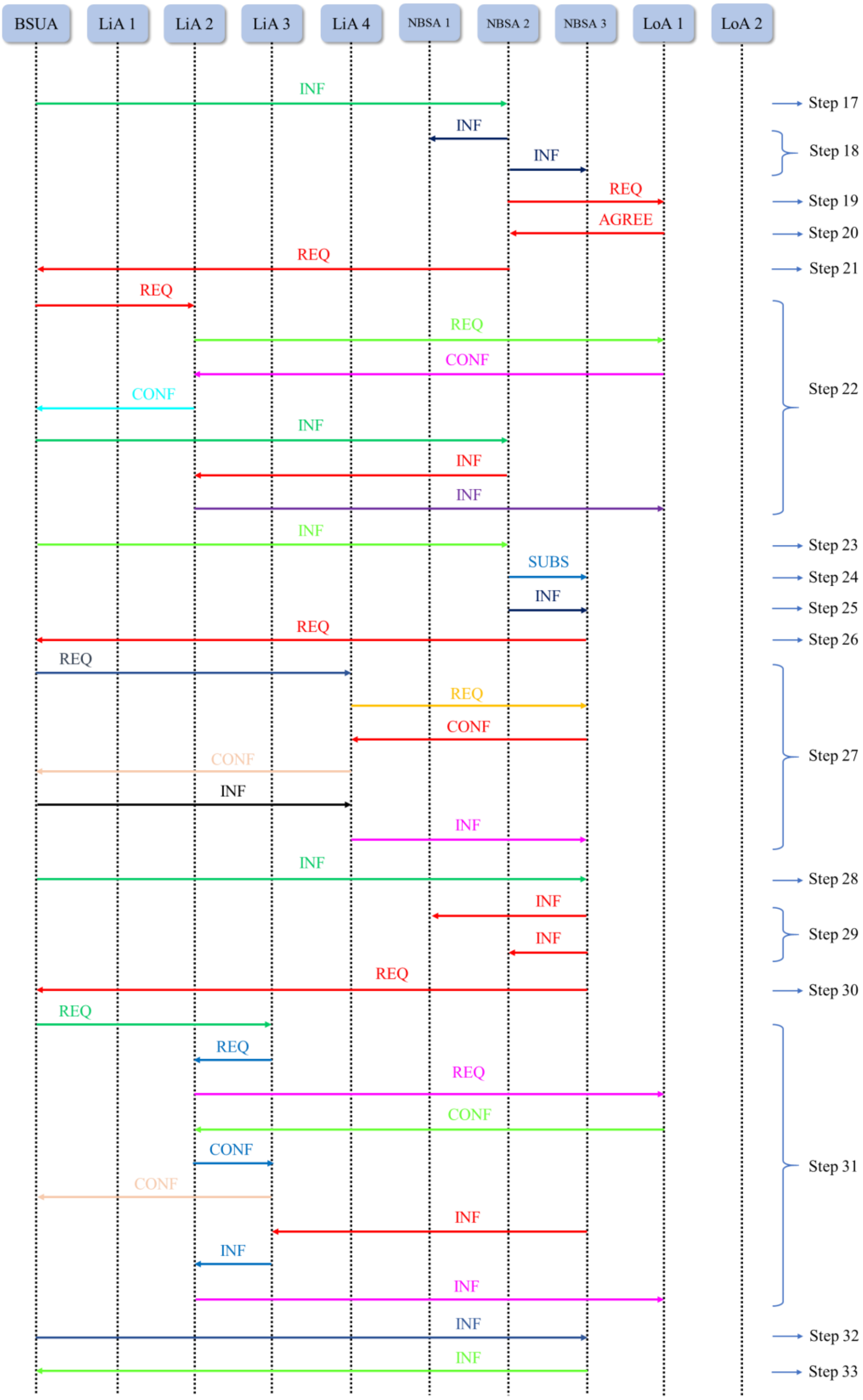


Figure 7.34 Agent interactions in grid restoration, continuation

Table 7.4 Actions performed in each process step (scenario 1)

Step	Action
Step 1	BSUA sends information to NBSAs to start the restoration process
Step 2	Information exchange between NBSAs and selection of one NBSA which will initiate the restoration process. It will be the one which has the shortest restoration time
Step 3	NBSA 2 and NBSA 3 send starting permission to NBSA1
Step 4	NBSA 1 requests BSUA to calculate the restoration path
Step 5	Requesting, confirming and informing about readiness components to execute path to NBSA 1
Step 6	BSUA sends message to NBSA 1 regarding system stability
Step 7	NBSA 1 sends starting notification to NBSA 2 and NBSA 3
Step 8	Sending request to available loads regarding load data: bus at which load is located, priority of load, load demand
Step 9	Load 1 and Load 2 send parameters required to NBSA 1
Step 10	Selecting of load which has the highest priority. NBSA 1 sends request to the BSUA to calculate the path to Load 2 (demand 10 MW)
Step 11	Checking, confirming and informing regarding load restoration
Step 12	Checking stability after restoration of given amount of load. The BSUA sends message to the NBSA 1 regarding system stability
Step 13	NBSA 1 sends notification regarding status of restored loads to the NBSA 2
Step 14	Sending starting notification to the next NBSA selected – NBSA 2
Step 15	NBSA 2 sends request to the BSUA regarding the restoration path
Step 16	BSUA checks the components readiness to execute the restoration path to NBSA 2
Step 17	BSUA sends message to NBSA 2 regarding system stability
Step 18	NBSA 2 sends a notification regarding its restoration to NBSA 2 and NBSA 3
Step 19	NBSA 2 sends the request to Load 1 regarding partial restoration. Load demand of Load 1 is 15 MW and the capacity of the NBSU is 5 MW
Step 20	NBSA 2 receives agreement from Load 1 for the partial restoration
Step 21	NBSA 2 sends request to the BSUA to calculate the restoration path to Load 1
Step 22	Checking, confirming and informing about readiness of components creating the restoration path to Load 1
Step 23	BSUA sends message to NBSA 2 regarding system stability
Step 24	NBSA 2 sends restoration status to the next NBSA selected – NBSA 3
Step 25	NBSA 2 sends starting permission to NBSA 3
Step 26	NBSA 3 sends the request to the BSUA to find the restoration path

Step	Action
Step 27	Checking, confirming and informing about the readiness of components creating the restoration path to NBSA 3
Step 28	BSUA checks the stability of the system after integration of NBSU 3 and sends notification to NBSA 3 regarding system stability
Step 29	NBSA 3 sends notifications to NBSA1 and NBSA2 about its restoration
Step 30	NBSA 3 sends the request to the BSUA for the restoration path to Load 1
Step 31	Checking, confirming and informing about readiness of the components creating the restoration path to Load 1
Step 32	BSUA checks the stability after restoration of Load 1 and sends a message to NBSA 3 regarding system stability
Step 33	NBSA 3 sends notification to the BSUA regarding the complete restoration of all loads

In the next scenario, only full load restoration can be performed. The stability of the system in each restoration step is assessed by lines utilization since GAs do not have any information about the initial load demand. Table 7.5 and Table 7.6 show the line utilization and bus voltages for each restoration step, respectively. There is an overload of line 3 during the restoration since the load demand of Load 2, having the highest priority, exceeds its nominal value. In this case, the next generation unit is energized to cover the increased load demand. The NBSU 2 is restored in Step 3. The provision of additional power to the restored load alleviates the line overload. Since the load demand at the beginning of the restoration is unknown, starting of subsequent units can support the supply of the loads required. After energizing NBSU 3, the system remains stable and the last step constitutes the restoration of Load 1, which has a minor priority. Although the increased demand of load 1 is considered in this case, its restoration does not contribute to system instability. Black start units, represented by the slack node, cover all the losses and power mismatches between load and generation. Considering real power networks, such as an island having no connection with an external network, such a situation would not happen. Here, due to a simplified network modeling, its dynamic behavior and physical interactions between components are neglected. This can, however, show the conception of grid restoration and the influence of each step on system stability. Figure 7.41 and Figure 7.42 show agent interactions during system management. In this case, the interactions in the frame of the FIPA Request Protocol are limited to sending request messages and receiving either *agree* or *refuse* notification. Figure 7.35 to Figure 7.40 shows each restoration step together with the line utilization.

Table 7.5 Line utilization during the load restoration

Restoration step	Line utilization in %				Remarks
	Line 1	Line 2	Line 3	Line 4	
Step 1	54.9	0	0	0	Restoration of NBSU 1 (10 MW)
Step 2	58.7	170.1	0	0	Restoration of Load 2 (20 MW)
Step 3	29.5	126.9	0	0	Restoration of NBSU 2 (5 MW)
Step 4	29.5	126.9		82.5	Restoration of NBSU 3 (10 MW)
Step 5	13.3	63.0	62.5	20.1	Restoration of Load 2
Step 6	21.1	10.5	52.2	30.5	Decreasing of demand of Load 2 to its nominal value (10 MW) and restoration of Load 1 (15 MW)

Table 7.6 Bus voltages during the restoration

Restoration step	System voltages in p.u.			
	Bus 1 (slack node)	Bus 2	Bus 3	Bus 4
Step 1	1.0000	1.0152	-	-
Step 2	1.0000	1.0004	0.9828	-
Step 3	1.0000	1.0065	0.9946	-
Step 4	1.0000	1.0065	0.9946	1.0143
Step 5	1.0000	1.0134	1.0079	1.0120
Step 6	1.0000	1.0073	1.0105	1.0133

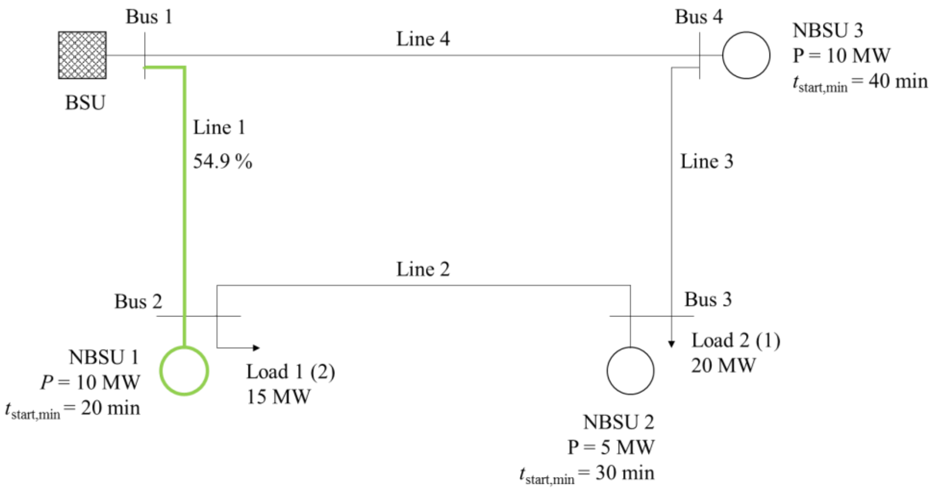


Figure 7.35 Step 1: Restoration of NBSU 1

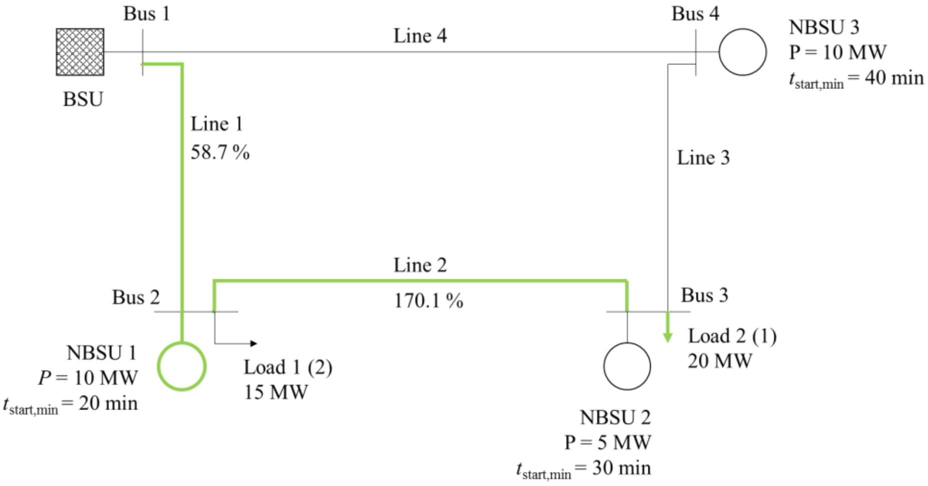


Figure 7.36 Step 2: Attempt of the full restoration of Load 2

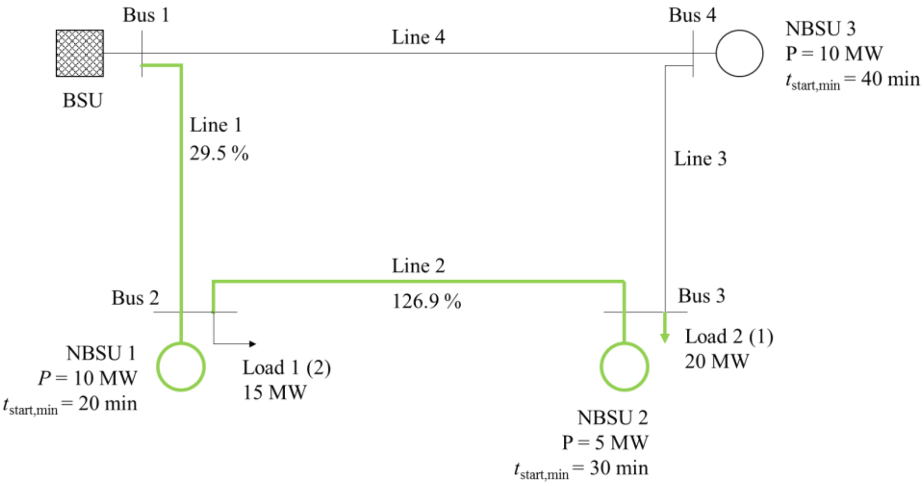


Figure 7.37 Step 3: Restoration of NBSU 2

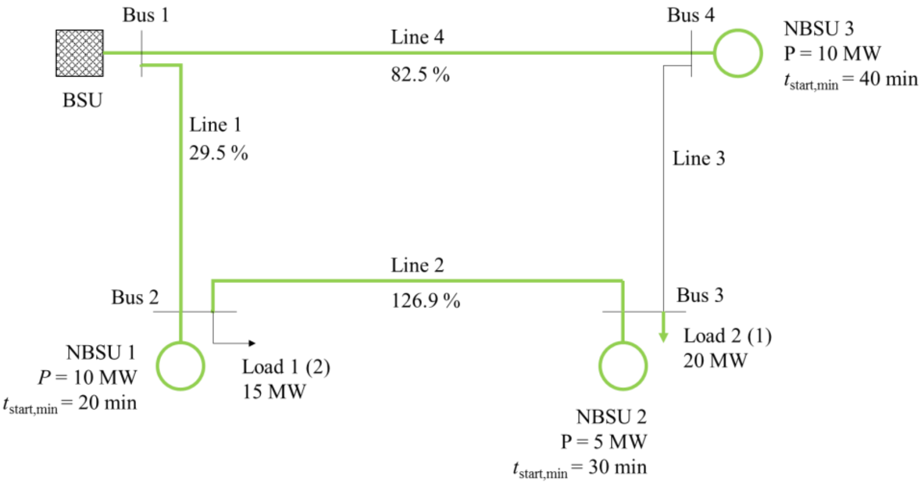


Figure 7.38 Step 4: Restoration of NBSU 3

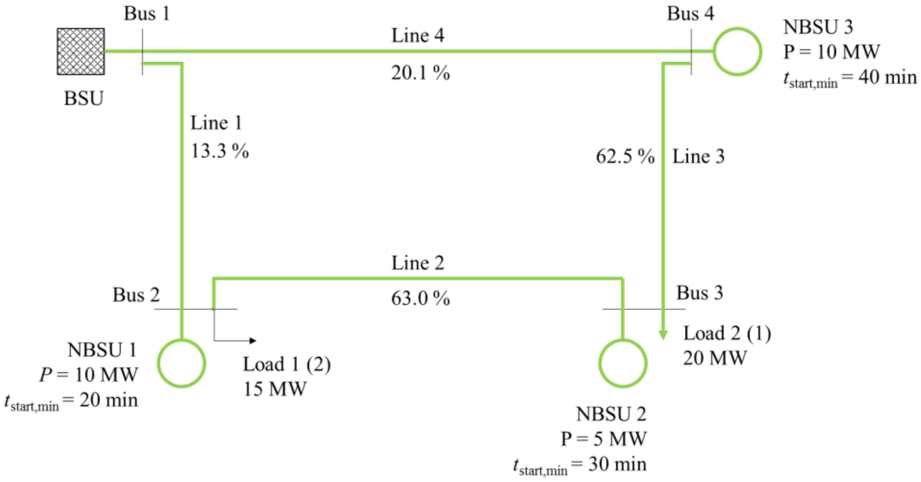


Figure 7.39 Step 5: Support in the restoration of Load 2

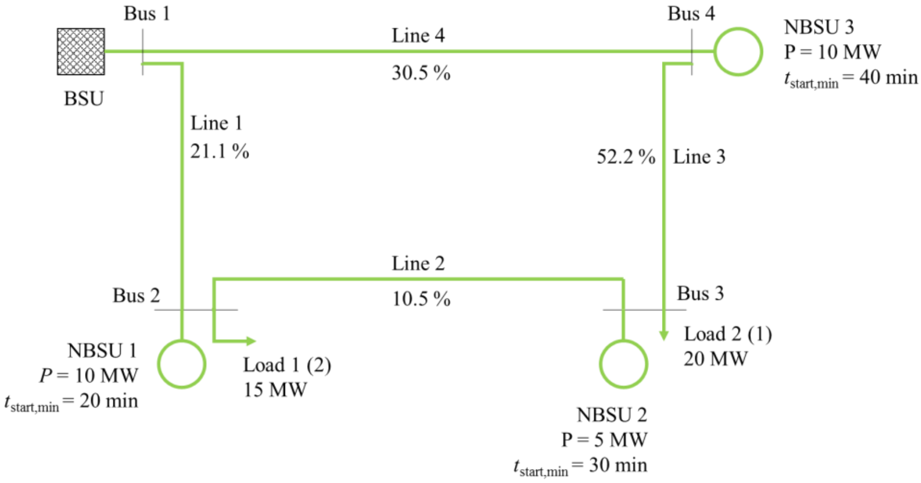


Figure 7.40 Step 6: Full restoration of Load 1

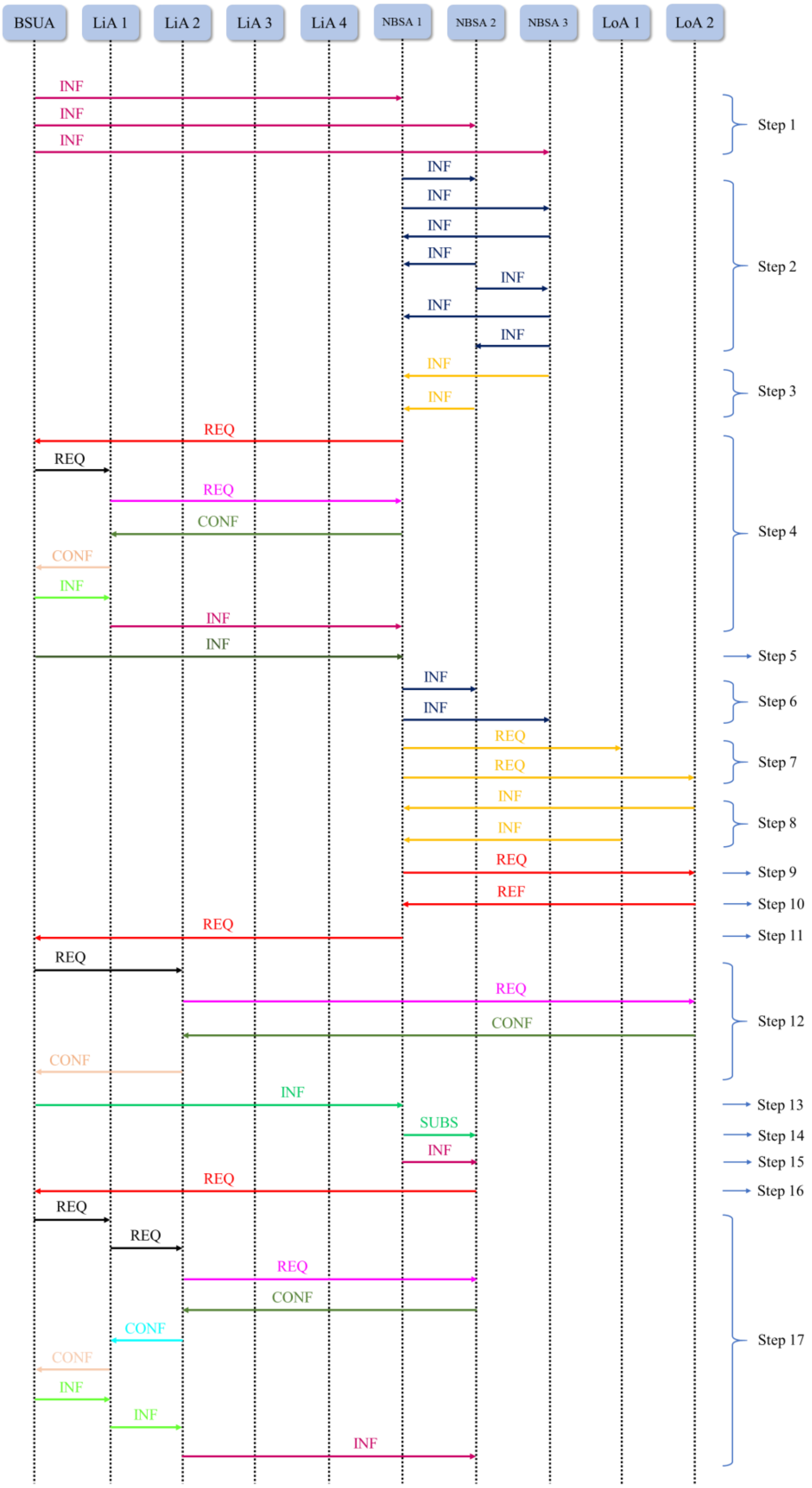


Figure 7.41 Agent interactions in grid restoration (scenario 2)

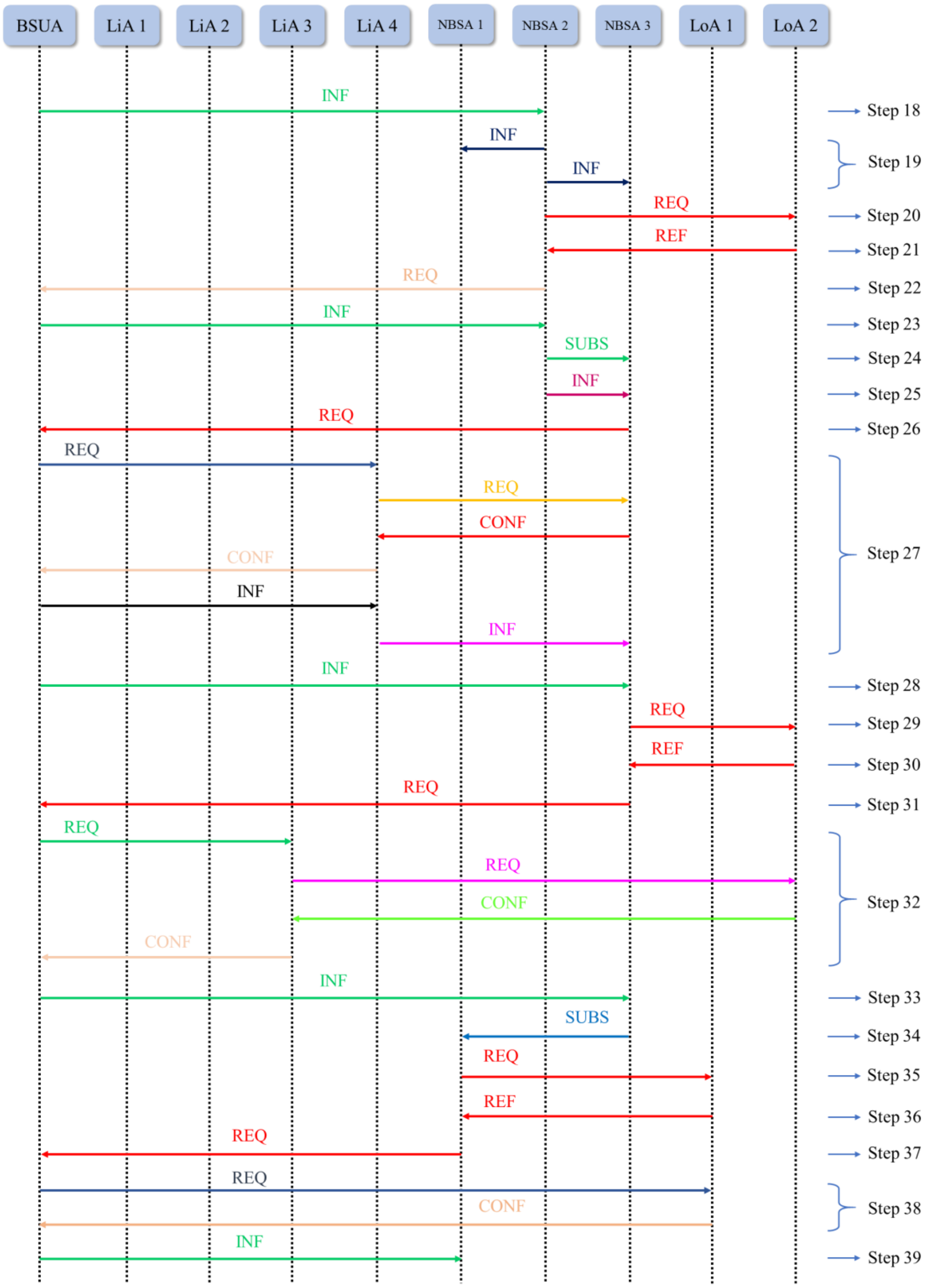


Figure 7.42 Agent interactions in grid restoration (scenario 2), continuation

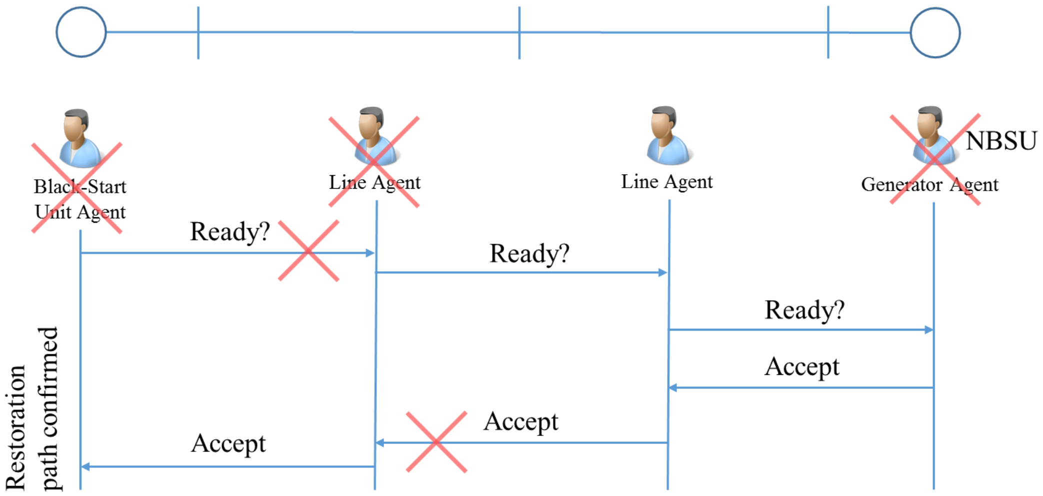
Table 7.7 Actions performed in each process step (scenario 2)

Step	Action
Step 1	BSUA sends information to NBSAs to start the restoration process
Step 2	Information exchange between NBSAs and selection of the one NBSA who will initiate the restoration process. It will be the one who has the shortest restoration time
Step 3	NBSA 2 and NBSA 3 send starting permission to NBSA 1
Step 4	NBSA 1 requests the BSUA to calculate the restoration path
Step 5	Confirming and informing about the component readiness to execute path to NBSA 1
Step 6	BSUA checks the system stability and sends notification about the system instability to NBSA 1
Step 7	NBSA 1 sends notification about its start to NBSA 2 and NBSA 3
Step 8	NBSA 1 sends the request to available loads regarding load data: bus at which load is located, priority of load, load demand
Step 9	Choosing the load with the highest priority and sending a request to Load 2 for the partial restoration. Demand of Load 2 (20 MW) is much higher than the capacity of NBSA 1 (10 MW)
Step 10	Load 2 sends a refusal message to NBSA 1 regarding the possibility of partial restoration
Step 11	NBSA 1 sends the request to the BSUA to calculate the restoration path to Load 2.
Step 12	Checking, confirming and informing NBSA 1 regarding the load restoration
Step 13	BSUA sends a message to NBSA 1 regarding the system instability
Step 14	NBSA 1 sends the status of restored loads to NBSA 2
Step 15	NBSA 1 sends the starting notification to the next NBSA selected – NBSA 2
Step 16	NBSA 2 sends the request to the BSUA regarding the restoration path
Step 17	BSUA checks the component readiness to execution the restoration path to NBSA 2
Step 18	BSUA sends a message to NBSA 2 regarding the system instability
Step 19	NBSA 2 sends a notification about its restoration to NBSA 1 and NBSA 3
Step 20	NBSA 2 sends a request to Load 2 for the partial restoration
Step 21	NBSA 2 receives a refusal message – the amount of Load 2 must be restored at once (internal requirement of Load 2)
Step 22	BSUA checks the stability after restoring Load 2 at the same bus where NBSA 2 resides.
Step 23	NBSA 2 receives a message from BSUA regarding the system instability
Step 24	NBSA 2 sends a notification to the next NBSA 3 selected regarding the status of the restored load
Step 25	NBSA 2 sends the starting notification to NBSA 3
Step 26	NBSA 3 sends the request to the BSUA regarding the restoration path to NBSA 3

Step	**Action**
Step 27	BSUA checks the component readiness for the restoration
Step 28	NBSA 3 receives the message from the BSUA regarding the system instability
Step 29	NBSA 3 sends the request to Load 2 for the partial restoration
Step 30	Load 2 sends a refusal message to NBSA 3
Step 31	NBSA 3 sends the request to the BSUA regarding the restoration path to Load 2
Step 32	BSUA checks the readiness of components to execute the restoration path
Step 33	BSUA sends a message to NBSA 3 about the system stability – Load 2 fully restored
Step 34	NBSA 3 notifies NBSA1 about the status of restored loads
Step 35	NBSA 1 searches for the load that has not been restored yet and sends the request to Load 1 regarding partial restoration
Step 36	Load 1 sends a refusal message to NBSA 1 – partial restoration impossible
Step 37	NBSA 1 sends a request to the BSUA to calculate the path to Load 1 (priority 2)
Step 38	BSUA checks the readiness of components to execute the restoration path
Step 39	NBSA 1 receives a message from the BSUA regarding the system stability. All loads restored

7.8 Treatment of potential failures

It is necessary to introduce remedial or management actions which will help to continue the further operation through redundancy available in the system to keep the system working robustly and reliably. Possible system failures encompass communication disturbances and incorrect data transmission. The description below gives a proposal of schemes to overcome the disorders mentioned. The breakdown below is only an example of treatments for possible system interruptions and maloperations as the restoration process presented is very complex and contains many dependencies and various agent interactions. However, it can constitute a starting point for the further development of MAS functionalities, including procedures aiming to solve or bypass problems related to the technical nature of the system operation. Figure 7.43 shows an example of possible interaction disorders during the sending of queries to agents regarding readiness for restoration.



Outage of:
- BSUA, NBSA
- LiA

Communication interruption during:
- The sending of queries regarding readiness for restoration
- The sending of confirmation messages

Figure 7.43 Potential interaction disturbances

Black start unit agent

Table 7.8 Potential failures of the BSUA

Failure	Treatment
Failure of the BSUA – resulting in inability to determine the restoration path and sending messages to other agents	Under temporary interruption – connection reestablishment and cyclic sending renewed notifications to other agents Under permanent outage – inability to perform management process
Incorrect interpretation of line parameters	Request for renewed sending parameters If, after several inquiries, data is still incorrect, attempt to send the request for parameters through another LiA
Incomplete receipt of line parameters	Sending request for renewed sending parameters If, after several inquiries, data is still incorrect, attempt to send the request for parameters through another LiA
No response regarding readiness for restoration	Sending renewed query regarding readiness for restoration If the message is negative or has not been received – the new restoration path needs to be determined
Inability to determine restoration path	Sending notifications to NBSAs Restoration of load only in buses in which NBSUs reside

Failure	Treatment
	Due to the inability to determine a restoration path and, therefore, building up the initial structure of the power system, only selected components will be restored

Line Agent

Table 7.9 Potential failures of the LiA

Failure	Treatment
Agent failure – no response to queries regarding readiness to restore	Under temporary interruption – renewed sending of queries to LiAs Under permanent interruptions (determined through time expired for reestablishing the communication with components) – component not included in further path calculations
Incorrect passing of line parameters – possible data uncertainty	Sending renewed request for data

Non-Black Start Agent

Table 7.10 Potential failures of the NBSA

Failure	Treatment
Incorrect receipt/interpretation of data received from other NBSAs	Sending renewed request for data provision
No response to request for non-black start generation data provision	Renewed communication establishment and request for data
No response to request for restoration	Renewed communication reestablishment with NBSA and sending subsequent requests
Incorrect sending of subscription, incorrect receipt of subscription	Renewed request to provide the subscription if again incorrect subscription is received after subsequent attempts, notification to NBSA is sent In the case of permanent receipt of incorrect subscriptions – attempt to receive the subscription from another NBSA through information rerouting
Incomplete recognition/registration of other NBSAs	Information received from NBSAs available

Failure	Treatment
BSUA not registered – inability to send messages to the BSUA by NBSA	Sending notification to NBSA available with request for rerouting the message required
Failure to send request to determine the restoration path to the BSUA	Rerouting of request to the BSUA through another NBSA
Outage of NBSA – total deactivation of NBSA	Agent not considered in the restoration process

Load Agent

Table 7.11 Potential failures of the LoA

Failure	Treatment
Incorrect sending of load demand data	Sending renewed request for load parameters
No response to request for load restoration	Renewed communication establishment with the LoA and sending the query regarding readiness for restoration
Failure by registration of other agents – inability to send messages to other agents	Necessity to send messages required through other agents
Agent outage – total deactivation	Agent not considered in restoration process

8 Conclusions and outlook

The increasing complexity of future power systems imposes special requirements on control algorithms and data processing methods. A centralized structured power system may suffer from failure of the central controller, making information exchange impossible. The information flow needs to be realized in a decentralized way to make the future system operation more robust and reliable. The problematic attained in the scope of this dissertation demonstrates the complexity and importance of the proper assignment of agent behaviors in MASs. The approaches presented in this dissertation offer an overall model on agent-based power system management performed in a decentralized manner and demonstrate schemes for decentralized information flow modeling.

The agent-based voltage control presented shows an example of how the system can use information to solve voltage problems. In the frame of the voltage control scheme, recognition of critical system states based on results from load flow calculations is performed. The agents’ cooperation and interactions aim at performing remedial actions and only GAs, excluding the SA, make decisions. In this way, decentralized decision-making is realized, which is independent of the central unit. New set points are calculated using the Jacobian matrix methodology. The strategy has been proposed in the control process in which operation conditions can be adjusted to enable interactions between all agents and give the possibility to all agents to participate in voltage control. That contributes to minimizing the provision of reactive power under the conditions assumed. Since this study concentrates on a multi-agent control scheme in which the SA derives results from the load flow calculations, future work should consider an approach in which only GAs perform load flow calculations. In this case, other agents cooperating with each other will replace the tasks of the SA. As an extension of given behaviors, development of additional functionalities allowing the estimation of parameters in case of uncertain or unavailable data as well as consideration of other control strategies encompassing different characteristics describing P-Q relationships constitutes further work.

The problematic of an agent-based congestion management shows which behaviors might be proposed to agents performing such management processes. This approach considers behaviors and interactions of specific generation agents instead of task aggregation of certain control zones presented in previous works. That provides the advantage of detailed modeling of agent behaviors and designing interactions between them adopted to a given control algorithm. New set points are calculated based on Power Flow Decomposition methodology, which does not simplify power flow equations and uses all parameters needed to calculate an accurate load flow. Additionally, the introduction of the new merit order incorporating generation costs and sensitivity factors creates the possibility of performing the redispatch, which can be efficient from a technical and economical point of view.

Communication abilities assigned to agents provide the significant advantage of task distribution and requests for support in the control process if a given agent has insufficient generator capacity. The system proposed can be expanded by considering generation ramps, indicating how fast generators can react to set point changes and how it would influence the network response. An integration of several management strategies constitutes an outlook of this work as well. Moreover, extended behaviors in case of communication errors and agent unavailability, including requesting other agents to pass information and set points as well as additional functionalities enabling communication with smart grid conformation standards (e.g. IEC61850) will be considered in the future work.

The last aspect considered is agent-based grid restoration. It is challenging to find a strategy which will guarantee meeting the initial load demand, because the exact load demand at the beginning of the restoration process is unknown due to load diversification and its dynamic and thermal behavior. The methodology based on searching for the shortest restoration path has been applied in the grid restoration scheme proposed. The procedure deploys Dijkstra’s algorithm, which finds the path so that the sum of line weights is the smallest. An advantage of the approach proposed is characterized by considering the restoration process starting from a total blackout. Based on selected parameters, an non-black start unit is selected, among others, to initiate the restoration process and looks for loads in the system which need to be restored. Additionally, during the restoration, the availability of components, such as lines and non-black start generators, are checked. Based on that, the decision is made if the generated restoration path can be executed.

The problematic of the grid restoration shows that many interconnected factors need to be considered and analyzed to perform efficient power system restoration. Therefore, additional parameters should be introduced in future investigations to model the system component behaviors. This encompasses not only a generation ramp of NBSUs, but also the dynamic model of loads.

Since this study concentrates on multi-agent control strategies regarding voltage control, congestion management and grid restoration, future studies should analyze the interconnection between the aspects mentioned to create more complex infrastructure reflecting the real operation and management of the power system better together with additional functionalities, including the adaptation of communication protocols conforming to Smart Grid and protection issues.

9 References

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Appendix

A System data

Table A.1 Network parameters used in the voltage control approach

Bus from	Bus to	***R*** in p.u.	***X*** in p.u.	***B*** in p.u.
1	2	0.02	0.18	0.06
1	3	0.08	0.72	0.05
2	3	0.06	0.54	0.04
2	4	0.06	0.54	0.04
2	5	0.04	0.36	0.03
3	4	0.01	0.36	0.02
4	5	0.08	0.72	0.05

Table A.2 Transmission limits in the 5-bus system considered, used in the congestion management

Line	Transmission limit in p.u.
1 – 2	0.480
1 – 3	0.180
2 – 3	0.180
2 – 4	0.120
2 – 5	0.228
3 – 4	0.360
4 – 5	0.300

Table A.3 Bus data for the 5-bus system considered, used in the congestion management

Bus no.	Generation		Load	
	MW	Mvar	MW	Mvar
1	0	0	0	0
2	40	0	80	0
3	40	0	0	0
4	40	5	80	5
5	40	0	0	0

Table A.4 Network parameters used in the grid restoration approach

Bus from	**Bus to**	***R* in p.u.**	***X* in p.u.**	***B* in p.u.**
1	2	0.01	0.18	0.06
1	4	0.01	0.18	0.05
2	3	0.01	0.18	0.04
3	4	0.01	0.18	0.02

B Scenario for congestion management

Figure B.1 Agent interactions for scenario 3 with limited generation of generator G3