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FACULTY OF ELECTRICAL ENGINEERING



BACHELOR THESIS

Optimization of operation of distribution
grids utilizing load control

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Author: Ondřej Zlevor

Supervisor: Ondřej Malík

České vysoké učení technické v Praze
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katedra řídicí techniky

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

Student: **Ondřej Zlevor**

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Název tématu: **Optimalizace provozu elektrických VN sítí pomocí řízení spotřeby**

Pokyny pro vypracování:

1. Seznamte se základními principy modelování elektrických sítí [1].
2. Implementujte vizualizaci zapojení sítě a hlavních veličin (proudy, napětí, zatížení linek) na existující síťový model pro výpočet ustáleného stavu optimalizované sítě.
3. Rozšířte model o fotovoltaické zdroje v optimalizované oblasti na základě veřejně dostupných zdrojů.
4. Seznamte se s existujícím algoritmem pro řízení spotřeby v NN elektrických sítích [2].
5. Přizpůsobte existující systém pro optimalizaci provozu VVN sítí pro účely optimalizace VN sítí pomocí řízení spotřeby.

Seznam odborné literatury:

- [1] Sadaat, H., Power System Analysis, PSA Publishing, 3rd edition
[2] Malík, O. - Havel, P.: Active Demand-side Management System to Facilitate Integration of RES in Low Voltage Distribution Networks. IEEE Transactions on Sustainable Energy, DOI 10.1109/TSTE.2013.2288805

Vedoucí: Ing. Ondřej Malík

Platnost zadání: do konce letního semestru 2014/2015


prof. Ing. Michael Šebek, DrSc.
vedoucí katedry




prof. Ing. Pavel Ripka, CSc.
děkan

V Praze dne 8. 1. 2014

Declaration

I declare that I have created my Bachelor Thesis on my own I have used only literature in the included reference list.

In Prague _____

signature

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I'd like to thank my supervisor ing. Ondřej Malík for his help by leading my work, then I'd like to thank ing. Ondřej Novák and ing. Jan Zábojník for their patience and time spent by numerous consultations of solved problems.

Abstrakt

Tato bakalářská práce se zabývá rozšířením stávajícího simulátoru přenosových soustav, MAGMA, přizpůsobením tohoto modelu k použití pro simulaci a optimalizaci provozu sítí vysokého napětí s velkým množstvím fotovoltaických elektráren pomocí řízení odběru.

Prvním úkolem byla implementace modelů spotřebičů, které jsou schopny měnit svůj příkon dle potřeby, tj. boilers a obecné "chytré spotřebiče" umožňující posouvat svoji spotřebu elektrické energie. Výhody použití takových spotřebičů jsou předvedeny na jednoduchých tříúrovňových modelech.

Dále bylo vytvořeno propojení mezi modelem MAGMA a simulátorem nízkonapěťových (NN) sítí, čímž vznikl model schopný simulovat a optimalizovat provoz distribuční soustavy od VN úrovně až po úroveň NN spotřebičů. Pro testy výsledného modelu byla použita topologie zjednodušeného modelu skutečné přeštické distribuční soustavy VN Přeštice, který byl rozšířen o modely existujících fotovoltaických elektráren na základě dat získaných z veřejně dostupných zdrojů.

Testy prováděné na výsledném modelu porovnávají energetickou bilanci simulované oblasti pro případ, kdy jsou boilers řízeny signálem hromadného dálkového ovládání (HDO) a kdy optimalizátorem MAGMA. Testy ukázaly, že řízením spotřeby v závislosti na lokální produkci energie z obnovitelných zdrojů lze značně snížit energetické toky v síti.

Pro vizualizaci simulované sítě a jejich výsledků byl vytvořen nástroj s pomocí Google Earth Toolboxu.

Abstract

Subjects of this bachelor thesis is to extend power grid simulator and optimizer MAGMA, to adjust it for utilization by simulation and optimization of power distribution in low-voltage power grids containing high number of photovoltaic (PV) power plants. The power distribution is optimized by utilization of load control.

First, models of devices capable of load control were implemented. These are electric water heaters (EWHs) and smart loads that are able to shift their operation in time. Benefits of utilization of these controlled loads are shown on simulations done on 3-node models.

Moreover, fusion of MAGMA model and simulator of low-voltage (LV) power grids was designed. The final model is applicable for simulations of power grid from the high-voltage (HV) level to the LV level of electrical devices. There were several test done on a simplified model of existing Prestice HV power grid which were extended by models of actual PV power plants.

The tests run on the final model compare energy balance of the simulated area in cases of controlling EWHs by centralised ripple control (CRC) or by the MAGMA optimizer. The results show that by load control depending on actual local PV power production it is possible to significantly decrease power flows through the distribution network.

For visualization of simulated power grids and results of simulations a tool using Google Earth Toolbox was implemented.

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Introduction

According to current trends in power generation, the amount of renewable energy sources (RES) is increasing. There is especially rapid growth of number of wind and photovoltaic power plants. With the higher number of installed RES power plants, several problems appear. RES power production depends on weather, which makes it intermittent and not easily predictable. There has to be a balance between the produced and consumed power in a power grid. There is a power demand from customers and power production should correspond to it to satisfy them. If an unexpected power overproduction appears due to a weather situation change and if it is not consumed, it could cause problems like power lines overloading or increased losses. The electricity overproduction could be compensated by energy storage in pumped hydro plants, but there is not enough capacity to rely on this option only and it doesn't solve the problem of the overloaded power lines. Another way is to control loads to reflect the local power production.

The idea is, that an operation of some electrical appliances could be remotely controlled, which means, that the signal from an operation control center would define, if the machine runs or not at a specific time. There are several types of electrical machines which possibly don't have to operate at a time the customer specifies, but the customer lets them to shift their operation, e.g. electric water heaters have to contain always enough hot water, but it doesn't matter when the water is heated. If there was a possibility to control these devices in smaller areas, it could improve the consumption of locally produced power and according to it, power flows through the power grid would stay smaller.

It is worked with the MAGMA (Market And Generation Modeling and Analysis) model in this thesis. It is a tool for modeling and optimization of power production and distribution in power grids which is implemented in MATLAB [1]. The goal of this thesis is to extend the MAGMA model by models of controllable loads. These are electric water heaters and 'smart loads'. The extended model is going to be used by optimization and simulation of the model of a high-voltage (HV) power grid in the Prestice area. As a

data source for this model, an AC load flow model VN Prestice is used, but it had to be extended by models of existing photo-voltaic (PV) power plants. The finished MAGMA model of the Prestice area is supposed to be utilized together with a low-voltage (LV) power grid model, modeling an area supplied by one electrical substation. VN Prestice model is visualized with a usage of the Google Earth.

This thesis consists of 5 chapters. In the first chapter the MAGMA model is described and its function is outlined. It discusses the definition and implementation of the power distribution optimization problem and it is presented on a 3-node model. The second chapter deals with an extension of the MAGMA model by controlled loads. Electric Water Heaters (EWH) and smart loads are described there. The mechanism of separation of a local area from the whole power grid and modeling its connection with the outer power grid by Slack Node are mentioned. The third chapter outlines a mechanism of conversion of the HV Prestice power grid model to the MAGMA model and its fusion with a simulator of LV power grids Bioze. The fourth chapter contains several simulations of 3-node MAGMA models with smart loads and EWH connected and simulation of the HV Prestice power grid done by the combination of MAGMA and LV model. The fifth chapter shows several visualizations of the Prestice power grid.

Chapter 1

MAGMA

This chapter deals with the basic concept of the power grid simulator MAGMA. Topology, units and optimization are explained. With usage of a 3-node model the principle of function is demonstrated.

1.1 Basics

MAGMA (Market And Generation Modeling and Analysis) is designed as a tool for modeling and optimizing power production or power consumption and simulating load flows in large transmission networks. For the load flow modeling, DC load flow method is used (explained in [2]). It solves standard tasks - Unit Commitment (UC), Economic Dispatch (ED) and Power Flow (PF) optimization. UC determines, whether power source should be on or off and ED determines the power it should be running at. UC, ED and PF are described in details in [3]. The aim is to find such UC, ED and PF, to be cost-optimal and satisfying transmission constraints.

The inputs of the optimization problem are the topology of the power grid, prediction of the fixed power consumption and parameters of components capable of control. These controlled components are originally power generators, but MAGMA was extended to control loads too (described in the chapter 2).

MAGMA model uses LP (linear programming) or MILP (mixed integer linear programming). Utilizing MILP is needed in cases of involving units with discontinuous states, e.g. generators not able to run with less than specified minimal power. Typical use cases requiring to use MILP formulation include cases when the UC needs to be explicitly defined - for example in order to model units with non-zero minimal power output

or to formulate minimal up and down times of the generator.

1.2 Problem definition

MAGMA optimization model is defined by:

- **Transmission network** composed of electrical substations connected together by power lines, power generators and loads. Power generators and loads are connected to electrical substations. It is possible to connect multiple power generators to an electrical substation, but it is not possible to connect one generator or load to multiple electrical substations.

There are all basic generator types modeled - nuclear plant, thermal plant, hydro plants, accumulative hydro plants, pumped hydro plants and renewable sources plants. Generator models are described in detail in [4].

- **Fixed load/power generation** are values of required power of uncontrollable loads and fixed delivered power of generators (e.g. RES).
- **Controllable generation/load** parameters.

The optimization problem is limited by a set of constraints influenced by all parts of the model:

- **Transmission network:** the power flow through an electrical substation is constrained by a law of conservation of energy, so the sum of power injected to it from lines and generators must be equal to the power leaving it. The limit limiting power lines is the maximal power it is able to transport.
- **Fixed load/power generation** - the generator with the power production fixed could not run at different power.
- **Controllable generation/load** is constrained by the maximal power production/consumption the generators/loads are able to run at and other constraints specified for given generator/load.

Power plants are operated in five different operation modes. In this thesis only with PV power plants with fixed power production are used.

Each of power plants produces power with different costs and the transmission costs are involved in the model too. The aim of the optimization is to schedule power production satisfying customers with minimal production and distribution costs.

1.3 Problem implementation

The model of the simulated power grid contains components Node, Line, Load and Generator representing the electrical substation, power line, consumer and generator. The criterion being optimized is called an objective function and the problem is limited by a set of constraints. The objective function should be primary cost of the power production or the power transfer, but it may also contain penalization of unwanted phenomena (i.e. soft-constraints).

This section gives an overview of units and optimization problem implementation.

1.3.1 Node

Class Node represents an electrical substation in power grid. It contains references on connected generators, loads and lines. There is no cost of power flow through the node so it doesn't impact the objective function.

1.3.1.1 Constraints

Constraints constraining model of electrical substation describe balance of power produced by generators connected to node, power injected through lines and power consumed by load as shown in (1.1).

$$\sum P_{generator,i} + \sum P_{line,j} - P_s = 0 , \quad (1.1)$$

where $P_{generator,i}$ is the i-th generator delivered power, $P_{line,j}$ is power transmitted by j-th line into the node and P_s is power consumed by load.

1.3.2 Line

Class Line represents wired connection between two nodes in the power grid. It contains a variable P_{line} representing power transmitted through the line. This variable is divided into positive P_{line+} and negative P_{line-} part. It is impossible to transmit

power in both directions at single moment so there is always P_{line+} or P_{line-} zero. The transmitted power is then (1.2)

$$P_{line} = P_{line+} + P_{line-} . \quad (1.2)$$

1.3.2.1 Objective function

Power line increases objective function by cost of power transmission through it. There is an option to set transmission costs to zero.

$$J_{line} = P_{line} \cdot C_{line} , \quad (1.3)$$

where P_{line} is power transmitted through line and C_{line} is cost of power transmission.

1.3.2.2 Constraints

Value of P_{line} is limited by maximal and minimal possible values (1.4).

$$P_{lineMin} \leq P_{line} \leq P_{lineMax} . \quad (1.4)$$

1.3.3 Power generators

Each generator adds variable vector $P_{generator,t}$ representing delivered power in set of optimization variables. This variable is used as a vector of length equal to number of hours of the time vector the problem is solved in.

$$\mathbf{P}_{generator} = (P_{generator,t_1}, P_{generator,t_2}, \dots, P_{generator,t_N}) .$$

Objective function is increased by cost of produced power (1.5)

$$J_{generator} = E_{generator} \cdot C_{generator} , \quad (1.5)$$

where $E_{generator} = \sum P_{generator,t} \cdot \Delta t$ is energy produced in generator in simulated time interval and $C_{generator}$ is cost of produced power. $C_{generator}$ depends on generator and fuel type.

In tests described in this paper , only photovoltaic (PV) power plants are used, so only these ones are discussed in 1.3.4.

1.3.4 Renewable sources

MAGMA operates with energy from renewable sources (RES) and no cost is associated with RES power generation. Unlike other generators, RES could instantly start producing PV power without any limits of minimal power being produced. RES isn't limited by minimal time of being on too.

1.3.4.1 Constraints

The only limit extra set on RES is obligation to deliver as much power as possible under actual weather conditions. Unit representing RES in MAGMA model gets a vector P_{fixed} of fixed power production values. There is only one constraint constraining power production of RES (1.6)

$$P_{RES,t} = P_{fixed,t} , \quad (1.6)$$

where $P_{RES,t}$ is actual RES power production and $P_{fixed,t}$ is the fixed RES power production, which is inserted to MAGMA as a result of prediction of PV power production.

1.3.5 Load

Unit load represents uncontrolled load. This device could not plan its power consumption and doesn't add any optimization variables into the problem. In implementation of uncontrolled load, the time vector of required power is included and there is no way to consume different amount of power than it is defined by this vector.

1.4 Example of MAGMA model

3-node model is used to show the MAGMA work by an example. Only units operating with linear programming (LP) will be used.

1.4.1 3-node model

As a simple example of a power grid model, the 3-node model is used. It is completed by 3 nodes (N1, N2, N3) connected together by 3 power lines (PL1, PL2, PL3). The scheme of this model is shown in fig 1.1. There are two loads connected (load L1 to node

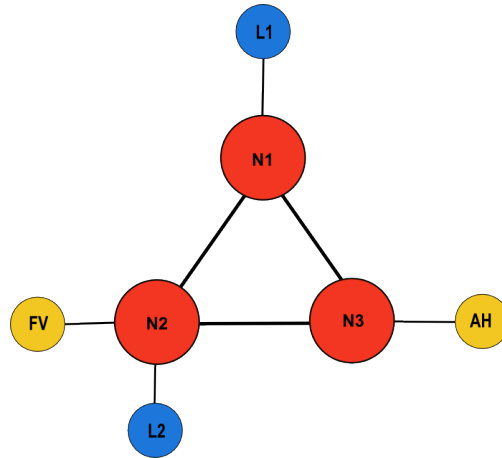


Figure 1.1: Scheme of 3-node model: N1,N2,N3 - nodes, PL1, PL2, PL3 - power lines, L1,L2 - loads, AH - AccuHydro generator, FV - photovoltaic power plant

N1, L2 to node N2), an accumulative hydro plant (AH) to node N3 and a PV power plant (FV) to node N2. It is important to set the direction of the positive power flow through the power line. At this case, the directions positive power flow are:

- Line1 : from node N1 to node N2
- Line2 : from node N2 to node N3
- Line3 : from node N1 to node N3

1.4.2 Optimization problem

The optimization problem is defined by a set of variables, constraints and an objective function constructed from all units.

1.4.2.1 Variables

Optimization variables of this optimization problem are listed in table 1.1 and constants in table 1.2.

$P_{line1}, P_{line2}, P_{line3}$	power flows through lines
P_{RES}	power production of a PV power plant
E_{AHin}	energy inflow to the accumulative hydro plant
P_{AH}	power generated by the accumulative hydro plant
E_{AHrel}	released energy from the accumulative hydro plant
$E_{AHstate}$	energy state in the accumulative hydro plant

Table 1.1: Variables used in example presented in sec:1.4

P_{RESmax}	maximal possibly produced power at single moment
P_{load1}, P_{load2}	power consumed by loads

Table 1.2: Constants used in example presented in sec:1.4

1.4.2.2 Constraints

The whole set of constrains constraining the optimization problem is shown

$$-P_{line1} - P_{line3} - P_{load1} = 0 , \quad (1.7)$$

$$P_{RES} + P_{line1} - P_{line2} - P_{load2} = 0 , \quad (1.8)$$

$$P_{AH} + P_{line2} + P_{line3} = 0 , \quad (1.9)$$

$$E_{AHrel} > 0 , \quad (1.10)$$

$$E_{AHstate,t+1} = E_{AHstate,t} - P_{AH} \cdot \Delta t - E_{AHrel} + E_{AHin} , \quad (1.11)$$

$$0 \leq P_{RES} \leq P_{RESmax} , \quad (1.12)$$

where eq. (1.7-1.9) are constraints added by nodes, eq. (1.10,1.11) are added by accumulative hydro plant and eq. (1.12) is constraint added by PV power plant.

1.4.2.3 Objective function

The only components influencing the objective function are power lines transmission costs at this case. The objective function is in eq. 1.13

$$J = \sum_{t=1}^n (P_{line1,t} + P_{line2,t} + P_{line3,t}) \cdot \Delta t \cdot C_{line} , \quad (1.13)$$

where $P_{line1,t}$, $P_{line2,t}$, $P_{line3,t}$ is transmitted power through lines in hour t and C_{line} is cost of power transmission.

Chapter 2

MAGMA extension by controlled loads

This chapter deals with an implementation of controllable loads to be utilized by the MAGMA model. As mentioned in chapter 1, the optimization problem has following inputs - the model of a power grid, predictions of uncontrolled power consumption and generation and parameters of controllable generators and loads. In sake of loads controlling the data of generation prediction are inserted into the model instead of data of uncontrolled consumption prediction.

The MAGMA model was extended by two types of controlled loads. The first one, Electric water heater (EWH) is described in section 2.2. The second one, load which could be partially shifted in time, is named Smart load and is described in section 2.3.

2.1 Model of an extracted power grid area

The only power generators connected directly to the HV power grid are small generators and RES generators. These power sources could not ensure power self-sufficiency of some power grid area and the area is supplied from generators connected by power lines of higher voltage than HV. To model an area with only HV power lines, some connection point with the rest of the power grid is needed. For this purpose, element Node was extended by an option of becoming a slack node (explained in subsec. 2.1.1).

2.1.1 Slack node

As mentioned above, slack node represents a connecting point between the observed area and the rest of the transmission network. There are two variables used to describe power flows through the slack node. Power inflow P_{In} and power outflow P_{Out} .

2.1.1.1 Objective function

According to the requirement of locally produced power it is useful to penalize the flows in and out of the observed power grid. There are two different approaches of slack node power flows penalization used in following tests. Linear and quadratic penalization are used.

Linear penalization If the linear penalization is used the contribution to the objective function added by the slack node (eq. 2.1) is a penalization of maximums of energy flow (positive and negative).

$$J_{SN} = P_{maxIn} \cdot C_{maxIn} + P_{maxOut} \cdot C_{maxOut}, \quad (2.1)$$

where P_{maxIn} is maximum of power inflow into observed area, P_{maxOut} is maximum of power outflow out of the observed area, C_{maxIn} is a penalization coefficient penalizing maximal positive energy flow, C_{maxOut} penalization coefficient penalizing the maximal negative energy flow.

Quadratic penalization This approach penalizes squares of power flow through the slack node. In cases simulated during this thesis the sum of produced and consumed electrical energy is predefined. If the power flows were penalized linearly, the increase of the objective function would be the same for increasing already high power flow as increasing low power flow. This wouldn't contribute to decreasing of power flows. The contribution to the objective function by quadratic penalization is in (2.2)

$$J_{SN} = \sum_t [(P_{In,t} \cdot \Delta t)^2 + (P_{Out,t} \cdot \Delta t)^2] C_{UP}, \quad (2.2)$$

where $P_{In,t}$ is power inflow to the simulated region, $P_{Out,t}$ power outflow and C_{UP} is penalization constant.

2.1.1.2 Constraints

Variables of the slack node are constrained by the same function as variables of a non-slack node, but beside of that, there are conditions (2.3,2.4), which sets to variable P_{maxIn} / P_{maxN} the maximum of power inflow/outflow.

$$\forall P_{In,t} \in \mathbf{P}_{In}, P_{maxIn} \geq P_{In,t} \quad (2.3)$$

$$\forall P_{Out,t} \in \mathbf{P}_{Out}, P_{maxOut} \geq P_{Out} \quad (2.4)$$

2.1.2 Example of a 3-node model with no controlled load

PV power production could cause overload of the power grid and could cause reverse power flows. It increases power losses and transmission costs. The impact is shown on 3-node model for the sake of simplicity. It is based on a model shown in fig 2.1. This model contains PV power plants connected to nodes N2, N3, an uncontrolled load connected to node N3 and an EWH. EWH in this case is controlled by the centralized ripple control (CRC) signal so it is not possible to control it by MAGMA.

The sign convention used in plots in this thesis sets power production to be negative and power consumption to be positive. Power inflow has positive sign and power outflow negative sign.

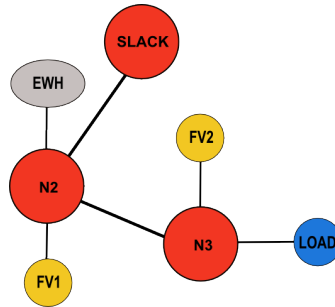


Figure 2.1: Scheme of 3-node model with no controlled load

Figure 2.2 shows results of a 24 hours simulation. The PV power production data are estimated from actual meteorologic measurements on a specific day at the Prestice area. The EWH power and uncontrolled load prediction are generated from data based on actual consumer's information.

At time 9-17 h, the production of the PV power is higher than the load consumption within the area. It causes power to leave the area and the power flow through the

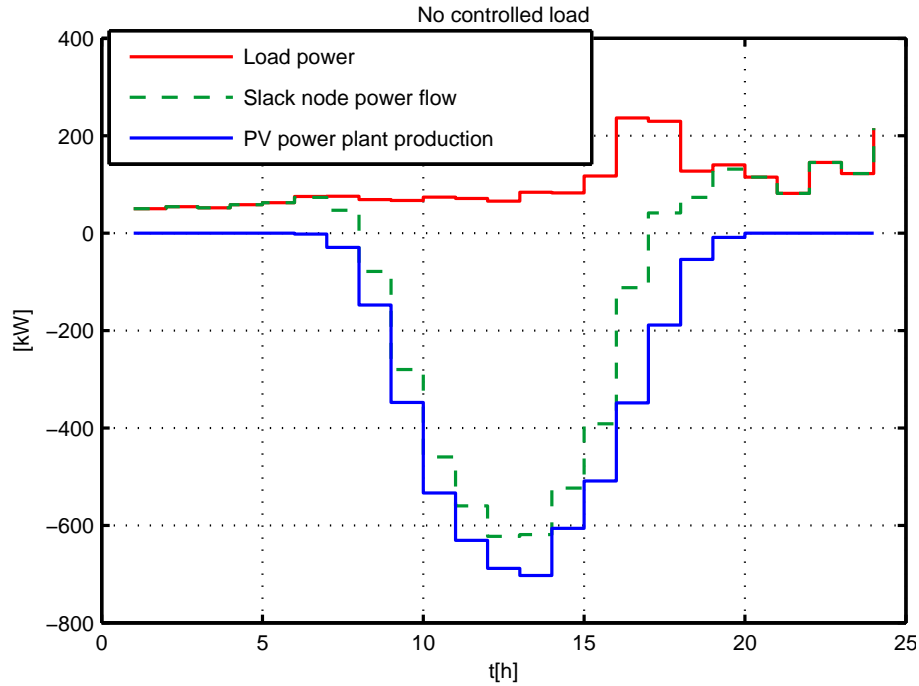


Figure 2.2: Results of test with controlled devices used

slack node changes its direction. As the peaks of the PV power production are hardly predictable the power grid faces problems. The power grid infrastructure might not be prepared for reverse power flows and overloading. To avoid or reduce these problems it is aimed to consume as much PV power as possible within the area it is produced in. However, there is no way to control the power production, so another way is to shift power consumptions from times of no PV production to peak time. It could be achieved by utilizing controlled loads.

2.2 Electric water heater

Electric water heater (EWH) used in the MAGMA model is a component representing a device, whose heating power could be controlled. One instance of EWH in MAGMA is modelling EWHs of all consumers within the modeled area. This model has got a lot of common with the accumulative hydro plant model. The difference is, that the value of the variable of delivered power P_{EWH} is always negative in case of the EWH, so it could be considered as a positive power consumption. As it is in an accumulative hydro plant case, EWH could accumulate energy. It is possible to control charging of EWH (increase of energy state) and not possible to control EWH discharging (consumption of

hot water).

The limitations imposed on EWHs are set both by technical parameters and demands on comfort of consumer. The EWH gets a vector of prediction of hot water consumption, which represents the change of energy state of the EWH. The amount of energy accumulated in hot water in EWH is titled energy state E_{EWH} . The zero energy state is representation of an EWH filled with cold water.

2.2.1 Constraints

There are a few limitations imposed on EWH. The energy state E_{EWH} has to be always higher than some minimal level E_{min} and it is not allowed to exceed capacity of EWH E_{max} , as described by eq 2.5,2.6

$$E_{EWH} \geq E_{min} , \quad (2.5)$$

$$E_{EWH} \leq E_{max} . \quad (2.6)$$

The only detectable information about the energy state of an EWH is reaching the maximal capacity of charge, because then it stops charging. Values of energy state lower than the maximal capacity are only predictions. Constraint 2.5 functions as a protection against wrong estimation of the EWH energy state.

The length of the optimization horizon is going to be 24 hours or multiple of it. The amount of hot water at the end of the run is required to be close to the amount at the beginning, because the household hot water consumption is supposed to be periodical with period of 24 hours (eq. 2.7)

$$0.9 \cdot E_{init} \leq E_{EWH} \leq 1.1 \cdot E_{init} . \quad (2.7)$$

The change of the energy state is generated by difference between the energy inflow (representing integral of heating power) and the energy outflow (consumption of hot water).

$$E_{EWH,t+1} = E_{EWH,t} + P_{EWH,t} \cdot \Delta t - E_{cons}[i] , \quad (2.8)$$

where $E_{EWH,t}$ is the energy state of the EWH at hour t , $P_{EWH,t}$ is the heating power of EWH during hour t , E_{cons} is the energy of water consumed during hour t and $\Delta t = 1 h$ is a length of the time interval.

2.3 Smart load

Smart load implements a load that contains controllable and uncontrollable part. Smart load is defined by a vector of required power \mathbf{P}_t in time. In the controllable part, the required power could be flexibly shifted in time to better reflect power situation in the network. To be more specific, it is desired to shift power consumption from time with no production of RES power to time with high RES power production.

2.3.1 Constraints

Smart load is constrained by maximal power it is able to run at (2.9) and by necessity of completing demanded work (2.10).

$$\forall t; P_{SL,t} < P_{SLmax} , \quad (2.9)$$

$$E_N = E_{SL} , \quad (2.10)$$

$$E_N = \sum_t P_{demand,t} \cdot \Delta t , \quad (2.11)$$

$$E_{SL} = \sum_t P_{SL,t} \cdot \Delta t , \quad (2.12)$$

where $P_{SL,t}$ is actual power smart load is running at, P_{SLmax} the maximal power smart load could run at and $P_{demand,t}$ the power load is demanded to run at.

2.3.2 Objective function

Smart load increases the objective function by penalization of the difference between the required power and the actual power. It represents the loss of comfort of customer. Contribution to the objective function is specified in (2.13),

$$J_{SL2} = \sum_t |P_{demand,t} - P_{SL,t}| \cdot C_{wNoT} , \quad (2.13)$$

where $P_{demand,t}$ is the demanded power of the load, $P_{SL,t}$ is the actual power the load is running at and C_{wNoT} is a penalization coefficient penalizing the difference between the required and an actual power at a single moment.

2.4 Sequential optimization

Power grid model computes with input data representing a prediction of power production and consumption. This data in the real power grid control would be results of meteorological measurements applied periodically during day. The actual situation could be different than the prediction and predicted data for sooner time are more accurate. To reflect better the real situation, load control is applied periodically with updated predictions. Simulation is simulated with step 1 hour and the optimization problem is solved for a 24h interval. The reason to use 24h interval is the periodicity of PV power production and power consumption, which depends on day cycle of the sun and consumers.

The problem of length N hours is solved in N runs. The algorithm of solving one run is:

- optimize the problem for time interval $\langle t, t + 24 \rangle$
- cut all results at interval $\langle t + 1, t + 24 \rangle$
- merge the rest with data from the previous runs
- increase t

At the end, results of all single runs have been merged and it is taken as a solution of the whole problem.

Chapter 3

Power Grid Models Fusion

The final form of the desired model is supposed to be a fusion of the MAGMA model, model of Prestice power grid and LV simulation and optimization model [5]. Topology of Prestice power grid was taken from the AC load flow model HV Prestice. It was extended by existing PV power plants and simplified. It was then converted to model implemented in MAGMA and connected with the LV power grid model. This chapter outlines fundamentals of this fusion. Figure 3.1 shows a scheme of cooperation of the models.

The HV Prestice power grid was used basically as a source of data and as a construction for PV power plants connection. During simulation, MAGMA provides references computed from UC, ED and PF. According to these references, LV model simulates load, power generation and EWHs commitment. Then it generates predictions of load power and power production that are used by MAGMA for the next simulation run.

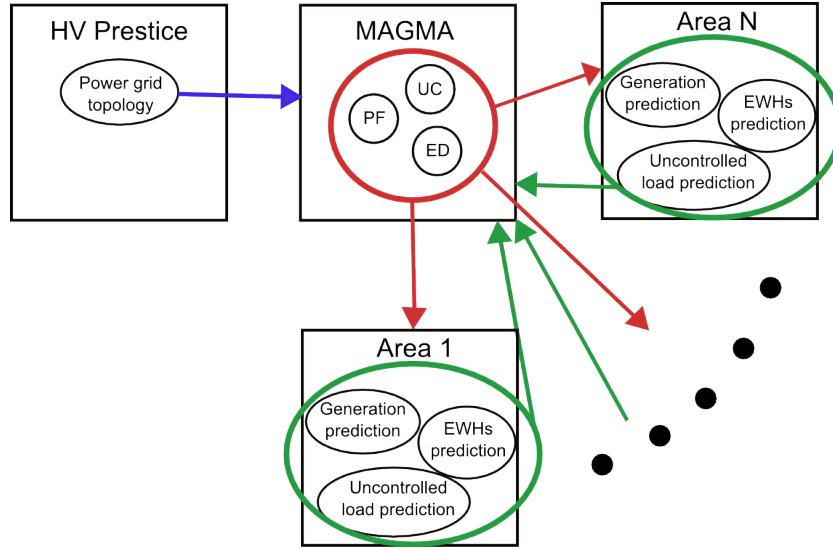


Figure 3.1: Scheme of cooperation of models

3.1 HV Prestice power grid

Model of Prestice power grid is built by several entities. They are basically nodes, lines, LV loads connected to electrical substations and PV power plants. LV parts of the power grid are not modeled as a network but they are represented by an area specified by numbers of consumers of consumer classes, their yearly consumption and nominal power of installed PV power plants. Some nodes represent electrical substations as it is in MAGMA model (chapter 1), but there are some nodes connecting exactly two lines, which are involved only because of better reflection of real power lines position during visualization. Each line is defined by two end nodes. There are two types of power lines in this model - high voltage (22kV) lines and low voltage (400V) lines.

This model is designed as a simulator using AC load flow method. Inputs of it is information about power production and power consumption and it is able to compute power flows through power lines. Actually, in this thesis this model is used primarily as a source of data and topology of Prestice power grid.

3.1.1 Prestice power grid PV extension

The modeled Prestice power grid is spread on 103 cadastral areas. Over the last few years, the number of installed PV power plants has rapidly increased to number almost 500 in this area. These are from small photovoltaic panels installed on house roof with power about 10kW to large photovoltaic arrays with power up to 2.69MW. Statistical

Sum of installed power [kW]	18 082
Largest PV power plant [kW]	2 691
Number of power plants	483
Installed power median [kW]	5
Average installed power [kW]	37.4

Table 3.1: PV power plants information

data of PV power plants installed in Prestice area are presented in table 3.1 and histogram of PV power plants with installed power less than 40 kW is in fig. 3.2. These smaller power plants are 94 % of all power plants number, but they produce only about 20 % of the total produced power.

The source of geographical location and installed power are energy production licenses published on the website of Energy Regulatory Office (viz [6]). According to these data, units representing these PV power plants were added to model of Prestice power grid. Licences were found thanks to categorization by cadastral area.

Energy production licenses contain number of parcel the PV power plant is installed on. By these numbers, it was possible to get coordinates of relevant parcels. These coordinates were parsed from website of Czech Office for Surveying, Mapping and Cadastre [7]. No data about which electrical substation the specific PV power plant is connected to are available, so it was essential to find another way. The idea was, that the PV power plant is connected to the nearest electrical substation.

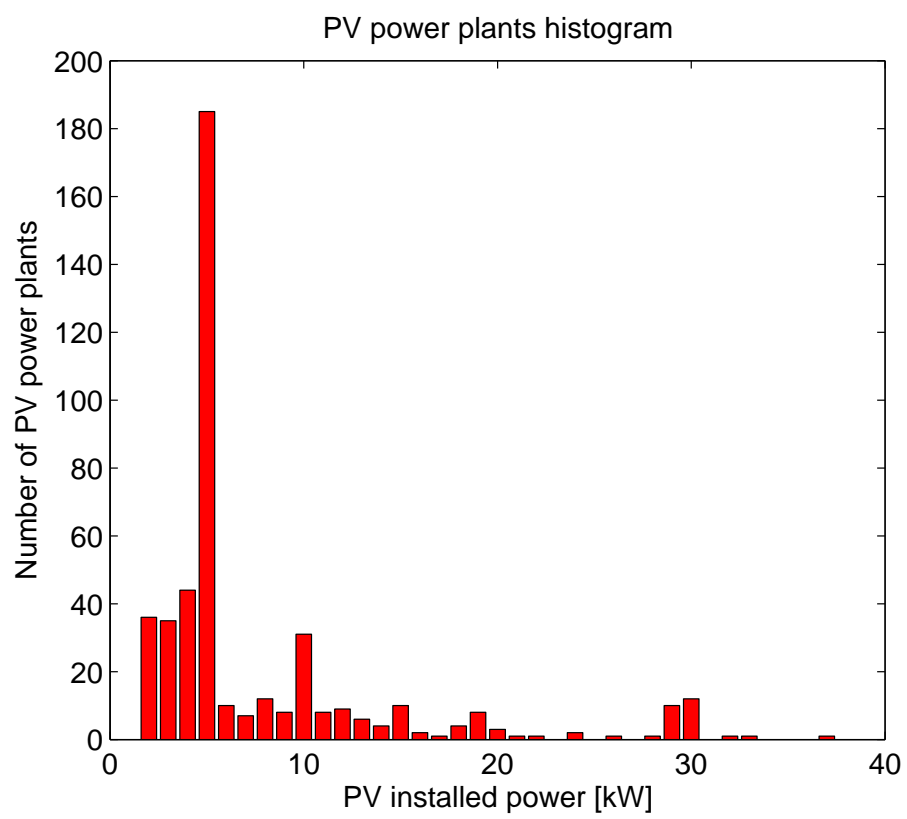


Figure 3.2: Histogram of installed PV power plants in Prestice power grid

3.2 LV model

LV model connected with the MAGMA model is a tool for simulation and prediction of power consumption of an area whose electricity supply is provided by one electrical substation. Electrical energy distributor distinguishes 8 classes of consumers, who differ by purpose and amount of power consumption. LV model models all classes of consumers and according to the number of consumers of given class and their annual power consumption it creates a model of an supplied area. The area contains as many EWHs as it is needed to build relevant EWH consumption.

This model generates predictions of PV power production, uncontrolled load consumption and hot water consumption. According to reference set to this model it computes EWHs commitment so that the simulated balance should correspond with the reference value.

3.3 Power grid simplification

As mentioned in section 3.1, Prestice power grid model contains several nodes involved only for visualization. In MAGMA model, number of nodes increases optimization problem and solving time. Hence it is useful to get rid of redundant nodes to simplify the optimization problem.

The redundant node is defined as a node connecting exactly two lines with no load or PV power plant connected. These nodes were removed and the two lines it was joining together were replaced by one line. Another issue were LV (low voltage) power lines, which were involved in model too. MAGMA is concerned with problems of HV (high voltage) level, so LV lines were removed due to redundancy. Loads and PV power plants connected to the end of redundant LV lines were connected the node on the beginning of the line.

In the Prestice power grid model, electrical transformers (from 22 kV to 400 V) are modeled too. Their topology is constructed by set of 400 V power lines. In MAGMA model, there is no need of proper transformer model. It is sufficient to replace the whole transformer model by a node representing an electrical substation.

The algorithm of power grid simplification is:

- to find root node of all transformers (backtracking of foregoing power line of each 400 V power line leads to node either with no foregoing power line or with a 22 kV

power line),

- to find periphery nodes of the transformer (nodes connecting 400 V power line on one and 22 kV power line on the other side),
- to connect 22 kV power lines connected to periphery nodes of the transformer to the root of the transformer,
- to remove all inner power lines and nodes of the transformer.
- to remove redundant nodes (nodes connecting only two power lines with no load or generator connected)

This simplification decreased number of nodes from 4629 to 704 and number of lines from 4631 to 705.

3.4 Conversion to MAGMA

The topology of the Prestice power grid model is a radial network, so if there is a need to simulate only a part of the whole power grid, the power grid part is defined by setting a new root node which is an electrical substation connecting the simulated are with the rest of the transmission network. The HV Prestice model uses the same topology as MAGMA does. The subtree diagram with the root node is browsed and all power grid segments are converted from HV Prestice format to MAGMA format.

3.4.1 Load and EWH conversion

The HV Prestice representaion of loads contains information of annual energy consumption in kWh. In the HV Prestice model, there are several loads connected to each electrical substation. There are several classes of loads and on the class depends the information of EWH presence and how much of the consumed energy is used for water heating. Uncontrolled load prediction and EWH energy outflow (consumption of hot water) prediction are generated by LV model from input data of annual energy consumption, number of consumers, class of consumers, measured data of actual energy consumption and simulation of actual consumption (viz [5]).

The other data used for the EWHs - the minimal and maximal energy state (amount of energy stored in hot water) and the initial energy state.

For each electrical substation, LV simulator creates a model of all consumers connected to the electrical substation. From the data of an annual power consumption and the number and class of consumers it implements appropriate number of EWHs with appropriate heating power. The rest of the consuming power is supposed to be an uncontrolled load.

3.4.2 PV power plants conversion

For each PV plant connected in the Prestice area the HV Prestice power grid model contains information about the nominal PV power. Generation predictor contained in LV model generates power production for PV power plant for the next 24 hours P_{RESmax} .

It is supposed, that the simulated area is not large enough to allow huge weather diversity inside it and the simulation step is 1 hour. Due to this fact, one generation prediction is used for the whole observed area.

3.4.3 Interaction with the LV model

All power generators and consumers connected to an electrical substation are represented by a LV model of an area. Each node in the MAGMA model contains a reference of the related area.

3.5 Problem solution of the final model

The LV power grid model simulates power consumption and PV power generation within an area connected to a single electrical substation. Moreover, this model computes power generation and consumption predictions. Once in each hour of the simulation, MAGMA model solves UC,ED and PF tasks for next 24 hours based on data from the predictions. Results of MAGMA optimization are used to compute balances (consumed power minus produced) for each nodes which are used as references for LV model for the next simulation hour. The simulation cycle operates as follows:

- each simulation step (5 minutes) LV model simulates Operation of EWHs, state change of EWHs, uncontrolled load and PV power production according to reference from MAGMA and data of current weather situation. For each electrical substation (node in the MAGMA model) an area is simulated separately by LV model and EWHs are committed to follow the reference set by MAGMA.

- Once in an hour:

LV model computes 24 hours prediction of uncontrolled load power, PV power generation and EWHs hot water consumption.

MAGMA schedules power consumption of the EWHs for next 24 hours according to the prediction of power consumption and PV power production.

References generated by MAGMA are stored to be used the next hour by LV model.

Depending on the length of the simulation, this cycle is repeated.

Chapter 4

Testing

This chapter presents testing of controlled load utilization in power grid. It briefly outlines setup of penalization coefficients and models being tested. These models are 3-node models with EWH or uncontrolled and controlled loads connected. They represent local area of power grid that is connected with the distribution network via slack node. In section 4.3 advantages of using controlled EWH are shown and discussed. Section 4.4 focuses on smart loads. Results of test with different controllable loads are compared. Section 4.5 shows, that smart loads behave like uncontrollable loads, if there is no benefit from controlling load consumption. Simulations done by the final model combining MAGMA and LV model are presented in sections 4.6 and 4.7.

4.1 Penalization setup

In the following test two types of penalization of power flows through slack node (inflow and outflow) were used. It was a linear penalization and quadratic penalization. As a reference penalization cost, the penalization of undelivered power in node C_{UP} is used. To this cost, all coefficients of other penalization are related. Options of penalization are presented in table 4.1

4.1.1 Linear penalization in slack node

If it is desired to use linear programming one way is to linearly penalize maximums of power flows through the slack node (2.1). Linear programming needs less computing power to be solved so the optimization software could run on a simpler and cheaper

	Object of penalization	Value
C_{wNoT}	Difference between demanded and operated power	$0.5 \cdot C_{UP}$
C_{maxIn}	Maximal power inflow	C_{UP}
C_{maxOut}	Maximal power outflow	$2 \cdot C_{UP}$

Table 4.1: Penalization options

machine. Minimized maximums of power flows prevent overloading.

In slack node, maximums of power flows are being penalized as shown in (2.1). Maximums of positive power outflows and inflows are expected to differ quite a lot so it is needed to penalize it separately. It is better to penalize more the negative undelivered power than the positive $C_{maxIn} > C_{maxOut}$, because consequent on the aim of using controlled loads is to avoid power outflows from the area if it possible could be consumed within the area.

Power flows through the slack node are linearly penalized in tests described in sections 4.3, 4.4 and 4.5.

4.1.2 Quadratic penalization in slack node

At several cases the linear penalization is insufficient. During the interval of optimization there could appear a peak of consumption or PV production causing that power flows could not be minimized (e.g. the peak is caused by uncontrolled load) and it sets a maximal value of power flow that could not be changed. Controlled loads are then operated ineffectively because it doesn't increase the objective function anyway.

Quadratic penalization penalizes squares of power flows for each hour which minimizes power flows in the power grid and it works a bit as an optimizer of maximums of power flows too. It is described in (2.2), section 2.1.1, chapter 2.

Power flows through the slack node are quadratically penalized in tests described in sections 4.4, 4.6 and 4.7.

4.1.3 Penalization in smart load

In smart load the difference between required and actual power in every single hour is penalized (2.13). Cost of penalization C_{wNoT} represents consumers discomfort, while his service is being executed not at the time he requires. This cost shouldn't be too high, because in that case it would behave as a normal uncontrollable load. To be more specific, the inequality $C_{wNoT} < C_{maxOut}$ should hold. In opposite case, optimal strategy would be not to put load control in action at all.

4.2 3-node model containing EWH

A 3-node network is used to test proposed control scheme. This model contains one slack node and two non-slack nodes. Nodes are connected together by two lines. First connects slack node with node N1 and the second connects nodes N1 and N2. In both nodes N1 and N2 the PV power plants are connected. EWH is connected to node N1 and uncontrollable load is connected to node N2. Three versions of 3-node model are shown in fig. 4.1a.

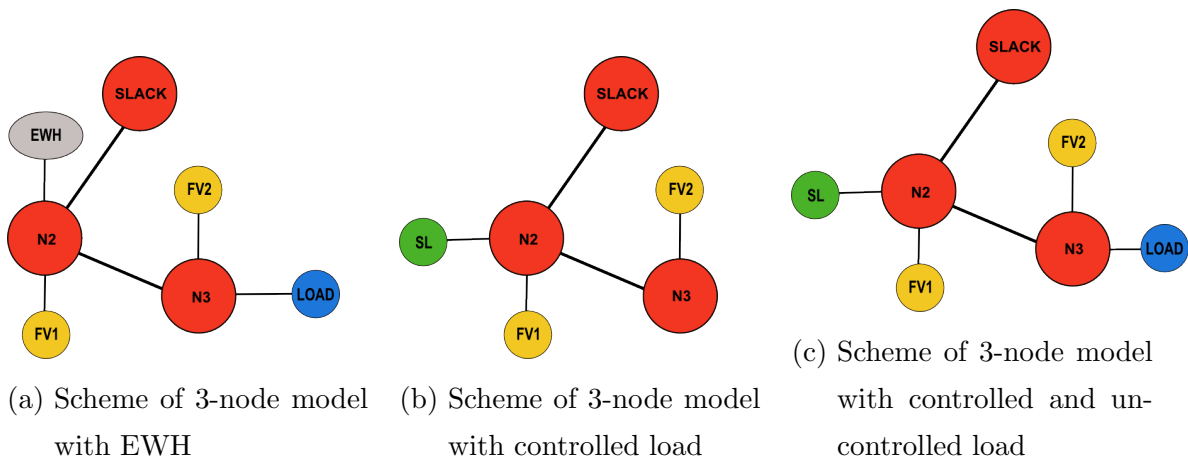


Figure 4.1: Schemes of used 3-node models: SLACK - slack node; N1,N2 - nodes; FV1,FV2 - photo-voltaic power plants; LOAD - uncontrollable load; EWH - electric water heater; SL - smart load

Test	Components connected to node 2	Components connected to node 3
Test 1: EWH	EWH, FV1	FV2, Load
Test 2: Smart load	Smart load, FV1	FV2
Test 3: Redundancy of smart load	Smart load, FV1	FV2, Load

4.3 Test 1: EWH Control

The aim of this test is to show benefits of using controlled EWHs in distribution networks. The situation, in that no devices controlled by MAGMA are used is represented by 3-node model described in subsection 4.2. The EWH connected to node N2 is controlled by Centralised Ripple Control (CRC) signal, so its power consumption is generated by LV power grid simulator and it can't be changed by the optimizer. The results are shown in figure 2.2 in chapter 2. Apparently, there is no way to reduce the PV energy production peaks and there are significant power flows through the slack node.

In the following situation, the same model is used but the CRC control is substituted by MAGMA control. The simulation results are shown in figure 4.2. Usage of EWH with controlled consumption helped to decrease power flow through slack node as it is seen in in hours 10-15. The power consumption was shifted from hours 16-17 of low PV power production to hours 13-16 when the peak of PV power production appears. At the 14th hour of the simulation the EWH was fully charged so it didn't compensate the power overproduction anymore. Maximums of power inflow and outflow through slack node and imported and exported electrical energy are displayed in table 4.2.

		$P_{In}[kW]$	$P_{Out}[kW]$	Imported energy [kWh]	Exported energy [kWh]
Sc. 0	EWH CRC cont.	132	622	1326	3646
Sc. 1	EWH MAGMA cont.	82	414	892	2995

Table 4.2: Test1: power flows + transmitted energy

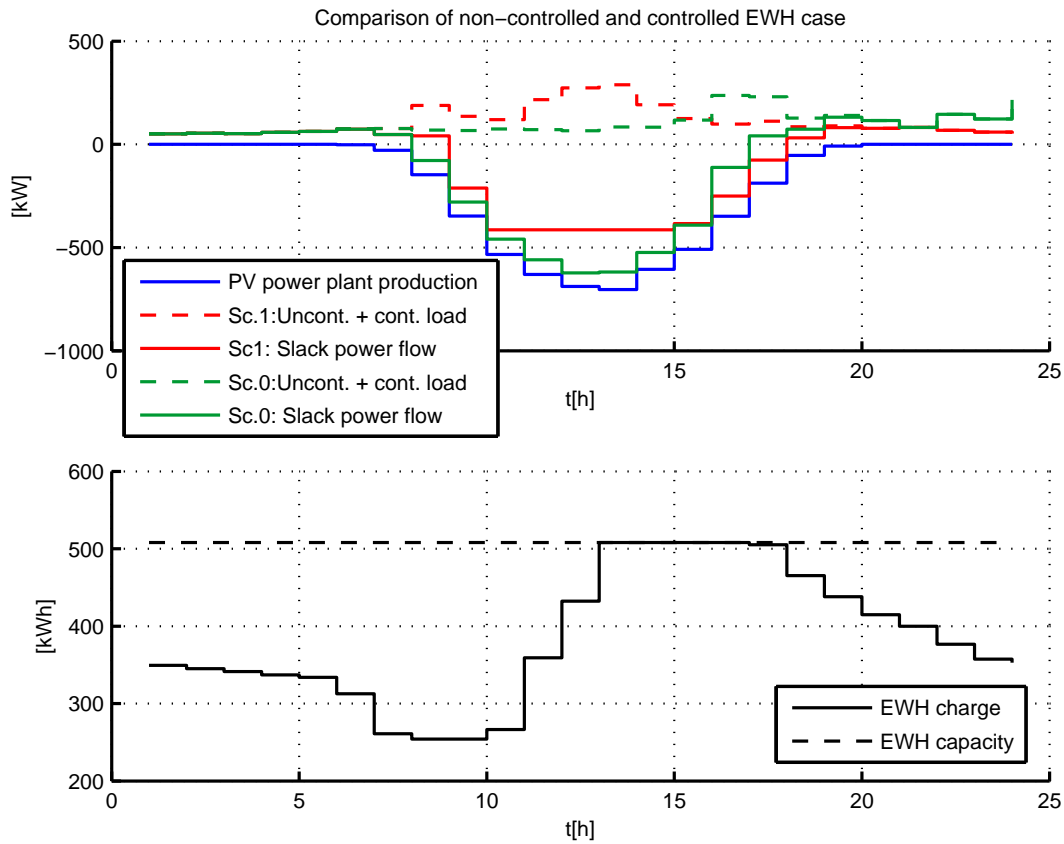


Figure 4.2: Comparison of power flows through slack node with EWHs controlled by CRC or MAGMA¹

4.4 Test 2: EWH and smart load

Test	Components connected to node 2	Components connected to node 3
Test 1: EWH	EWH, FV1	FV2, Load
Test 2: Smart load	Smart load, FV1	FV2
Test 3: Redundancy of smart load	Smart load, FV1	FV2, Load

At this test, PV power plants were connected to both of the non-slack nodes. A smart

¹Scenario 0: EWHs are controlled by CRC

Scenario 1: EWHs are controlled by MAGMA

Scenario:	Size of controlled part [%]
0	0
1	5
2	10
3	20

Table 4.3: Controlled part sizes of scenarios

load was connected to node $N2$ and this network was tested in 4 scenarios. The scenarios differ only in a size of controllable part of smart load. It is presented in table 4.3. Values of penalization costs are shown in table 4.1.

The goal is to compare the simulation results of models with different ratio of controlled and uncontrolled loads. In figure 4.3 the comparison of load power in cases of 5 %, 10 % a 20 % controllable load is shown. The controlled part is defined as $N < 1$ of load and it means, that required power of uncontrolled load is (4.1). The maximal load of controlled $P_{SLContMax}$ is the same for all cases of controlled part size in this test. The maximal power the smart load could run at (controlled plus oncontrolled part) is in (4.2). It shows that with of 5 % of controlled part the smart load could run at higher power than smart load with 20 % controlled part.

$$\mathbf{P}_{UC} = (1 - N)\mathbf{P}_{load} , \quad (4.1)$$

$$\max(\mathbf{P}_{SLContMax} + \mathbf{P}_{UC}) \leq \max((1 - N)\mathbf{P}_{load}) + P_{SLmax} , \quad (4.2)$$

The comparison of power flows through slack node in that cases is shown in figure 4.4. In table 4.4, there are written maximal values of power flow through the slack node, the maximal power of load and completed work. According to information in that table, increasing the controllable part decreased power flows through the slack.

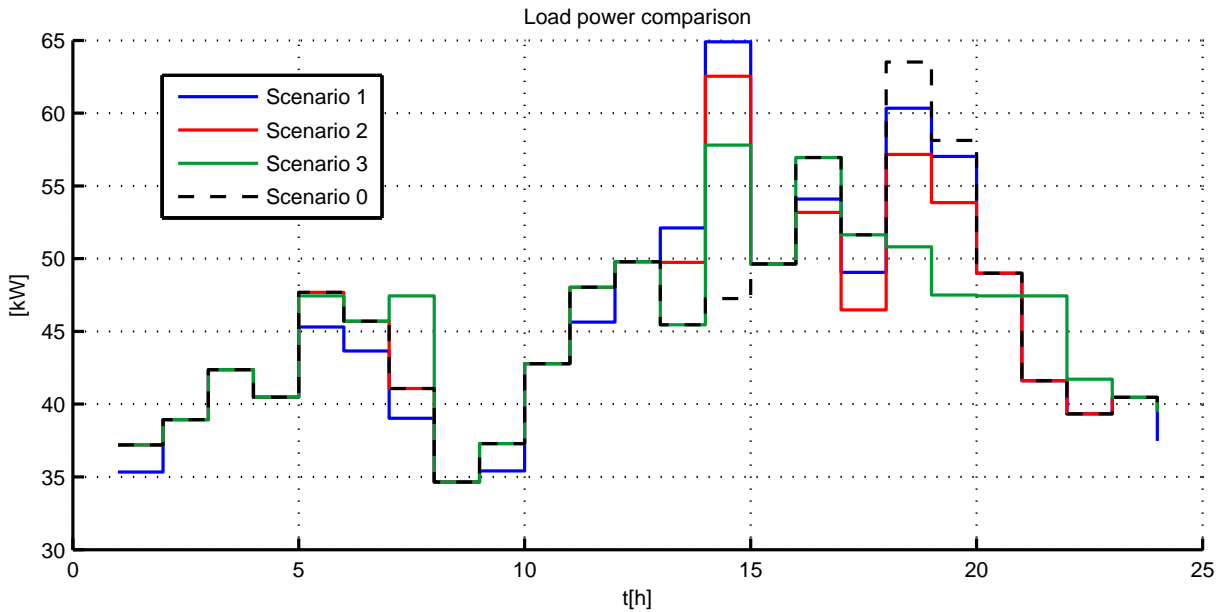


Figure 4.3: Comparison of loads by test 2 of different controllable parts of load ²by linear penalization

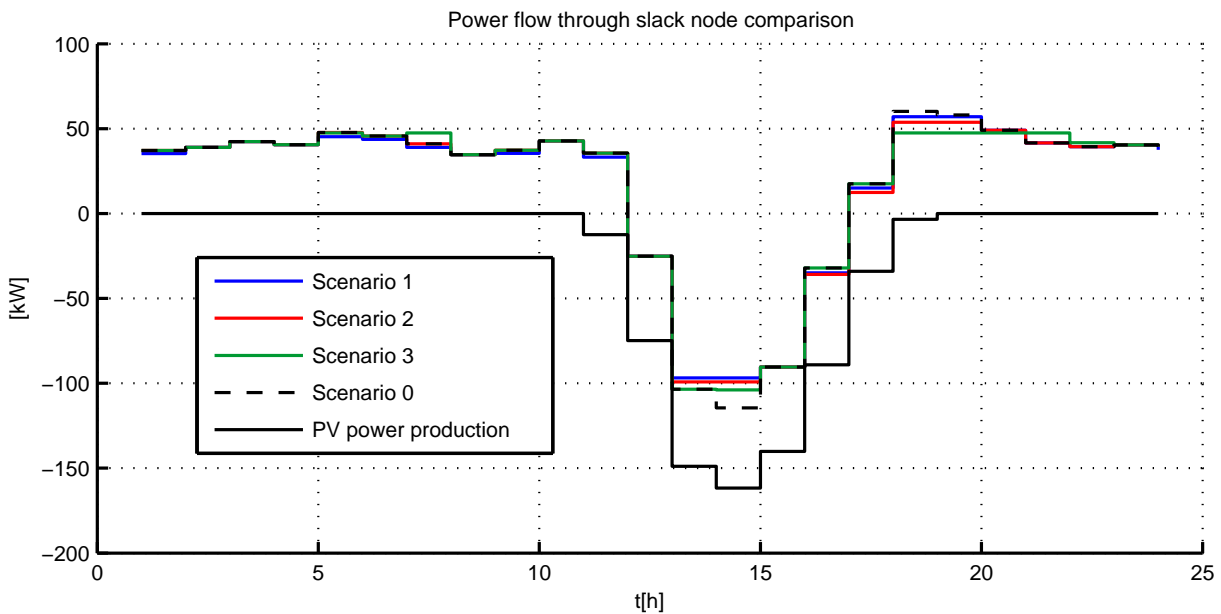


Figure 4.4: Comparison of flows through slack node in test 2 by linear penalization

²Scenario 1: 5 % of load required power could be operated with control
 Scenario 2: 10 % of load required power could be operated with control
 Scenario 3: 20 % of load required power could be operated with control
 Scenario 0: there are only uncontrollable loads in model

Scenario	Max. inflow in slack node [kW]	Max. outflow in slack node [kW]	Max. power [kW]	Completed work [kWh]
Sc. 0	60.14	114.46	63.51	1088
Sc. 1	56.96	96.83	64.89	1088
Sc. 2	53.79	99.19	62.53	1088
Sc. 3	47.44	103.91	57.80	1088

Table 4.4: Test 2: power flows + load by linear penalization

To be more specific lets compare results of no controllable load and 10 % controlled load. Situation from time 13 h to the end of the simulation shows, that power of controlled load is really shifted from times with no PV energy production to times with plenty of it. Using controllable load decreased the maximums of power flow through slack node, as seen in hour 13, where without usage of controlled load the maximum outflow was 114.46 kW and utilization of load with 10 % of power being controlled it was reduced to value 96.83 MW. The maximum of outflow was reduced by 15.4 %.

The same situation was simulated with quadratic penalization with the same penalization coefficients. Load power comparison is presented in figure 4.5 and slack node comparison in 4.6. Maximal values of observed variables are in table 4.5. It is interesting that even that the linear penalization was optimizing maximal value of power flows, by quadratic penalization it was able to achieve lower power flows than by linear penalization. It is because at this case values of variables were high enough so the quadratic penalization produces higher penalty.

Scenario	Max. inflow in slack node [kW]	Max. outflow in slack node [kW]	Max. power [kW]	Completed work [kWh]
Sc. 0	60.14	114.46	63.52	1088
Sc. 1	56.96	96.83	64.89	1088
Sc. 2	53.79	99.19	71.25	1088
Sc. 3	47.44	103.91	65.56	1088

Table 4.5: Test 2: power flows + load by quadratic penalization

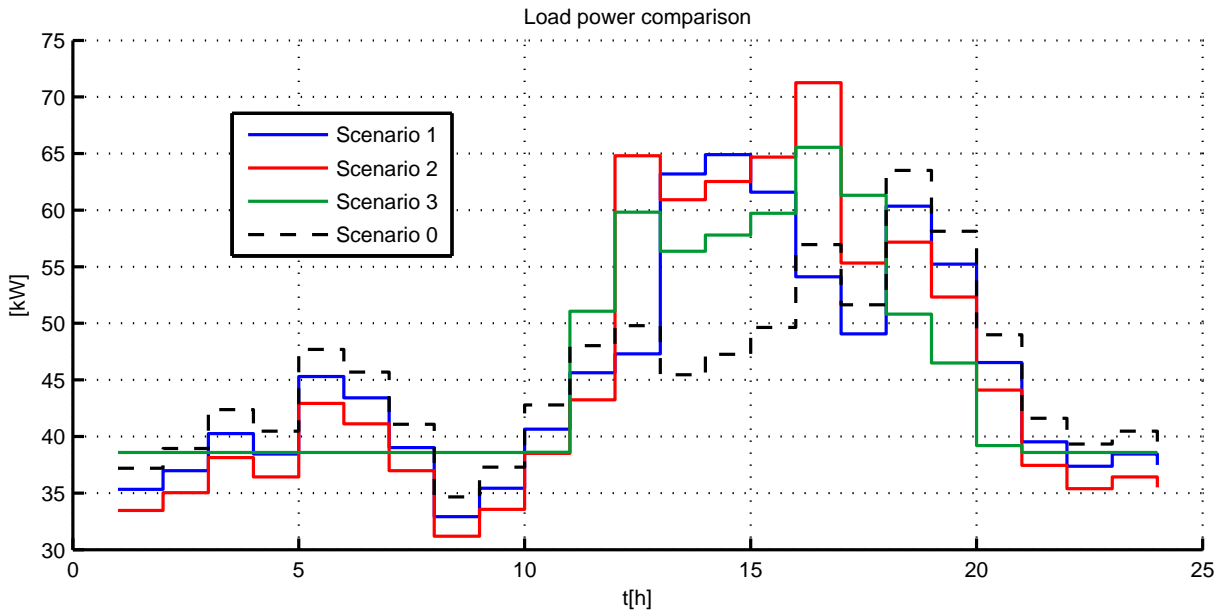


Figure 4.5: Comparison of loads by test 2 of different controllable parts of load ³by quadratic penalization

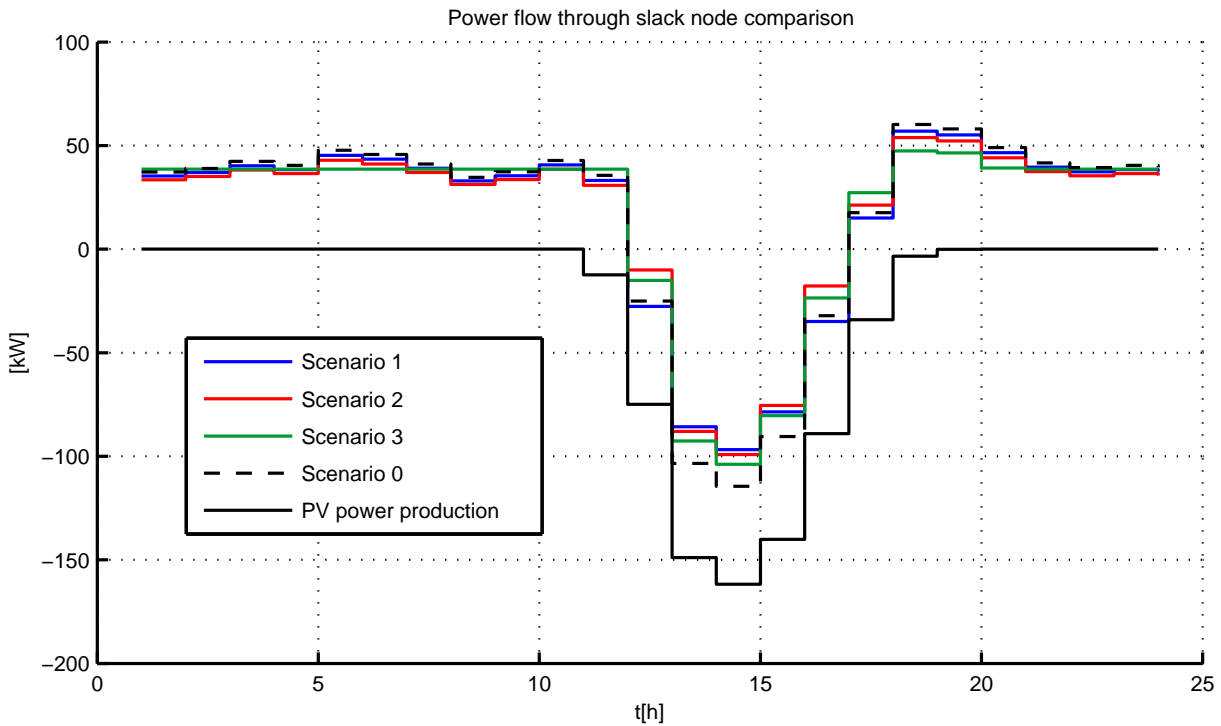


Figure 4.6: Comparison of flows through slack node in test 2 by quadratic penalization

³Scenario 1: 5 % of load required power could be operated with control

Scenario 2: 10 % of load required power could be operated with control

Scenario 3: 20 % of load required power could be operated with control

Scenario 0: there are only uncontrollable loads in model

4.5 Test 3: Redundancy of smart load

Test	Components connected to node 2	Components connected to node 3
Test 1: EWH	EWH, FV1	FV2, Load
Test 2: Smart load	Smart load, FV1	FV2
Test 3: Redundancy of smart load	Smart load, FV1	FV2, Load

This test is almost similar to the test 2 discussed in the subsection 4.4. It differs in the number of connected uncontrolled loads and no controllable EWH is connected. In this case, uncontrolled load is connected to the node N2 too. This network is shown in fig 4.1c. The aim of this test is to demonstrate, that no load control is used in the case it is not needed. By an addition of another uncontrolled load the energy consumption within the observed area is always higher than the energy production so there is no risk of power outflows. Smart load then operates similarly as normal uncontrolled load.

Comparison of power consumption of loads and power flows through slack node are shown in fig 4.7. In table 4.6 the maximal values of observed variables are shown. The same scenarios as in previous test are used (described in table 4.3).

Scenario	Max. inflow in slack node [kW]	Max. outflow in slack node [kW]	Max. power [kW]	Completed work [kWh]
Sc. 0	121.11	0	122.63	1762
Sc. 1	117.94	0	119.46	1762
Sc. 2	114.76	0	116.28	1762
Sc. 3	108.41	0	110.43	1762

Table 4.6: Test 3: power flows + load

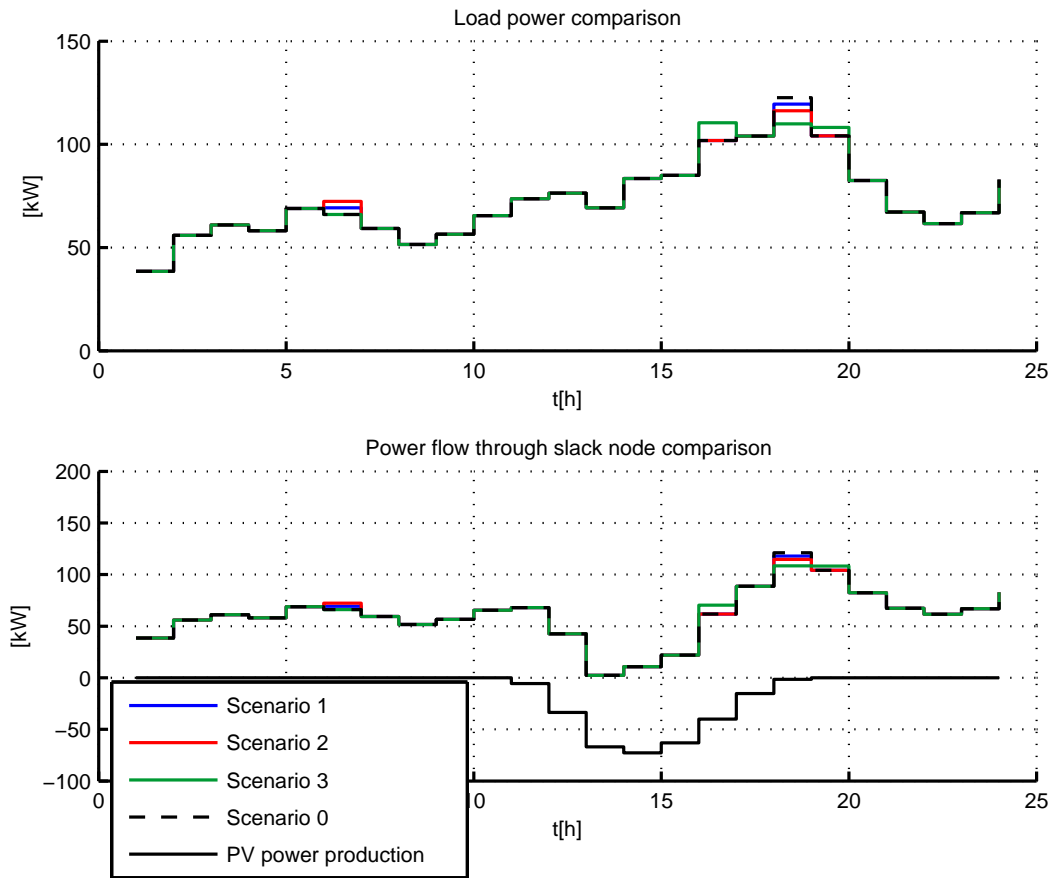


Figure 4.7: Comparison of test 3 for different controlled parts of smart loads ⁴

There is a maximum of PV energy production in hour 13. All loads run at the same power independently on amount of controllable load power. Loads consume enough power to avoid energy outflows from the area. In some hours (e.g. 7,16) the actual load power doesn't correspond with the required one, because there is a possibility of decreasing the maximum of power inflow.

4.6 Test of LV-MAGMA 3 - node model

This test shows a simulation of a simple model simulated by the LV-MAGMA model (combination of LV power grid model and MAGMA model). The power grid model is a

⁴Scenario 1: 5 % of load required power could be operated with control

Scenario 2: 10 % of load required power could be operated with control

Scenario 3: 20 % of load required power could be operated with control

Scenario 0: there are only uncontrollable loads in model

Area	Num. of consumers	Yearly consumption [kWh]	EWHs power [kW]	PV nominal power [kW]
Area 2	97	405372	124.8	566
Area 3	93	552319	128.8	0

Table 4.7: Data of 3-node model areas simulated in 4.6

3-node model containing one slack and two non-slack nodes. There are EWHs connected to both non-slack nodes and a PV power plant to node N2. Each of the non-slack nodes keeps a reference to an area simulated by LV simulator. These areas are models of several consumers and PV power plants. The areas data are shown in table 4.7.

There were two test done on this 3-node model. The first one represents current situation, the CRC wasn't blocked which means that EWHs weren't controlled by MAGMA dependently on the power production and consumption predictions. So at this case no controlled load is used in sense of load power scheduling. Results of this test are shown in fig 4.8. Curve of simulated load culminates at time of 17 h but it is time of low PV power production. Obversely, peak of PV power production is at 12 h when there is only low power consumption.

The second simulation was done on the same model but the CRC control was substituted by MAGMA control. It lets the EWHs to be controlled by the LV model. The aim of this simulation was to let the power being consumed at the time it is produced at the observed area. The simulation results are compared with results of the previous simulation in fig 4.9.

The results of simulation of non-controlled EWHs are marked by number 1, the one with controlled EWH by number 2. The 'computed reference' is a power balance of the slack node. The reference is a result of the MAGMA optimization. The 'simulated load' is a sum of the uncontrolled load and controlled EWHs load and the 'predicted load' is prediction of the uncontrolled load only. Table 4.8 presents information of energy inflow and outflow.

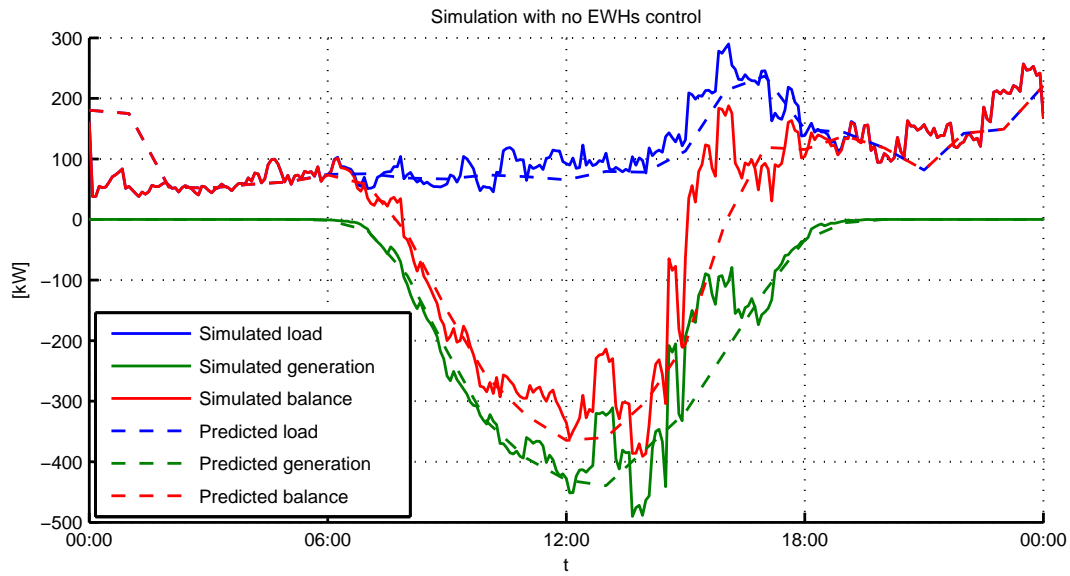


Figure 4.8: Simulation results of LV-MAGMA 3-node model with CRC controlled EWHs

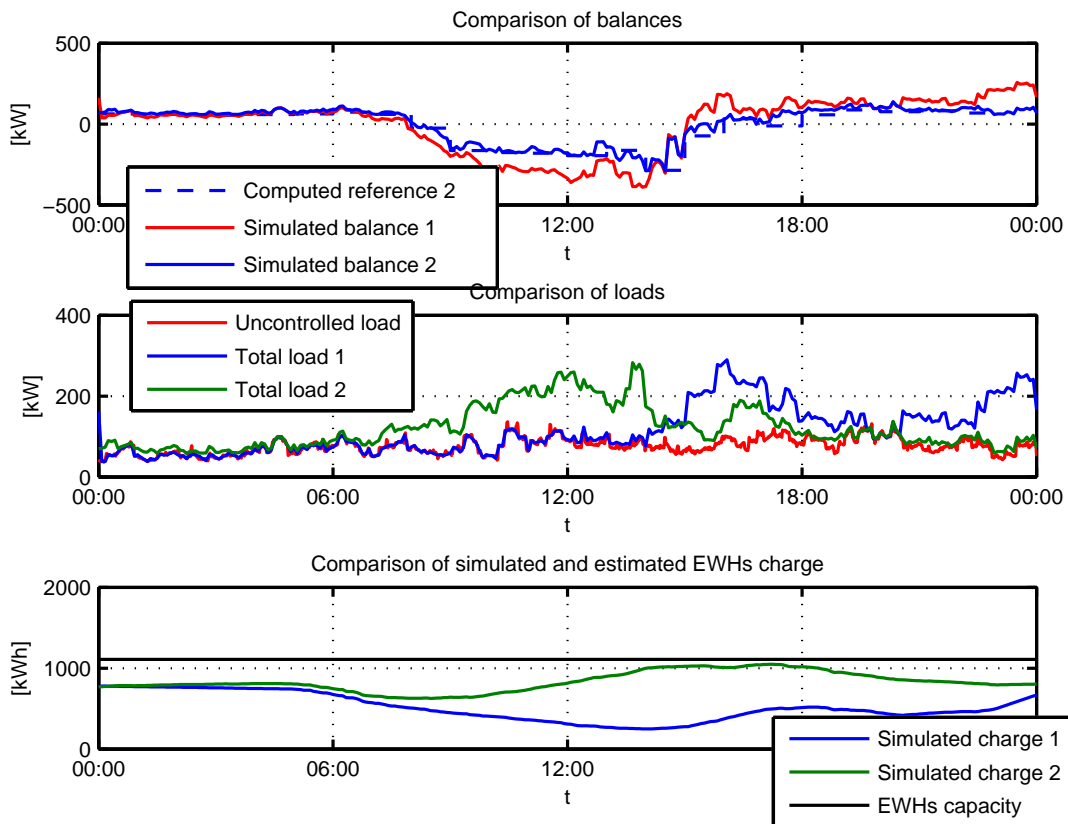


Figure 4.9: Comparison of simulation results of LV-MAGMA 3-node model

	Max. inflow [kW]	Max. outflow [kW]	Imported en- ergy [MWh]	Exported en- ergy [MWh]	Total en- ergy transfer [MWh]
Sc.1	256	391	20.54	20.74	41.28
Sc.2	138	290	14.82	13.00	27.82

Table 4.8: Test of 3-node model: maximal values of observed variables

Balance B of the area is a difference between produced and consumed power (4.3)

$$B = \sum P_{load_i} - P_{RES_i} , \quad (4.3)$$

where P_{load_i} is power consumption of i-th load and P_{RES_i} is power production of i-th PV power plant. 'Computed reference 1' is a reference computed by MAGMA in case with no controlled EWHs and the 'Computed reference 2' in case with controlled EWHs. The same notation is used by simulated balance.

4.7 Test of the Prestice power grid

Number of electrical substations	66
Number of consumers	1720
Number of EWHs	805
Sum of nominal PV power	2107 kW

Table 4.9: Data of power grid simulated in 4.7

The object tested in this test is a part of the Prestice power grid. It was built as the LV-MAGMA model similar to the 3-node model described in section 4.6. The conversion mechanism is outlined in section 3.4 in chapter 3. Data for LV model for generating consumers data and PV power plants data are taken from the HV Prestice power grid model. Specifications of the simulated power grid are shown in table 4.9.

The heating power of used EWHs is usually 2 kW or 2.2 kW. Visualization of the simulated part of the Prestice power grid is shown in fig 5.4 in chapter 5.

The simulation results of test with not controlled EWHs are shown in fig 4.10. It is quite similar to simulation done on the 3-node model in test 4.6. The EWHs are charged

	Max. inflow [kW]	Max. outflow [kW]	Imported en- ergy [MWh]	Exported en- ergy [MWh]	Total en- ergy transfer [MWh]
Sc.1	1909	854	196.75	36.88	233.63
Sc.2	1094	186	179.1	2.99	182.09

Table 4.10: Test Prestice: power flows + transmitted energy

at the time when PV power plants aren't producing much power.

There is a comparison of simulation results of two scenarios in fig 4.11. First scenario ('Simulated balance 1', 'Total load 1', 'Simulated charge 1') is running the simulation with non-blocked CRC, so the EWHs weren't controllable. In the second scenario ('Computed reference 2', 'Simulated balance 2', 'Total load 2', 'Simulated charge 2'), the EWHs were controlled by MAGMA. Both scenarios are simulated on the same power grid and with the same power consumption and generation predictions. Table 4.10 shows the balance data of both scenarios. By controlled EWHs utilization the maximal power outflow was decreased by 78 % and the total energy transfer by 22 %.

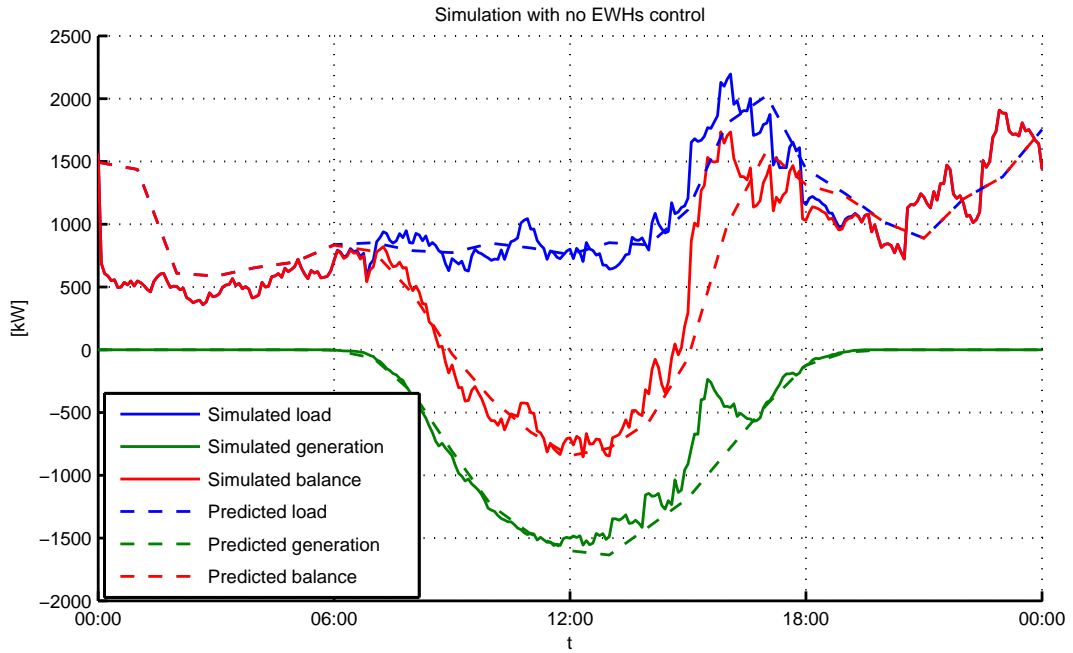


Figure 4.10: Simulation results of the Prestice power grid

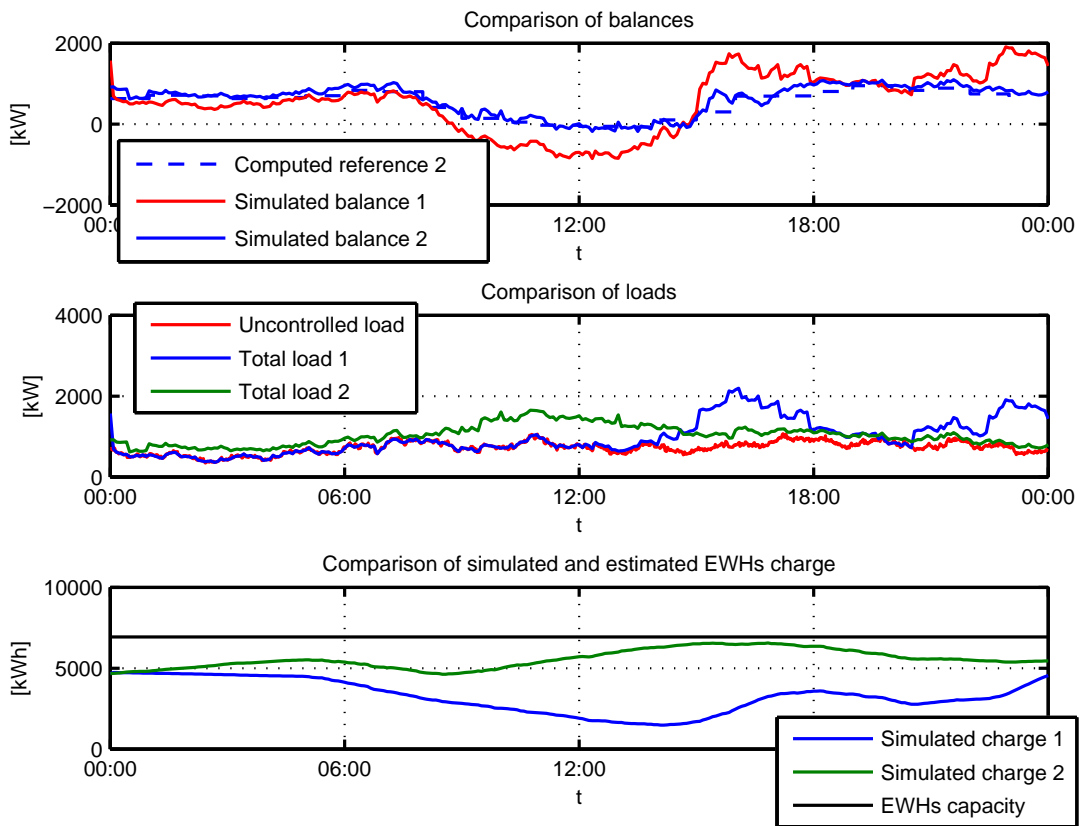


Figure 4.11: Comparison of simulation results of the Prestice power grid

Chapter 5

Visualization

This chapter describes an implementation of visualization of the HV Prestice model and it contains visualized pictures of it. For the visualization, the by the Google Earth toolbox for MATLAB was used.

5.1 Google Earth visualization

5.1.1 Conversion of coordinates

Position of power grid parts is set in the S-JTSK (Jednotna trigonometricka sit katastralni = Uniform Trigonometric Cadastral network) coordinate system. This system is used in cadastral maps in the Czech republic and in Slovakia and it considers mapped area as a flat. S-JTSK coordinate system is based on the cartesian system. However, Google Earth works with coordinates in WGS84 format, because it maps points all over the world.

The conversion is realized by 3 th order polynomial. Coefficients of the polynomial were found from Helmert transformation. The accuracy of the coordinate conversion is said to be 1 m. Conversion function was implemented in MATLAB as a transcription from an MS Excel file [8].

5.1.2 Electrical substations visualization

The electrical substations are represented by a segment Node in MAGMA model. However, not all models of an electrical substation in the Prestice model could be con-

sidered as representations of an actual electrical substations, because some of them were added just for a "cosmetic" purpose - to let the power lines of the model correspond with reality.

The picture of a yellow pin was used as a visualization of an electrical substation. As shown in fig. 5.1 it is possible to display information about the electrical substation - ID, sum of power of installed PV power plants connected to the electrical substation, sum of load power connected to the electrical substation.

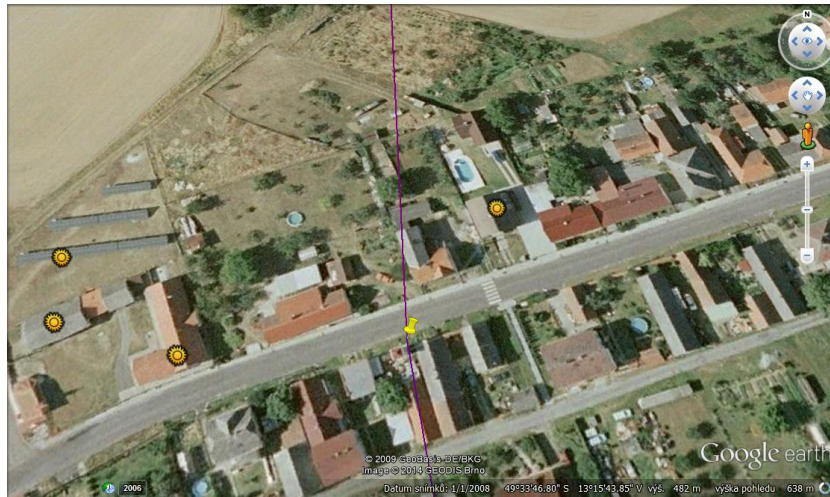


Figure 5.1: Visualization - Node

5.1.3 PV power plants visualization

PV power plants are represented by a symbol of the sun. The position of the symbol visualizing each PV power plant is defined by coordinates of the parcel the PV power plant is built on. The visualized PV power plant (5.2) contains the name of the PV power plant and installed power.

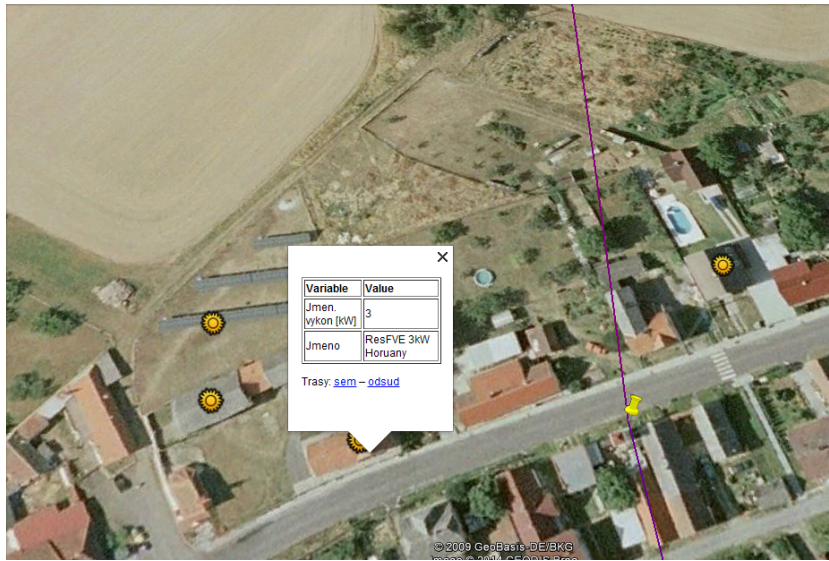


Figure 5.2: Visualization - PV power plant

5.1.4 Power lines visualization

Power lines between two electrical substations are visualized. The Prestice power grid model contains several nodes included only in sake of reflecting physical design of the real power grid, but they are redundant in power grid topology and don't represent any existing electrical substation. These data of the Prestice power grid model are used by a visualization and a shape of the visualized power lines correspond to the existing ones.

The color of the visualized line is set by ratio of the transported power maximum to the power line capacity. Visualized power line contains information about the transported power maximum and the power line capacity.

5.1.5 Prestice area

The visualization of the whole Prestice area is shown in fig. 5.3

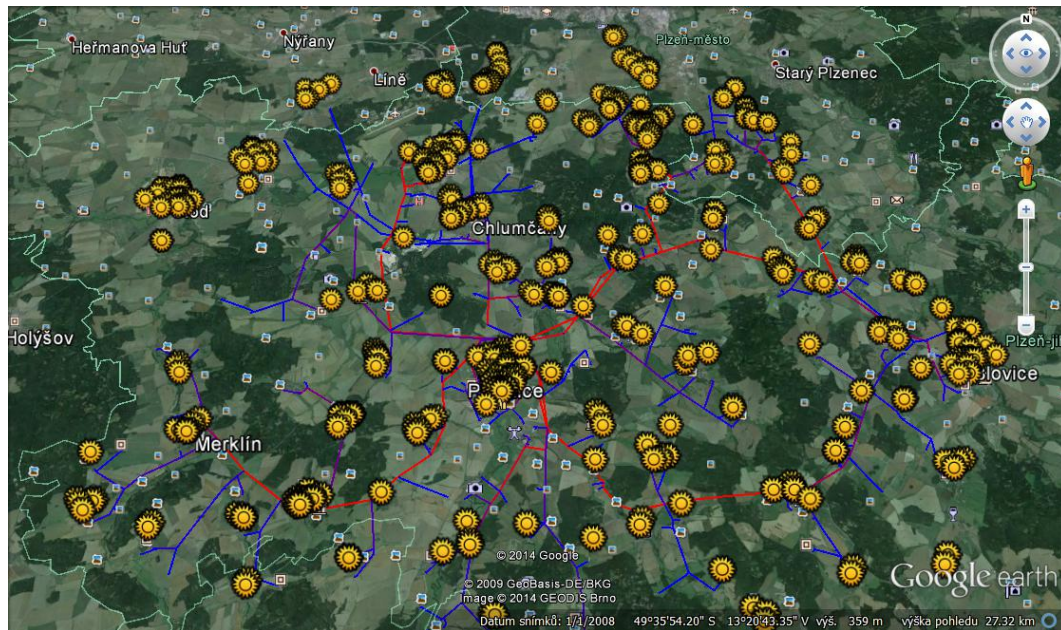


Figure 5.3: Visualization - Prestice power grid

The area simulated in section 4.7 in chapter 4 is shown in fig 5.4.

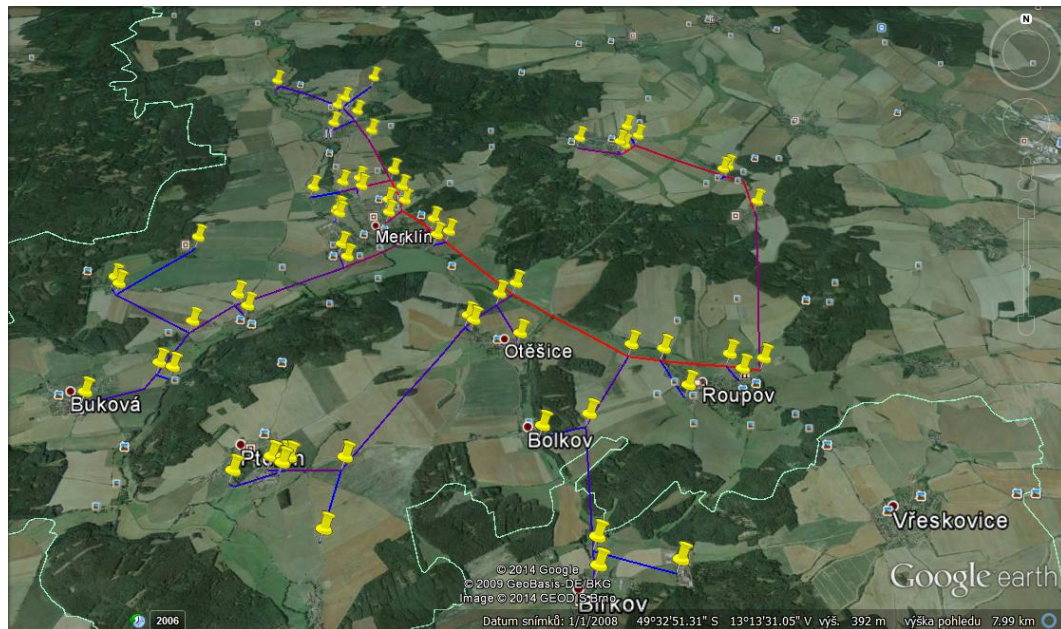


Figure 5.4: Visualization - simulated part of Prestice power grid

Chapter 6

Conclusion

This bachelor thesis brought several modifications and extensions of the MAGMA model. Current version of model that is built as a fusion of the three models combines a simulator and an optimizer. If there was a possibility to use it for control of existing distribution networks the simulation part would be substituted by actual measurements and weather predictions.

Theoretically, if there are devices capable of control in the existing power grid, it will be able to use this controlling mechanism. Results of the simulations done during this thesis show that controlled loads utilization could improve quality of distribution networks operation. According to the simulation results load shifting causes decrease of power leaving or incoming a power grid area which could save cost of power transmission. Another consequence of decrease of power flows in the power grid is prevention of overloading.

Due to the HV Prestice model and its extension by PV power plants there was created a model simulating an existing distribution network so it could be in future possible to compare simulation results and the reality. Moreover it could be used for example to simulate potential future situations and based on the simulation results maybe change the form of the power grid.

The subordinate goal of this thesis was to implement some tools for visualization. Now it is possible to visualize both the MAGMA model and the HV Prestice model.

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Appendix A

Contents of the included CD

The included CD contains an electronic version of this bachelore thesis.