Design Specification

TSRT10 project group 7

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DOCUMENT HISTORY

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1 INTRODUCTION

The purpose of this document is to deliver an in depth description of the system architecture of the project "Real Time Control of Electric Vehicle Charging and Heat Pump in Grid Perspective".

1.1 Background Information

The project is given in the course *TSRT10 - Automatic Control Project Course at Linköping University*. Originating from a collaboration between the department of Vehicular Systems (FS) at Linköping University and the company Tekniska Verken, power grid owners in Linköping municipality. They are especially interested in whether their network will manage the increasing voltage fluctuations, caused by households whom are installing photovoltaics as well as connect rechargeable vehicles to the into the low-voltage grid.

1.2 Definition of terms

In this chapter, shorts that will be used in the project are defined.

LV	Low-voltage
HV	High-voltage
AC	Alternating Current
DC	Direct Current
PV	Photovoltaics
EV	Electric Vehicle
HP	Heat Pump
AT	Accumulator Tank
GUI	Graphical User Interface
V2G	Vehicle to Grid

2 SYSTEM OVERVIEW

The design of the system is divided into subsystem 1 and 2. The first system includes the models concerning the residential house and its internal optimization, while the second system includes the low voltage power grid with a number of nodes representing a residential area and simulates the voltage fluctuations in the grid.

Figure 1 shows the simulation running on a computer hard drive, being fed data and running it through an optimization algorithm. Lastly data will be returned to the user, which in turn can give input to the system. For testing purposes, model parameters can be altered to set the conditions of the household, resulting in different results. These will in the beginning be set, but can later on be altered randomly to get a more real life prediction.

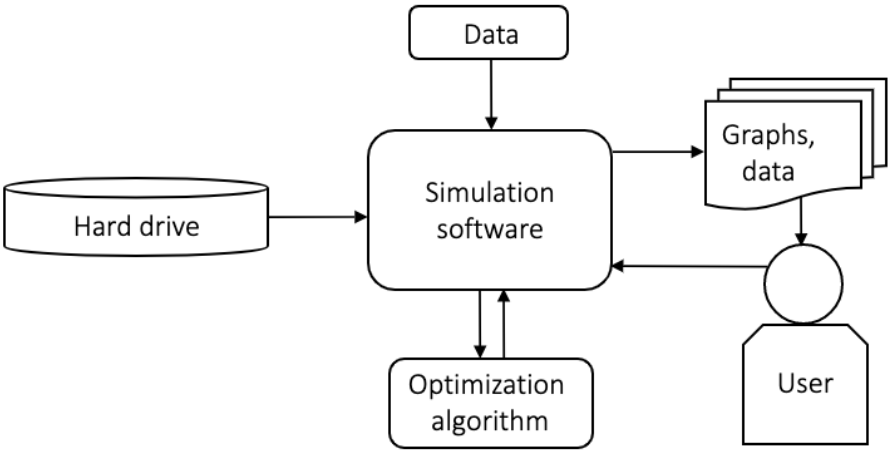

Figure 1: An overview of the system.

3 MODELS OF SUBSYSTEM 1

The subsystem 1, seen in *Figure 2*, will consist of the following components:

- A model for a connected electric vehicle, from which energy can be stored and used
- A model for photovoltaics, providing energy while the sun shines
- A model for usage of a heat pump and accumulator tank to store energy for later use of hot water
- A model calculating the temperature of the house
- The main algorithm which will use historic data to balance the different energy sources to minimize cost for the household

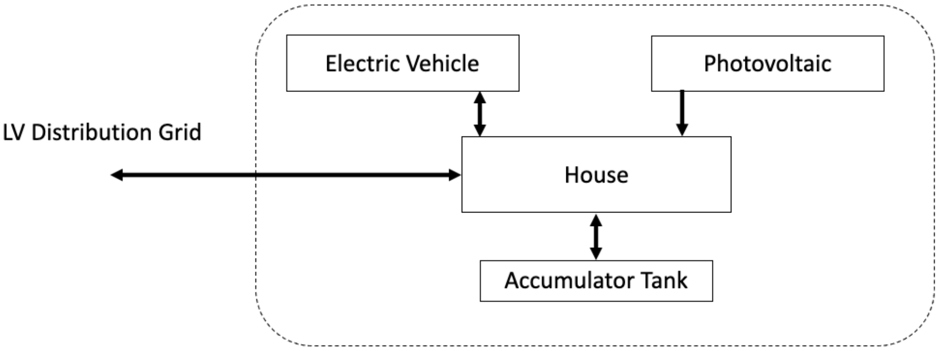

Figure 2: Subsystem including residential house, electric vehicle, photovoltaics and an accumulator tank.

3.1 Thermodynamic model of building

The thermodynamic model of the building is a model of the house (figure 2). The indoor temperature depends on the power heating (P_{heat}), transmission heat loss (P_{loss}), radiation power by sun through window (P_{rad}), electric power by usage of electric devices inside the house $(P_{electric})$, the heat losses form the hot water accumulation tank (P_{tank}) and the ventilation power losses (P_{vent}).These powers are then divided by the thermal capacity of the house (R_{tot})

$$\frac{dT_{in}}{dt} = \frac{P_{heat} - P_{loss} + P_{radiation} + P_{electric} - P_{vent}}{R_{tot}} \tag{1}$$

where the heat transfer per time unit is calculated according to *equation 2*.

$$P_i = A_i U_i (T_{in} - T_{out}) \tag{2}$$

The total transmission heat loss is calculated according to *equation 3*

$$P_{loss} = \sum_i P_i \tag{3}$$

where P_i is the transmission heat loss through a certain part of the building and the sum of all these losses equals to P_{loss}.

3.2 Charging of EV

The equation below describes how the batteries state of energy (SOE) varies with the charging rate. η denotes the charging efficiency. SOE is a value varying in between zero and one where 0 means empty battery and 1 means fully charged battery. The electric vehicle is assumed to be away from the house during normal work hours (8am-5pm from monday-friday) and stationary outside the house during the rest of the time. The battery is required to be charged before usage (i.e SOE=0.9 at 8am from monday-friday).

$$\frac{dSOE}{dt} = \frac{\eta P_{charge}}{Q_b} \tag{4}$$

3.3 Accumulator Tank and Heat Pump

A model of an accumulator tank and heat pump will be made. The water usage will be predicted given historic data and the hot water can be used for heating. Electric power input: W is the electric input, Q_H is the heat generated from the pump and COP is the coefficient of perfomance (which is the efficiency of the heat pump).

$$COP = \frac{Q_H}{W} \tag{5}$$

The hot water accumulation tank is modelled in the following way.

$$P_{wt,tank} = \gamma_{tank,loss} h_{wt} \tag{6}$$

The power losses though the water tank is described according to *equation 6* where h_{wt} is a value between 0 and 1 describing the water level depending on the water usage in the household and $\gamma_{tank,loss}$ is a constant describing the losses.

$$\frac{dh_{ht}}{dt} = \frac{P_{heater} - P_{loss,ht} - P_{heat}}{\rho C V_{ht}} \tag{7}$$

The tank level used for indoor heating h_{ht} is described according to *equation 7* where P_{heat} (the power taken from the tank to increase the inside temperature) and P_{heater} (the power heating the water inside the tank) are the control signals. Moreover ρ is the water density, V_{ht} is the tank volume and C is the heat capacity for the water.

$$\frac{dh_{wt}}{dt} = \frac{P_{boiler} - P_{loss,wt} - P_{hw}}{\rho C V_{wt}} \tag{8}$$

The tank level used for hot water h_{wt} is described according to the *equation 8* where P_{boiler} (the power used to heat the hot water accumulation tank) is a control signal and P_{hw} is the power taken from the tank when a tap is open.

$$P_{tank,loss} = P_{loss,hw} + P_{loss,wt} \tag{9}$$

The resulting losses from the water tanks are then described according to *equation 9*.

3.4 Photovoltaics

The photovoltaics model uses weather to calculate energy production for a solar panel. The data consists of global radiation, diffuse radiation, direct radiation and ambient temperature. The data used is gathered from SMHI and from a weather station located in Norrköping. The model consists of equations for calculating angle of exposure to the sun dependent of latitude and what direction the panel is facing. Then with radiation data it calculates the electricity production with specific data of the panels.

Calculating exposure to sun depending on hour of day, orientation and tilt of panels for every hour of each day for the whole year.

Declination	δ
Current hour of the day	H
Current Day of the year	D
What angle the sun should have relative to south	α

Table 1: Units used in the photovoltaics model.

Maximum declination of the sun

$$\delta_{sun} = 23.45 \cdot sin\left((D-81)\cdot\frac{360}{365}\cdot\frac{2\pi}{360}\right)\frac{2\pi}{360} \tag{10}$$

Horizonal angle of the sun relative south.

$$\alpha = \left(H \cdot \frac{365}{24} - 180\right)\frac{2\pi}{360} \tag{11}$$

The suns angle to the ground.

$$\begin{aligned}\Gamma = asin\Bigg(\Bigg(&sin(Lat) \cdot sin(\delta_{sun})\Bigg) \\ &+cos(\delta_{sun}) \cdot cos(Lat)\Bigg) \cdot cos(\alpha)\end{aligned} \tag{12}$$

The suns angle relative south on the ground

From 00:00 to 12:00:

Azimuth angle

$$\gamma_1 = real\left(\pi - acos\left(\frac{sin(\Gamma) \cdot sin(Lat) - sin(\delta_{sun})}{cos(\Gamma) \cdot cos(Lat)}\right)\right) \tag{13}$$

From 12:00 to 24:00:

$$\gamma_2 = real\left(\pi + acos\left(\frac{sin(\Gamma) \cdot sin(Lat) - sin(\delta_{sun})}{cos(\Gamma) \cdot cos(Lat)}\right)\right) \tag{14}$$

$$\gamma_{sun} = \gamma_1 + \gamma_2 \tag{15}$$

Calculating the Incidence angle between the panels and the sun

$$\begin{aligned}\beta = acos\Bigg(&sin(\Gamma) \cdot cos(\delta_{panel}) \\ &+cos(\Gamma) \cdot sin(tilt) \cdot cos(\gamma_{sun} - \gamma_{panel})\Bigg)\end{aligned} \tag{16}$$

Calculating radiation on Photovoltaics

Reflective coefficient

$$c_{ref} = 0.2 \tag{17}$$

Direct irradiance depending on incidence angle.

$$I_{dir,panel} = I_{dir} \cdot cos(\beta) \tag{18}$$

Total irradiance of panel

$$I_{panel} = abs_{dir,panel} + I_{diffuse} \cdot \frac{1 + cos(\delta_{panel})}{2} + i_{global} \cdot c_{ref} \cdot \frac{1 + cos(\delta_{panel})}{2} \tag{19}$$

Calculating Photovoltaics-Current and Power

Calculating cell temperature using ambient temperature, the panel current times and nominal operating cell temperature.

$$T_{cell} = \left(Ta + \frac{I_{panel}}{800} \cdot NOCT - 20 \right) + 273 \tag{20}$$

With specific data of the photovoltaics used, the power can be calculated.

$$Vtn = Ns \cdot \frac{K \cdot Tn}{q} \tag{21}$$

$$Ion = Iscsexp\left(\frac{-Vocn}{a \cdot Vtn} \right) \tag{22}$$

$$Io = Ion \cdot \left(\frac{T}{Tn} \right)^3 \cdot exp\left(\frac{q \cdot Eg}{a \cdot K} \cdot \left(\frac{1}{Tn} - \frac{1}{T} \right) \right) \tag{23}$$

$$Iph = (Iscn + Ki \cdot (t - Tn)) \cdot \frac{G}{Gn} \tag{24}$$

$$Vt = Ns \cdot \frac{K \cdot T}{q} \tag{25}$$

$$VocVec = 0 : 0.1 : Vocn \tag{26}$$

$$I = zeros(length(I_{panel}), length(VocVec)) \tag{27}$$

For j=1 to length of Vocvec

$$I(:, j+1) = Iph - Io \cdot exp\left(\frac{VocVec(j) + I(:, j) \cdot Rs}{Vt \cdot a} - 1\right) \frac{VocVec(j) + Rs \cdot I(:, j)}{Rp} \tag{28}$$

$$P = max(VocVec \cdot I) \tag{29}$$

3.5 Data collection

To retrieve data of the solar irradiation the website [1] is used. By using the website API, a created Matlab script called *getSolarData.m* collects the global solar irradiance, direct irradiance and diffuse irradiance, all in W/m^2. These are later used to calculate the solar production with the photovoltaics model. In the figure below, the global irradiation of 2020 can be seen.

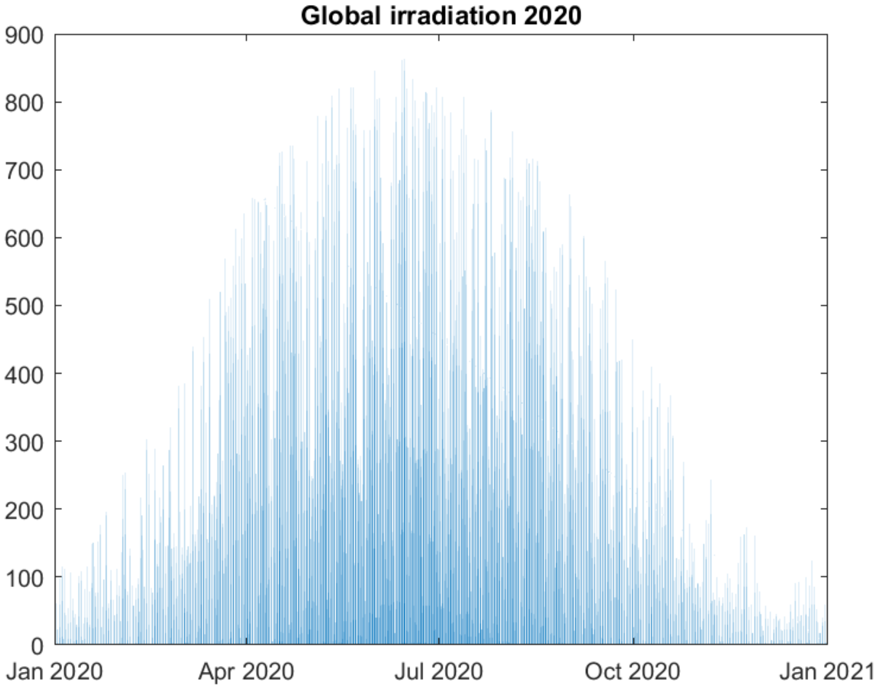

Figure 3: Global irradiation during 2020

4 MODELS IN SUBSYSTEM 2

Sub-system 2 consists of a local grid that connects a small residential area. The power is distributed to the different domestic establishments with a voltage around 230 V. Two types of cables composes the local grid, namely N1XV150 och N1XV10. The interconnections can be viewed in the illustration below where the nodes represents domestic establishments.

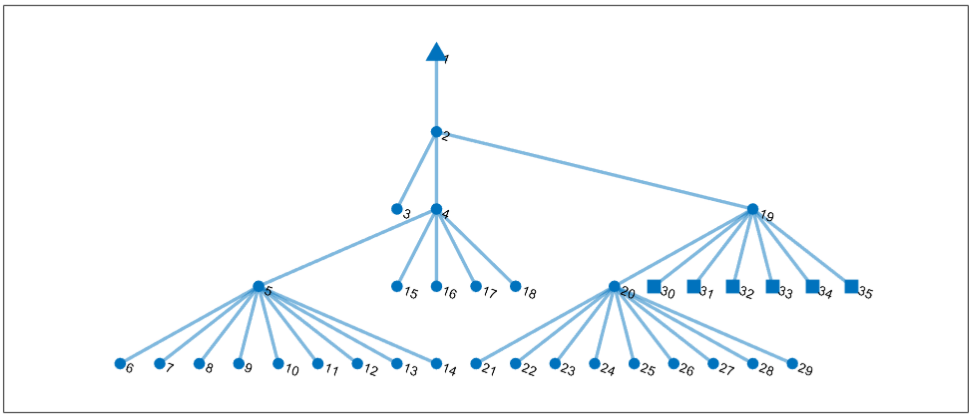

Figure 4: Overview of a the local distribution grid.

4.1 Low-Voltage Grid

According to Ohm's law the current can be calculated by dividing the impedance with the voltage. The square root of three term is added to describe the line to line voltage in three phase power distribution.

$$I = \frac{U\sqrt{3}}{S}$$

As current flows through a metal conductor some electrons collide with atoms or other impurities which causes resistance and generates heat. The heat is considered a power loss and may be reduced by increasing the cross section area of the cable. A general expression of the power loss is given by the formula below.

$$S_{loss} = 3IR^2$$

Power losses also occur in the transformers. The four main reasons are resistive losses, eddy current losses, hysteresis losses and flux losses. These qualities ultimately decide the efficiency of the transformer. An in depth assessment of different transformer configurations is not in the scope of this report.

4.2 Optimization model

The optimization model used is convex optimization. The usage consumption of electricity is optimized using real time control where an optimization is made given a certain time horizon (N) given a prediction of future electric consumption given historic data. The spot prices for the next day are released around 2pm every day. This means that the given time horizon for the electric spot prices varies between 10-34 hours. In the beginning a shorter time horizon will be used and this will later be compared to a longer time horizon to evaluate the importance of a longer time horizon.

The optimization problem which we will minimize is:

$$min \sum_{(} i) c_c(i) P_{tot}(i) \Delta t + c_m \sum \Delta P(i) \tag{30}$$

With the following constraints:

$$SOE_{lowerbound} \leq SOE \leq SOE_{upperbound} \tag{31}$$

$$0 \leq P_{charge} \leq P_{charge,max} \tag{32}$$

$$0 \leq P_{heater} \leq P_{heater,max} \tag{33}$$

$$0 \leq P_{heat} \leq P_{heat,max} \tag{34}$$

$$0 \leq P_{boiler} \leq P_{boiler,max} \tag{35}$$

$P_{ht,lowerbound}$ and $P_{wt,lowerbound}$ are bigger or equal to 0 and $P_{ht,upperbound}$ and $P_{wt,upperbound}$ are less or equal to 1.

$$P_{ht,lowerbound} \leq P_{ht} \leq P_{ht,upperbound} \tag{36}$$

$$P_{wt,lowerbound} \leq P_{wt} \leq P_{wt,upperbound} \tag{37}$$

$$i = 1, ..., N \tag{38}$$

Where $c_c(i)$ is the spot price with the time horizon i, c_m is the cost for the peak power.

4.3 Electricity Price Tariffs

A general assumption in this study is that the households are covered by variable rate electricity plans. Thus, the households have the opportunity to act in self-interested by minimizing the energy related expenses. As the prices of electricity [SEK/kWh] are set in advance there is room for planning the electricity related activities.

Other price tariffs will also be investigated, relying on other means of charging the customers. One such model is the *Peak Power Consumption* model that sets the cost of electricity on basis of the maximal kWh consumption within an hour of the month. The idea behind this model is frame incentives for households to keep the electricity consumption at a stable level.

REFERENCES

[1] *Smhi open data api docs - meteorological analysis strång*, 2022. [Online]. Available: https://opendata.smhi.se/apidocs/strang/.