

Object-Oriented Electrical Grid and Photovoltaic system modelling in Modelica

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Abstract

In this paper an object-oriented model for an electrical grid based on the IEEE 34 node test feeder and the integration of this grid with photovoltaic systems on residential level, i.e. 230 V, is presented. The goal is to demonstrate the flexibility of using Modelica to simulate a grid model and to show how this model can be used to simulate the influence of a household power demand and photovoltaic generation on this electrical grid. The idea is to clarify the voltage problem that might occur when implementing a large amount of photovoltaic (PV) systems into a residential grid.

Keywords: Electrical grid; Photovoltaic system; Residential building

1 Introduction

The models that are presented in this paper are a direct result of work that has been accomplished within the K.U.Leuven Energy Institute (EI) project *Optimized Energy Networks for Buildings*. This project focuses on the energy flows within a building and a group of buildings. These energy flows include thermal and electrical energy transfers combined with internal energy conversions. The developed models focus on the electrical aspect, the aspects of the building itself and the thermal installations in the building. These different aspects are modeled by different departments of the Faculty of Engineering at the K.U.Leuven. An object-oriented approach to modelling the building(s) with its interactions is advisable. This way, each model can be developed and tested in their respective domains, before interconnecting them. This paper only treats the electrical part.

The example, that is presented in this paper, is

developed to illustrate how the integration of the grid and photovoltaic system (PV) models can be accomplished. The choice for an object-oriented approach together with the multi-disciplinary nature of the project has led to the use of Modelica.

First, a photovoltaic (PV) system has been implemented based on the five parameter model, as a part of the electrical models being developed [1]. The parameters needed for this model can generally be obtained from data gathered from the manufacturer's specifications of the solar panels.

A second electrical model has been developed for an electrical distribution grid at low voltage (i.e. 230 V). This electrical distribution grid is based on the topology of the IEEE 34-bus model developed for a medium-voltage industrial 24.9 kV distribution grid [2]. The parameters of this distribution grid have been downscaled to represent a residential radial low-voltage electrical distribution network. The object-oriented model has been developed in such a way that the distribution grid topology and its impedances are characterized by a Modelica Record, ensuring maximum flexibility and scalability in the use of the model. As such, this model can be used to describe intra-building grids, which are radial as well. DC-networks follow the same methodology.

2 Photovoltaic system model

2.1 Introduction to the five parameter model

The five parameter model, which is temperature dependent, is based on the single diode equivalent circuit of a PV panel [3]. The five parameters used are:

- the light current I_{ph}

- the diode reverse saturation current I_0
- a shunt resistance R_{sh}
- a series resistance R_s
- the thermal voltage V_t

These parameters are indicated in the equivalent circuit presented in Figure 1.

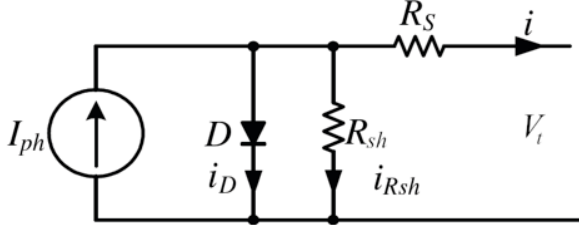


Figure 1: Five parameter model of a PV panel [3]

2.2 Calculation of the five parameters

The five parameters in the model (I_{ph} , I_0 , R_{sh} , R_s and V_t) can be calculated based on characteristics that are provided by the solar panel manufacturer. The necessary specifications to calculate the five parameters are the current I_{mpp} and voltage V_{mpp} at maximum power point (mpp) under standard testing conditions (STC), the short circuit current I_{sc} and open circuit voltage V_{oc} under the same standard testing conditions and the temperature coefficients k_i and k_v of respectively the short circuit current and open circuit voltage. Based on these specifications, Sera et al. [4] gives the calculation method for the five parameters.

The general current-voltage ($i - v$) equation for the single diode equivalent circuit is given in Eq. (1). In this equation V_t is the junction thermal voltage and n_s the number of cells in the panel connected in series. The voltage V_{mpp} and current I_{mpp} at maximum power point should satisfy this equation and according to Eq. (2), the derivative of the power with respect to the voltage should be zero at this point. Eq. (3) states that the derivative of the current with respect to the voltage at short circuit current should be the negative of the shunt conductance ($1/R_{sh}$). These equations lead to the calculation of the parameters R_s , R_{sh} and V_t .

$$i = I_{ph} - I_0 \cdot \left(e^{\frac{v+i \cdot R_s}{n_s \cdot V_t}} - 1 \right) - \frac{v + i \cdot R_s}{R_{sh}} \quad (1)$$

$$\left. \frac{dP}{dV} \right|_{\substack{V=V_{mpp} \\ I=I_{mpp}}} = 0 \quad (2)$$

$$\left. \frac{dI}{dV} \right|_{I=I_{sc}} = -\frac{1}{R_{sh}} \quad (3)$$

The reverse saturation current I_0 and light current I_{ph} at STC can be found based on Eq. (1) for the short circuit (Eq. (4)) and open circuit condition (Eq. (5)).

$$I_{sc} = I_{ph} - I_0 \cdot e^{\frac{I_{sc} \cdot R_s}{n_s \cdot V_t}} - \frac{I_{sc} \cdot R_s}{R_{sh}} \quad (4)$$

$$I_{oc} = 0 = I_{ph} - I_0 \cdot e^{\frac{V_{oc}}{n_s \cdot V_t}} - \frac{V_{oc}}{R_{sh}} \quad (5)$$

2.3 Five parameter PV model in Modelica

The five parameter model is implemented in a Modelica model to calculate the power output of the photovoltaic panels under operational conditions. The current and voltage at maximum power point can be found by solving Eqns. (1) and (2) for the non-reference conditions. The parameters for these conditions are calculated in the next paragraphs.

The PV parameters are adjusted to take into account the position of the sun, the direct and indirect radiation and the ambient temperature. The cell temperature has been adjusted to be the ambient temperature plus the losses of the panel.

The tilt angle and orientation of the PV panels are parameters of the PV model. Together with the sun's position, the incidence angle of the direct beam radiation can be calculated which allows to obtain the amount of radiation that gets reflected by and passes through the PV panel cover. This is done using incidence angle modifiers that are derived from De Soto et al. [3]. The incidence angle modifier $K_{\tau\alpha}(\theta)$ can be found from the transmittance τ of the cover system with Eq. (8), which is approximated in Eq. (7). The angle of refraction, θ_r , is determined in Eq. (6) by Snell's law, with θ the incidence angle and n the effective index of refraction of the cell cover. In Eq. (7), K is the glazing extinction coefficient and L is the glazing thickness. In the model K and L can be adjusted. By default, K is assumed to be 4 m^{-1} and L is assumed to be 2 mm .

$$\theta_r = \arcsin(n \cdot \sin\theta) \quad (6)$$

$$\tau(\theta) = e^{-\frac{K \cdot L}{\cos\theta_r}} \cdot \left[1 - \frac{1}{2} \cdot \left(\frac{\sin^2(\theta_r - \theta)}{\sin^2(\theta_r + \theta)} + \frac{\tan^2(\theta_r - \theta)}{\tan^2(\theta_r + \theta)} \right) \right] \quad (7)$$

$$K_{\tau\alpha}(\theta) = \frac{\tau(\theta)}{\tau(0)} \quad (8)$$

The incidence angle modifiers and the direct and diffuse radiation, which are inputs to the model, allow

together with the reflected radiation to calculate the absorbed solar radiation S in Eq. (9). In this equation G_b is the direct, G_d the diffuse and G the total radiation. The slope of the PV panel is characterized by β .

$$\frac{S}{S_{ref}} = \frac{G_b}{G_{ref}} \cdot K_{\tau\alpha,b} + \frac{G_d}{G_{ref}} \cdot K_{\tau\alpha,d} \cdot \frac{1 + \cos\beta}{2} + \frac{G}{G_{ref}} \cdot \rho \cdot K_{\tau\alpha,g} \cdot \frac{1 - \cos\beta}{2} \quad (9)$$

The light current I_{ph} , reverse saturation current I_0 and thermal voltage V_t at non-reference conditions can be calculated when the temperature, open circuit voltage and short circuit current are known [4]. The open circuit voltage V_{oc} can be calculated using Eqns. (10) and (11). The short circuit current I_{sc} can be found using Eq. (12).

$$e^{\frac{V_{oc}(S)}{n_s \cdot V_t}} = \frac{I_{ph}(S) \cdot R_{sh} - V_{oc}(S)}{I_0 \cdot R_{sh}} \quad (10)$$

$$V_{oc}(T) = V_{oc} + k_v \cdot (T - T_{stc}) \quad (11)$$

$$I_{sc}(S, T) = I_{sc} \cdot \left(\frac{S}{S_{ref}} \right) \cdot \left(1 + \frac{k_i}{100} \cdot (T - T_{ref}) \right) \quad (12)$$

The reverse saturation current I_0 can be calculated with Eq. (13). The light current I_{ph} is found using Eq. (14).

$$I_0 = \left(I_{sc} - \frac{V_{oc} - I_{sc} \cdot R_s}{R_{sh}} \right) \cdot e^{-\frac{V_{oc}}{n_s \cdot V_t}} \quad (13)$$

$$I_{ph} = I_0 \cdot e^{\frac{V_{oc}}{n_s \cdot V_t}} + \frac{V_{oc}}{R_{sh}} \quad (14)$$

The ambient temperature and the direct and diffuse radiation are read from a meteorological data file and can be given as parameters to the model of the photovoltaic panel. This meteorological data are taken from Meteororm 6.1 and give minute values for solar radiation and ambient temperature [5]. The direction of the beam radiation to the PV panel and the position of the sun are calculated in another model based on the simulation time.

2.4 Conclusion

Since the model of the PV panel takes I_{ph} , I_0 , R_{sh} , R_s and V_t as parameters, it can be used to model a large variety of PV panels for which these parameters are known. For most panels they can be calculated from manufacturer catalogue data, for which the method is described in section 2.2. The PV panel model calculates the power, current and voltage of the panel

and can be used to put several panels in series or in parallel. This leads to an optimal flexibility for the use of this model.

3 Electrical grid model

The goal of this paper is to demonstrate a working grid model to show the effects of the power demand of a household and the power generation of a PV system on a distribution grid.

First, the grid topology is described in section 3.1. This section discusses the simulated grid, the representation of the grid in matrix form and how this matrix form allows to model any radial grid topology.

Traditionally, electrical grids are examined using a power flow analysis to determine the nodal currents, line currents and nodal voltages. The background on power flow analysis is given in section 3.2. Next, section 3.3 gives an overview of the object-oriented implementation of this problem in Modelica. The grid is implemented in Modelica making full use of the object-oriented modelling language for component-oriented modelling of complex systems. A simple grid with two households and two PV systems is considered to illustrate schematically the use of the model in Modelica.

In section 4 the full IEEE 34 node grid is used to analyze the grid for any voltage problems that may occur when there is a certain penetration rate of photovoltaic systems in the grid.

3.1 Grid topology

In this paper a grid model is used on a district level for residential connections. Figure 2 shows the topology of the modelled IEEE 34 node test feeder [2]. This type of distribution grid is typically a radial network with a rated voltage of 230 V (400 V wye, or star, connection). In a radial network, there is only a single-feeder transformer, thus the reduced reliability is the major disadvantage, due to the lack of a redundant supply. An interruption at one node means all nodes downstream are interrupted. The IEEE 34 node test feeder, used in this paper, is based on a distribution grid of Arizona (USA) with a rated voltage of 24.9 kV. The voltage is downscaled to 230 V (Europe). Therefore, also the line impedances are adapted [6].

Each node in this grid represents a residential connection with a certain power demand. Besides it

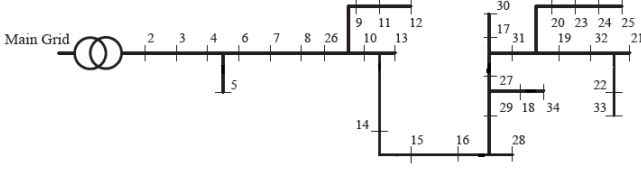


Figure 2: Grid topology IEEE 34 node test feeder [2]

is possible to have a random number of houses with a PV system.

The connections of the nodes of this grid can be represented by an incidence matrix (or connection matrix) \mathbf{T} . Each row in \mathbf{T} stands for a line between two nodes. Since there are 34 nodes in the grid, there are 33 lines. The number of columns equals the number of nodes. A line can then be represented by 1 and -1 at respectively the start and end node of the line. The other row elements are zero. To obtain a square matrix, an extra (first) row is introduced to represent the 'line' between the transformer and the first node, in which there is only an end node. Thus, in this example for the IEEE 34 node test feeder, the incidence matrix \mathbf{T} is a 34-by-34 matrix. This description with an incidence matrix \mathbf{T} basically allows any radial grid topology to be modelled.

Eq. (15) gives an example of the representation of an incidence matrix \mathbf{T} in which the nodes are all next to each other, which means branches are between consecutive nodes. In the example used in this paper (a radial grid as presented in Figure 2), the matrix is not as structured as in Eq. (15).

$$\mathbf{T} = \begin{pmatrix} -1 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 1 & -1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 1 & -1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 0 & 0 \\ 0 & 0 & 0 & \cdots & 1 & -1 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 1 & -1 \end{pmatrix} \quad (15)$$

The impedance matrix \mathbf{Z} represents the impedances of each line in the grid. The impedance of a line is defined as a combination of a real (resistance \mathbf{R}) and imaginary (reactance \mathbf{X}) part (Eq. (16)).

$$\mathbf{Z} = \mathbf{R} + j \cdot \mathbf{X} \quad (16)$$

3.2 Background of electrical grid modelling

The proposed grid can be used to perform a load flow analysis in order to characterize the impact of the load profile of each residential connection and

PV electricity generation on the grid. Traditionally, a power flow analysis is used to determine e.g. the voltage deviations at each node. This section gives the background of this method.

Several methods are available to determine the grid parameters in a power flow analysis. Generally, the *backward-forward sweep* is used. With this method it is possible to calculate the vector of nodal currents \mathbf{I}_{node} , line currents \mathbf{I}_{line} (between two nodes) and the nodal voltages \mathbf{U}_{node} for each time step. As such, the full flow of active power P and reactive power Q is known for each node. P and Q can be calculated from the apparent power S , using Eqns. (17)-(19), with \mathbf{I}^* the complex conjugate of \mathbf{I} .

$$S = P + j \cdot Q = U \cdot I^* \quad (17)$$

$$P = \Re(S) \quad (18)$$

$$Q = \Im(S) \quad (19)$$

The parameters (\mathbf{I}_{node} , \mathbf{I}_{line} , \mathbf{U}_{node}) are determined via iteration. In a first iteration a fixed voltage profile of 230 V for each node is assumed. For the next time steps this flat voltage profile for the first iteration step can be replaced by the voltage profile of the last simulated time step. When the time step is small enough, this will lead to a faster convergence of the iteration because this voltage profile will be closer to the actual one.

After this first iteration step, the backward-forward sweep will be used till convergence is reached. In the backward step, the nodal and line currents are calculated by Eqns. (20) and (21). Both currents are calculated based on parameters of the previous iteration step. In Eqns. (20) and (21), the nodal and line currents and the nodal voltages are complex. \mathbf{S}_{node} stands for the apparent power which consists of the active power (P) and reactive power (Q) (Eq. (17)). The incidence matrix \mathbf{T} is used to calculate the line currents. Note that the transpose of \mathbf{T} is taken in Eq. (21).

$$\mathbf{I}_{node} = f(\mathbf{S}_{node}, \mathbf{U}_{node}) = \left(\frac{\mathbf{S}_{node}}{\mathbf{U}_{node}} \right)^* \quad (20)$$

$$\mathbf{I}_{line} = (\mathbf{T}^T)^{-1} \cdot \mathbf{I}_{node} \quad (21)$$

In the forward step, the nodal voltage is calculated with the line currents calculated in Eq. (21). The nodal voltage given in Eq. (22) is then compared, just like all parameters, with the values from the previous iteration step. The iteration in Eqns. (20)-(22) starts again until convergence is reached (error: $\varepsilon \leq \varepsilon_{criterion} = 0.0001$).

$$\mathbf{U}_{node} = \mathbf{U}_{grid} - \mathbf{Z} \cdot \mathbf{I}_{line} \quad (22)$$

3.3 Electrical grid model in Modelica

The grid is implemented in Modelica making full use of the object-oriented modelling language for component-oriented modelling of complex systems. The implementation of the grid has been made very flexible by making use of the incidence matrix \mathbf{T} and the impedance matrix \mathbf{Z} . Only these two matrices have to be adapted when using another grid. This flexibility is thanks to the incidence matrix which contains the nodes that need to be connected for each line. Thus, the connection of the different nodes can be automated using this incidence matrix \mathbf{T} . Another advantage is the fact that the iteration for the calculation of the nodal and line currents and the nodal voltages is automatically carried out by Modelica, since Modelica is equation based.

The grid is set up as can be seen in the Modelica code presented in Code 1. This code builds the grid from different components and arrays of components. An array of nodes is used to facilitate the connection of different branches. These nodes are also useful to facilitate the connection of loads, electricity generation and households when the grid is used. An array of branches with impedances specified by the impedance matrix \mathbf{Z} is connected to the nodes in the for loop. This loop uses the incidence matrix \mathbf{T} to build up the network. Different grid layouts are being implemented as records containing the corresponding \mathbf{Z} and \mathbf{T} matrices. Components with a ground and a fixed complex voltage are used to complete the grid model.

To show how the usage of the node pins can greatly facilitate further use of the grid, the Modelica code in Code 2 is presented. As can be understood, the use of these nodes is not necessary, but it simplifies the implementation of larger grids. Nodes, household loads and PV systems are connected using a "pQtoVI" component (see further in this section), in which the grid side is connected to the "VI" pin, whereas households and PV systems are represented by a power flow. Households and PV systems are thus connected to the "PQ" pin.

The different components that are considered in the simulations in section 4 of this paper are further explained using a visual example of a simple grid with only two branches and households with PV systems, shown in Figure 3. This visual example uses the same components as the larger grid, with exception of the nodes, but is manually constructed. For larger grids, the Modelica code in Code 1 is used, supplemented with extra Modelica code, like the one in Code 2.

```
model Grid
  parameter ELECTA.Grids.MatVec grid;
  parameter Integer n=grid.n;
  parameter Integer T[n,n] = grid.T;
  parameter
    Modelica.SIunits.ComplexImpedance [n]
    Z = grid.Z;
  parameter SI.ComplexVoltage
    Vsource=230+0*j "Voltage";
  ELECTA.DisGrid.GridCom.CGround ground;
  ELECTA.DisGrid.GridCom.CVoltageSource
    source(Vsource=Vsource);
  ELECTA.DisGrid.GridCom.Branch branch[n]
    (R=Modelica.ComplexMath.real(Z),
     X=Modelica.ComplexMath.imag(Z));
  ELECTA.DisGrid.GridCom.CPosPin [n] node;

equation
  connect(ground.p, source.n);
  connect(branch[1].p, source.p);
  connect(branch[1].p, node[1]);
  for x in 1:n loop
    for y in 1:n loop
      if T[x,y]==1 then
        connect(branch[x].p, node[y]);
      elseif T[x,y]==-1 then
        connect(branch[x].n, node[y]);
      end if;
    end for;
  end for;
end Grid;
```

Code 1: Grid model

```
for y in 1:grid.n loop
  connect(pq[y].vi, grid.node[y]);
  connect(pq[y].pq, pv[y].pq);
  connect(pq[y].pq, h1[y].load_p);
end for
```

Code 2: Use of the grid model

A fixed source with a fixed complex voltage is used. The reference scenario is a voltage of 230 V. This means a DC power flow analysis will be performed. A DC power flow analysis is a static analysis which is a simplification of the transient AC power flow analysis. In an AC power flow analysis, a non-linear system describes the power flow through the lines (branches). In a DC power flow analysis a linear system is applicable. A DC power flow analysis is less accurate, but simulating all transients in an AC power flow analysis requires a much smaller simulation time step and thus a higher computation time. Furthermore, in a distribution grid (as given in

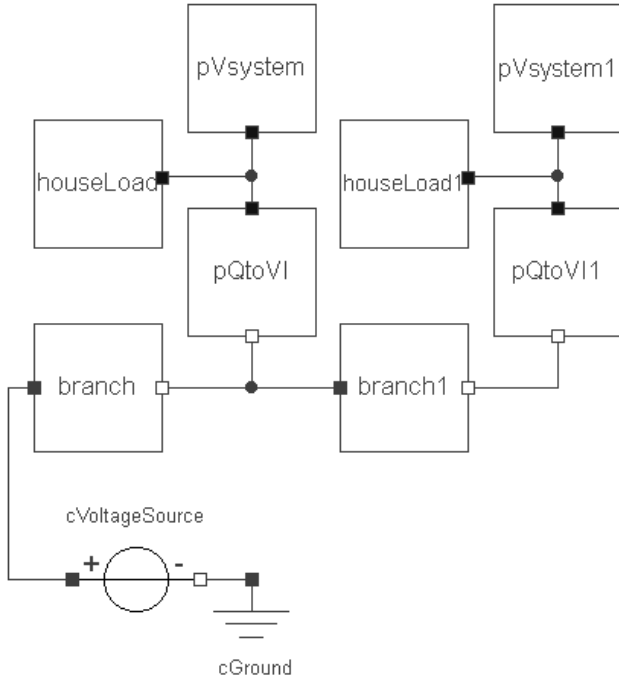


Figure 3: Visual example of a grid with two households with each a PV system

this paper) the resistance R of the lines is much higher than the reactance X , which justifies the use of a DC power flow analysis as a good approximation for an AC power flow analysis.

Each line between two nodes is represented by a branch which represents a line with a certain impedance Z (Eq. (16)).

The load profile of a household is represented in the component "houseLoad". The output of this component is an active power demand (see section 4.1) which will be fulfilled by the PV system and grid.

The PV system delivers an active power output which will be used to cover a part of the power demand of the household or will be put partly on the grid.

The difference between the power output of the PV system and the power demand of the household defines how much power is needed from the grid or will be injected in the grid. The component "pQtoVI" calculates with the fixed active power (to or from the household and PV system) the nodal voltage and nodal current (current to or from the household and PV system) at the node on the grid. Modelica takes care of the iteration to define the voltage and current.

3.4 Conclusion

The grid model is based on the incidence matrix T to connect the nodes in a radial grid. This flexibility

allows to model each radial grid topology by adjusting this incidence matrix. In this paper, the example of the IEEE 34 node test feeder is used. From the household power demand and the PV power production, it can be calculated how much extra power is needed from the grid or has to be put on the grid. With this, the nodal and line currents and nodal voltages can be calculated with Modelica. As such, it is possible to examine the influence on the voltage profile of the grid.

4 A residential electricity grid with variable density of PV integration

4.1 Load profiles of households

In this paper a distribution grid for a residential district is simulated. Each household has a specific load profile. Synthetic residential load profiles for households are provided by the Flemish Regulator for the Electricity and Gas market (VREG). A set of 16 different load profiles which cover each one day are available. These load profiles present the average load profiles of the Flemish population. These are corrected to obtain an average yearly electricity consumption in the order of 5,000 kWh. The dependency of the consumption upon outdoor temperature changes are given, but is however for simplicity not taken into account since the purpose of this paper is only to give an example of a grid application with a household and PV connection. Each profile gives the power demand on a 30-minute basis as shown in Figure 4.

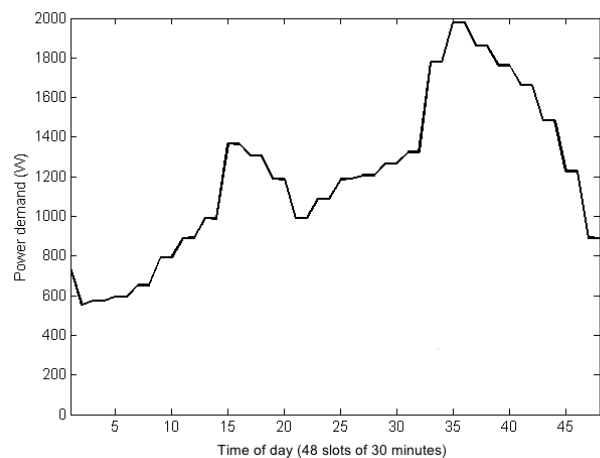


Figure 4: One of the 16 load profiles of an average Flemish household

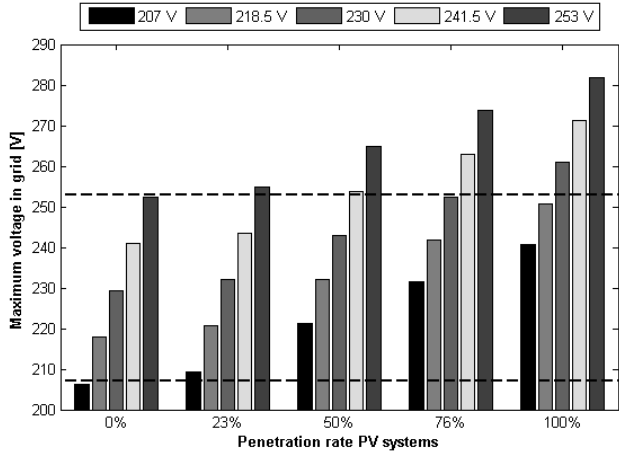


Figure 5: Maximum voltage in the grid at different PV system densities and fixed voltage at the transformer

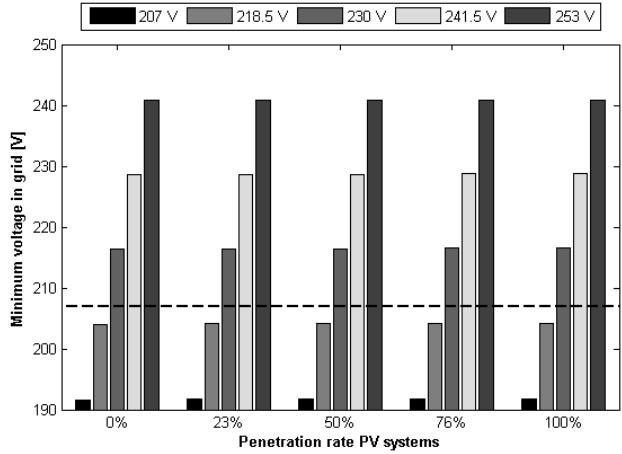


Figure 6: Minimum voltage in the grid at different PV system densities and fixed voltage at the transformer

4.2 Simulation parameters

It is supposed that at each node in the grid there is a household with a load profile. The 16 available load profiles are randomly assigned to each household.

A PV system can be installed for each household. The PV system consists of 30 panels resulting in a power of 6 kW_p . One goal of this paper is to evaluate the effect of the integration of PV systems on a distribution grid. The integration of PV systems¹ is evaluated for different penetration rates, namely a penetration of 0%, 17%, 23%, 32%, 50%, 67%, 76%, 82% and 100% of the nodes [7].

The reference scenario is a distribution grid with 0% PV systems. The source of the grid will be adapted to $230 \pm 5\% \text{ V}$ and $230 \pm 10\% \text{ V}$. A distribution system operator needs to keep the voltages at each node within certain voltage limits ($230 \pm 10\% \text{ V}$ for 95% of the time). To this end, the transformer tap will be changed to change the source voltage of the grid. E.g. when no PV systems are available, the voltage at the source has to be higher to compensate for lower voltages due to voltage drops in the feeders, caused by the power flow towards the household. When on the other hand PV systems produce power which is put back on the grid, these PV systems will lift the voltages by sending power back into the grid, thus the voltage at the transformer needs to be lower in this case (the transformer tap setting² has to be changed). This voltage lift will depend on the amount of power sent back to the grid.

¹All PV systems are oriented towards the south and have a 34° inclination angle of the panels.

²A transformer only has a discrete number of taps.

4.3 Results

In this paragraph some simulation results are shown. The idea is to clarify the problem that might occur when implementing a large amount of PV systems into a residential grid, since the voltages in the grid need to be kept between certain voltage limits ($230 \pm 10\% \text{ V}$).

Figure 5 shows the influence from leaving the transformer tap at a higher setting when PV systems are installed. It can be seen that overvoltages would occur at a PV system integration of 23% for a tap setting of $230 + 10\% \text{ V}$ and at an integration of 50% for a tap setting of $230 + 5\% \text{ V}$.

In contrast with this, Figure 6 shows undervoltage problems in the grid when the tap has been set on a low setting. It can be seen that the amount of PV integration has no effect on the minimum voltage in the grid. This can be explained by the consumption peaks that occur when there is no production from the PV panels, i.e. during a very cloudy period or during the evening. This shows that setting the transformer tap at a lower setting than 230 V is not a solution to the problem, since undervoltages will occur.

Generally tap settings will be made to anticipate only on load. This means that the voltage at the transformer will be kept higher than nominal to ensure it does not drop below 207 V anywhere. When there are only loads in the grid, the voltage at the transformer station will be the highest of the grid. The line at the bottom of Figure 7 shows this grid voltage profile without local generation (no PV systems). Figure 7 shows the voltage profile at the nodes indicated by the red line in Figure 8 at a time with high local electricity generation.

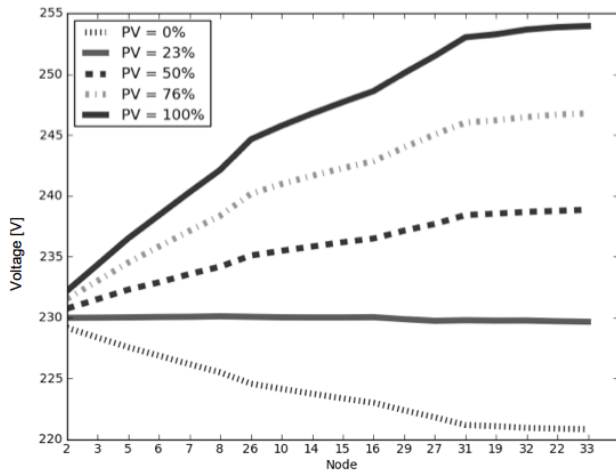


Figure 7: Voltage profile on a sunny day (at a time with high local electricity generation) in a 34 bus grid with different PV system penetration rates

The voltage profile in Figure 7 is visualized for different penetration rates for PV systems in the distribution grid. It is clear from the figure that when there is some PV penetration the voltage at the transformer is no longer the lowest in the grid. A closer look at the voltage profile for a PV density of 23% shows that the voltage profile is fluctuating around 230 V. This kind of profile is more difficult to control by adjusting the tap settings, because the voltage at different nodes needs to be known. For higher penetrations of PV systems, the grid voltage at the nodes at the end of the grid are much higher than the voltage at the transformer. At some nodes the slope of the voltage profile changes since some parts of the grid are not included in this figure, but still these nodes have their influence on the voltage profile for the rest of the grid.

5 Conclusions

This paper shows that object-oriented modelling in Modelica can be an attractive alternative for modelling electrical grids with power simulations.

A model for photovoltaic systems is described and implemented in Modelica, with an emphasis on the preservation of flexibility. Moreover, an electrical grid model is presented in Modelica. The grid model is structured around the incidence matrix \mathbf{T} and the impedance matrix \mathbf{Z} . This approach ensures optimal compatibility and flexibility with existing test feeder topologies.

Finally, an example case shows how these two

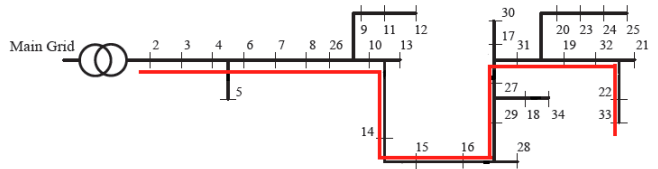


Figure 8: Grid topology IEEE 34 node test feeder indicating the nodes shown in the voltage profile of Figure 7 (red line)

models can be combined. A simulation of the IEEE 34 bus node test feeder with standard household load profiles and different degrees of PV density is shown and discussed regarding possible voltage problems in the grid. A high penetration of local generation by means of PV systems has a high influence on the grid voltage during sunny days. This is demonstrated for PV systems of 6 kW_p for different penetration rates. To prevent overvoltages, the transformer tap has to be adjusted to have a lower source voltage during these time periods.

Multidisciplinary research will be facilitated by further developing models that can be easily manipulated and interconnected.

6 Future work

In future work, Modelica *records* will be made for different network layouts. IEEE test grids will be implemented, but also an extension could be made to implement in home electricity grids. Modelica *records* for the parameters of different PV panels will also be implemented and the PV inverter will be modeled in more detail.

The grid model itself will be extended to include the possibility to simulate a 3 phase distribution grid and to include the distribution grid transformer.

In the future other types of distributed generation (e.g. small wind turbines) or storage (e.g. batteries to store a surplus of electricity from the PV panels to avoid too high grid voltages) may also be implemented, together with advanced control strategies for demand side management.

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References

- [1] R. De Coninck, R. Baetens, B. Verbruggen, J. Driesen, D. Saelens, and L. Helsen, "Modelling and simulation of a grid connected photovoltaic heat pump system with thermal energy storage using Modelica," in *8th International Conference on System Simulation in Buildings*, 2010, pp. 1-21.
- [2] W. Kersting, "Radial Distribution Test Feeders," in *IEEE Power Engineering Society Winter Meeting*, vol. 2, Columbus, Ohio, USA, 2001, pp. 908-912.
- [3] W. De Soto, S. Klein, and W. Beckman, "Improvement and Validation of a Model for Photovoltaic Array Performance," in *Solar Energy*, vol. 80, 2006, pp. 78-88.
- [4] D. Sera, R. Teodorescu, and P. Rodriguez, "PV panel model based on datasheet values," in *IEEE International Symposium on Industrial Electronics*, 2007, pp. 2392-2396.
- [5] Meteotest, 2008. METEONORM Version 6.1 - Edition 2009.
- [6] K. Clement-Nyns, E. Haesen, and J. Driesen, "The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid," in *IEEE Transactions on Power Systems*, vol. 25, 2010, pp. 371-380.
- [7] E. Haesen, J. Driesen, and R. Belmans, "A Long-Term Multi-objective Planning Tool for Distributed Energy Resources", in *IEEE PES Power Systems Conference & Exposition*, Atlanta, Georgia, USA, Oct.29-Nov.1, 2006, pp. 741-747.