LARGE SCHALE INTEGRATION OF PV SYSTEMS AND HEAT PUMPS IN A WORKMEN'S QUARTER

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ABSTRACT

Driven by the policy of the Dutch government a large project has started where in total 111.000 residential dwellings will be renovated and become energy neutral by installing heat pumps and PV-systems. The project will be executed by four Dutch construction companies in cooperation with six housing cooperatives.

This paper discusses a general design procedure to determine the impact of the heat pumps an PV-systems on the current LV-grid. This approach is applied on the LV-grid in the Soesterberg area. With the aid of load flow calculations the impact of heatpumps and PV-systems is determined on cable loading and voltage control. Solutions are discussed for the encountered bottlenecks in cable loading and voltage control

Keywords: Low voltage grid design, heat pumps, PV-systems.

INTRODUCTION

The last couple of years Europe had to deal with an economic crisis. The impact of this crisis is still noticeable in some of the European countries. In the Netherlands, amongst others, the building sector was struck and a significant amount of new housing projects were postponed. To boost the building sector and the building contractors the Dutch government has started a large project 'Stroomversnelling' where in total 111.000 residential dwellings will be renovated and become energy neutral by adding additional thermal isolation, electric cooking instead of gas cooking, installing heat pumps and PV-systems. The project will be executed by four Dutch construction companies in cooperation with six housing cooperatives.

In the project three stages are defined:

1. Prototyping phase (Sept 2013-Dec 2014), 1.000 dwellings
2. Industrialisation phase (Jan 2015-Dec 2016), 10.000 dwellings
3. Upscaling phase: (Jan 2017-Dec 2020), 100.000 dwellings

Approximately 30.000 of these dwellings are located in the service area of the Dutch DSO Stedin.

PROBLEM DEFINITION

Medio 2014 the first part of the project has started with the renovation of a complete neighbourhood of 109 residential dwellings dated from the mid 50ties. After the renovation process an outer shell is put against the existing walls and roof tops for extra thermal isolation as well as the installation of heat pumps and PV systems. The result of a prototype dwelling is shown in figure 1.

Figure 1: *Left picture: Dwellings before renovation, Right picture: Dwellings after renovation*

The integration of PV systems and heat pump has a huge impact on the local Low Voltage (LV) grid and MV/LV transformers. In total 600 kW of PV systems will be installed and 164 kW of extra load due to the installation of heat pumps. The complete renovation project will be completed in the first quarter of 2015. As a grid operator, Stedin must redesign and adapt the current LV grid and completed the adaptions by the end of the first quarter of 2015.

This paper addresses the technical challenges encountered during the LV-grid planning stage. Special attention will be paid to the developed grid planning approach with the aid of expected load profiles of the 'new' loads such as PV-systems and heat pumps and the impact they have on the LV grid.

LOW VOLTAGE-GRID DESIGN

General design procedure

The current Low Voltage (LV) grid design procedure is based on many years of experience. Major goal of LV-grid design is to comply with the loading capacity of the equipment and to provide the desired voltage to the customer. Furthermore the design has to meet the economic criteria such as capital costs, operating costs and costs due to losses [1].

For a LV-grid design which is in compliance with the technical and economic criteria it is essential to have a proper estimation of the expected load. Loads in LV-grids can be characterized by diversity and stochastic behaviour. It is difficult to incorporate this behaviour in the design of LV-grids and therefore several methods are developed to cope with the complex behaviour of LV-loads. A well-known method is the method of Rusck which calculates the effective demand of group of similar customers. Details of this method can be found in [2]. The main idea is that the peak load of n loads is smaller than the sum of the n individual peak loads. This is shown in equation (1).

$$P_{max} < \sum_{i=1}^{n} P_{max}(i) \quad (1)$$

In this approach it is possible to define a coincidence factor, g_n, which calculates the simultaneously effective load of a feeder as described by equation (2).

$$g_n = \frac{P_{max,n}}{\sum_{i=1}^{n} P_{max}(i)} \quad (2)$$

Based on extensive measurements and experience the peak value of a load of a single dwelling and the coincidence factor can be estimated and the simultaneously effective load can be determined. The relation between the individual load and the effective peak load is given in equation (3).

$$P_{max,n} = n \cdot P_{max,1} \cdot g_n \quad (3)$$

Within Stedin this method is used for LV-grid design. For various types of dwellings the maximum simultaneously peak load is defined and the total number of dwellings which can be connected to a standardized LV-cable type is determined. In table 1 an overview of the simultaneously peak load per type of dwelling is given as well as the total number of dwellings connected per LV-cable type.

Table 1: *Peak load per type of dwelling incl el. cooking*

	Simultaneous Peak load [kVA]	LV-cable type 4x150 mm^2
Apartment	1,5	85
Terraced	1,8	70
Semi detached	2,0	--[1]
Detached	2,2	--[1]

The peak load is estimated for the situation where the largest load is expected. Normally this is mid-December (around the shortest day). When for this case the LV-grid is able to serve the load the grid is able to serve the load at all other moments during a year. Furthermore, a pre-load factor of 80% is used. This allows load growth for the long term service period (30 years) of the LV-grid.

[1] For detached and semi detached dwellings the number of dwellings/cable will be determined by voltage drop rather than cable ampacity

Load profiles

As discussed in the previous section traditional distribution grid design is based on expected peak value, fit and forget fashion and uni-directional power flow. The future grid will face new and different challenges driven by decentralized renewable power generation and new high power demands, with bi-directional power flows and complicated loading patterns. These new high power demand loads have a significant impact on the peak load as well as the moment the peak load might occur. This means that the current design approach has to be modified and extended in order to incorporate the new type of loads and renewable generators.

The new design method is based on the incorporation of the time aspect of the load and generation profiles. These profiles are constructed for:

- Household loading
- PV-systems
- Heat pumps
- Electric vehicles

In figure 2 is shown how these patterns will be applied to construct the nett loading pattern for LV-grid design.

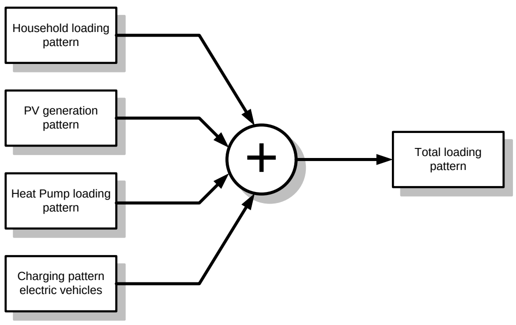

Figure 2: *Generic application of loading patterns*

Depending on the future development in a considered area the specific loading pattern can selected and combined to a total loading profile. In this paper this method will be applied for the evaluation of the LV-grid in the Soesterberg area. In this area it is not likely that there will be an early adoption of electric vehicles hence the charging patterns of electric vehicles are omitted in the analysis and in this paper.

Household loading pattern

As discussed in previous sections in the current design procedure the household load is represented by a simultaneously effective peak load for a maximum loading period. This is not sufficient to study the impact of PV-systems on LV-grids. Therefore the method of the simultaneously effective peak load is extended with a relative loading profile of a group of dwellings. The relative loading pattern is scaled with the simultaneously effective peak load to obtain the loading per dwelling for time *t* according equation (4).

$$P(t) = P_{max,n} \cdot f(t) \qquad (4)$$

Where P(t) is the consumed power/dwelling at time *t*, $P_{max,n}$ the simultaneously effective peak and f(t) the relative loading profile for households. In figure 3 the relative loading profile for households for two weeks is shown.

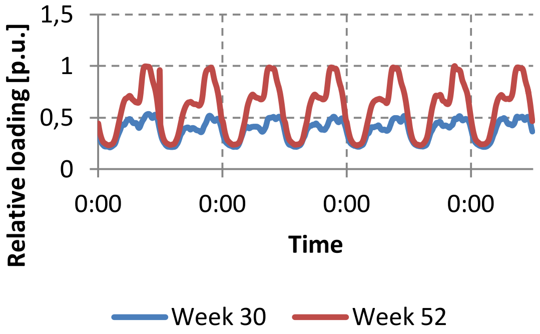

Figure 3: *Household loading patterns for week 30 and 52*

The household loading profiles are selected from 52 weekly load profiles where the maximum (week 52) and minimum (week 30) loading profile is chosen. The maximum loading profile is used to study the impact of heat pumps while the minimum load profile is used to study the impact of PV-systems.

PV-Systems

The generated power of PV-systems can be well described with the aid of metrological data, the orientation of the PV-systems, position of the sun and the capacity of the PV-systems. Based on a solar radiation of June the generation profiles for the north, south, east and west direction are calculated. These profiles are depicted in figure 4.

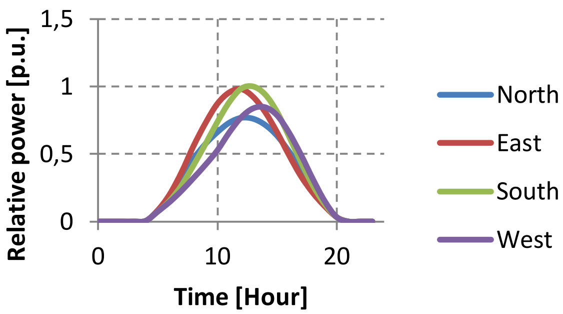

Figure 4: *PV generation profiles for different panel orientations*

These profiles can be applied in the same way as the household load profiles. Via equation (4) the generated power at time *t* can be calculated where P_{max} the maximum output and f(t) the generation profile of the PV-system is. The difference between the north-south as well as the east-west orientation can be clearly seen.

Heat Pumps

Another new type of load is the heat pump. The heat pump is used for heating purposes and uses a primary heat source with a relative low temperature. This can be the outside temperature or the temperature of a ground water source. Furthermore the heat pump uses, amongst others, a compressor to generate the heat used for space heating.

The LV-grid need to have sufficient capacity to feed the normal household load including the load of the heat pump. Therefore an estimation has to be made what load is to be expected of the heat pump. In figure 5 measurements on a heat pump are shown including the outside temperature. The compressor has a size of 2,5 kW_e. It can be concluded that for the majority of time the heat pump is switched on. Because of this large switch on times for LV-grid planning purposes the heat pump can be modelled as a constant load.

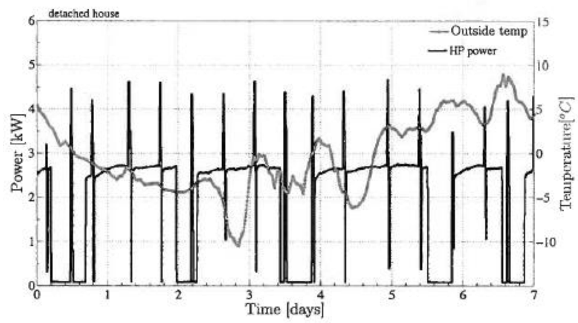

Figure 5: *Measurements of a 2,5 kW_e heat pump*

The heat pump is also equipped with an electric heating element which will be used in case the generated heat of the heat pump is insufficient. In this study the extra heating element is not taken into account. Reason for that is that the dwellings in the Soesterberg area will be equipped with very good thermal insulation. In [3] it is stated that dwellings with good thermal insulation has a time constant of 7 hours to change the room temperature by 1 °C and therefore in normal situations the use of the extra heating element is not likely. The short period of use of the heating element will also level out in the total load in the neighbourhood.

LV-GRID IN THE WORKMEN'S QUARTER

The approach as discussed in the previous chapter will be applied to study the impact of the integration of heat pumps and PV-systems in the existing grid of the workmen's quarter in Soesterberg. In figure 6 a schematic overview of the studied MV- and LV-grid is given. The original LV-grid, dated from the mid 50ties, has been designed as a meshed grid structure. For the upcoming project the original LV-grid will be converted to Stedin's current design policy which is a radial grid structure. In figure 6 the MV-grid is indicated in red while the LV-grid is drawn in blue. Furthermore the proposed grid openings are indicated.

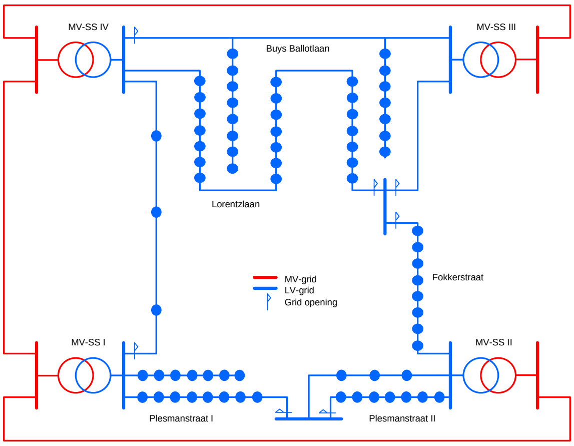

Figure 6: *Overview of the distribution grid in the workmen's quarter*

In figure 6 the circles indicate the dwellings connected to the distinct feeders. These circles are a schematic indication and do not correspond with the actual connected number of dwellings. Details of the connected number of dwellings as well as the household loads including PV-systems and heat pumps are given in table 2.

Table 2: *Details per feeder of the considered LV-grid*

Street	No. houses	PV-systems	Heat pumps	Household load
Plesmanstraat I	25	135 kW	38 kW	45 kVA
Plesmanstraat II	31	167 kW	47 kW	56 kVA
Lorentzlaan	51	81 kW	23 kW	92 kVA
Fokkerstraat	17	92 kW	26 kW	31 kVA
B. Ballotlaan	21	113 kW	27 kW	32 kVA

Figures given in table 2 are based on peak values. The heat pump which will be installed has a capacity of 1,5 kW_e while the installed PV-systems are rated at 5,5 kW_p. The household loads are modelled at 1,8 kVA which is the average simultaneous load per dwelling. For the PV-systems and household loads the load profiles discussed in the previous chapter are applied. Therefore in summer- and winter time the peak household load differ with approximately 40% ($P_{summer} = 0{,}6 \cdot P_{winter}$). The figures given in table 2 are the peak values during winter.

LOAD FLOW CALCULATIONS

According the approach discussed in chapter 2 the LV-grid of the workmen's quarter is evaluated. In simulation software a model of the LV-grid including load profiles has been setup. Because of the significant amount of PV-systems and heat pumps two cases are considered:

1. Summer case (June)
2. Winter case (December)

The focus in the load flow calculations is primarily on cable loading and voltage profiles.

Cable loading

The current LV-grid is mainly equipped with 1x4x50 mm^2 CU PILC cable with a current rating of 125 A (87 kVA). The result of the load flow calculations on the cable loading for the winter and summer case is depicted in figure 7. In this figure the result of the two dominant feeders in the LV-grid are shown (Plesmanstraat II and Lorentzlaan).

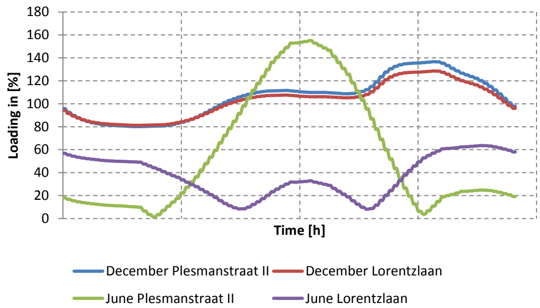

Figure 7: *Cable loading for the winter and summer case*

For the winter case the majority of time the cables are loaded above the maximum cable rating while for the summer case the Plesmanstraat II feeder only is loaded above the cable rating. This is because not all dwellings connected to the Lorentzlaan feeder are part of the project hence some extra load is present which limits the cable loading due to PV-activity.

To solve the overloading of the LV-cables these cables need to be replaced by the new standard VVMVksas 1x4x150 mm^2 Al cable. The total LV-grid consists of approximately 2.420 m LV-cable and in total about 1.000m have to be replaced to avoid overloading in the summer and winter case.

Voltage profiles and voltage control

Besides cable loading aspects of voltage level and voltage profiles are of importance. Because of the radial operation of the LV-grid it is to be expected that the largest voltage variation will occur at the end of the feeder. Therefore for both scenario's the feeder end voltage of the Lorentzlaan and the Plesmanstraat II feeder is monitored. The results are depicted in figure 8.

In figure 8 it can be seen that the PV-systems have a huge impact on the feeder end voltage. Especially for the Plesmanstraat II the allowable +10% voltage rise will be exceeded. The Lorentzlaan feeder shows a voltage rise as well but due to the extra available load this voltage rise is limited and does not exceed the +10% limit. For the winter case both feeders show a voltage drop however, this voltage drop is smaller than the allowable -10%.

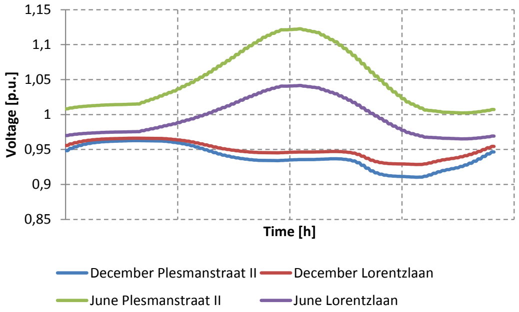

Figure 8: *Daily voltage profiles at the feeder end for the summer and winter case*

Controllable distribution transformer

Traditionally MV- and LV-grids are designed to cater for an expected load (incl. load growth) under restriction of the allowable voltage variation. Normally, the voltage variation consists of a voltage drop only. Distribution transformers are equipped with Off Load Tap Changers to mitigate the voltage drop in a maximum load situation. The action of the tap changer also limits the integration of distributed generation in LV-grids as shown in figure 9.

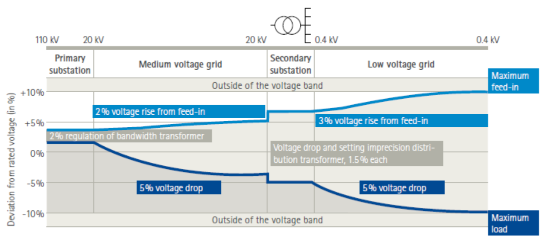

Figure 9:*Overview of classic voltage regulation*

This drawback can be overcome by equipping the distribution transformer with an On Load Tap Changer (OLTC). As shown in figure 10 the voltage rise and drop in the MV-grid is corrected by the OLTC. The reference voltage of the LV-grid is chosen such that a wider voltage variation, due to PV-infeed or extra load, can be allowed without violating the upper and lower voltage band.

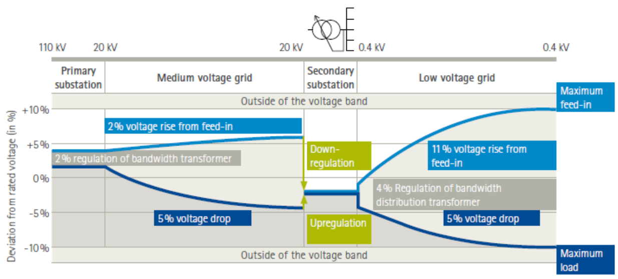

Figure 10: *Voltage regulation incl. OLTC distribution transformer*

The application of a distribution transformer including an OLTC is investigated to limit the voltage variation of the Plesmanstraat II feeder. The distribution transformer is equipped with a tap changer with seven positions of 1,5%. The voltage controller needs a reference voltage which is measured at approximately the middle of the Plesmanstraat II feeder. This can be considered as a new way of line drop compensation. The dead band of the voltage controller is set to ± 1%.

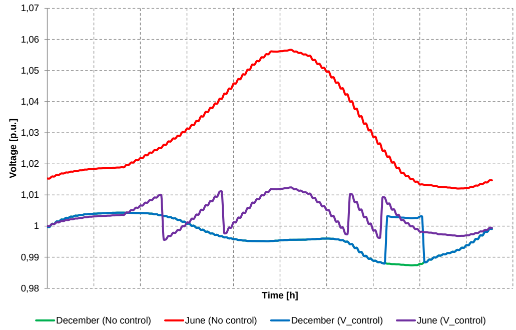

Figure 11: *Feeder end variation with and without voltage control*

In figure 11 the results of the feeder end voltage variation. Due to the cable replacement the voltage rise is reduced to +5% already. The voltage controller controls the voltage within the voltage band of ± 1%. In the winter case the voltage drop is caused by the extra load of the heat pumps. The accompanied voltage drop is also corrected to a value of ± 1%.

CONCLUSIONS AND DISCUSSION

In this paper large scale integration of PV-systems and heat pumps in an existing LV-grid in a workmen's quarter is discussed. For the evaluation of the impact of these systems on the LV-grid a general design procedure has been defined. Applying this design procedure shows there is a seasonal behaviour in the LV-grid resulting in loading- and voltage problems during summer time and loading problems in winter time. Traditionally in LV-grid design the maximum loading situation is studied only which let the voltage problems in during summer time unnoticed. Integration of heat pumps and PV-systems lead to overloaded cables to such a degree that cable replacement is the only option. This cable replacement is also beneficial in reducing the over-voltages. The application of a controllable distribution transformer is a promising option in further improvement of the limitation of voltage variation in the LV-grid.

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