Delft University of Technology

Modeling of PV Penetration in Residential Neighborhoods on Aruba

TU Delft

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1 Abstract

Aruba is a small island in the Caribbean. It has 101,484 inhabitants and its main income is tourism. As an island it is dependent on fossil fuel to generate its electric energy. As a result of the increasing oil price, it is attractive to be an island that generates its own electric energy through sustainable generators. This is the reason that the Aruban government made an ambitious plan to make the Aruba a self-sustainable island by 2020. To accomplish this plan, one of the goals that need to be accomplished is, to know what the current status is on integration of Photovoltaic (PV) systems is, and what is needed for in the future for integration more PV systems. To summarized; the main goal of this thesis is to know how many PV systems can be integrated in the current grid without modification and what modification is needed to integrate more PV systems into the grid.

Contents

2 Introduction

Aruba is a small island in the Caribbean. A land area of 179 square kilometers is densely populated, with a total of 101,484 inhabitants at the 2010 Census. Aruba has a dry climate and an arid, cactus-strewn landscape.

The island's economy has been dominated by five main industries: tourism, gold mining, phosphate mining, aloe export, and petroleum refining. Before 1986 oil processing was the dominant industry in Aruba despite expansion of the tourism sector. The size of the agriculture and manufacturing sectors also remains minimal. Nowadays about three quarters of the Aruban gross national product is earned through tourism or related activities. Today, the petroleum refining is closed. This means Aruba needs to find new ways to keep the economic growth [1].

In recent years, sustainability efforts within the travel industry have progressed from a niche consideration to an industry-wide priority. Following efforts to reduce dependency on fossil fuels and CO_2 emissions, Aruba built the Vader Piet Windmill Farm in the winter of 2009. Located on the island's northern coast are ten, 180-meter high wind turbines that currently produce 20 per cent of Aruba's electricity [2].

The island's constant supply of sun, eastern trade winds and ocean currents allow for research and field-testing of renewable energy technologies [3]. In June 2012, prime minister Mike Eman and entrepreneur Richard Branson announced a partnership between Aruba and the Carbon War Room, an initiative that seeks to reduce global carbon emission. The partnership will transition the island to 100 percent renewable energy while eliminating any reliance on fossil fuels and will create a model for other countries to replicate.

This thesis will focus on a small part of the big plan to make Aruba run 100 percent on renewable energy. It will focus on the integration of PV in the electric grid. What the status of the current grid is, and what to do with the grid for the future integration of more PV.

2.1 Project

In this section the motivation for the project is explained. The vision and the problem that comes with the vision is explained. Finally the outline of the thesis is written.

2.1.1 Vision

All major stakeholders involved in the energy market of Aruba have formulated an ambitious agenda in which at least 50% of all energy consumed in 2020 should be generated by renewable energy sources [2], based on its Aruba's favorable climate conditions [3]. ELMAR N.V.(grid operator), which is one of the stakeholders and the only electrical power distribution company on the island, has recently presented its policy on distributed generation (DG) , focused on the integration of PV technology. KEMA has conducted initial studies indicating that the electrical network of Aruba in its current form should be able to accommodate 5 MW of PV power without any modifications to the power grid. In fact, ELMAR N.V. is currently developing a solar PV park of approximately 3,3 MW installed capacity. However, ELMAR N.V. wants to push this boundary as far as possible by not only focusing on utility scale PV installations but also by stimulating the residential sector.

2.1.2 Problem definition and research questions

Even though ELMAR N.V. is encouraging its residential customers to embrace the PV technology it is evident that, if no modifications are made to the grid locally, then there will be a certain PV penetration point where the power balance has changed too much in order to guarantee the required minimum quality of grid operator [4]. Therefore, the main questions are:

- What is the current PV penetration level on a residential scale.
- How can ELMAR N.V. move beyond that point by locally adapting the electrical network.

2.1.3 Outline

First a literature study will be presented. As a result of this study the important work will be illustrated that have been done. The limiting factors for the integration of PV systems will be stated. Secondly the parameters of these limiting factors will be shown. Thirdly the methods to retrieve these parameters from the grid of Aruba will be discussed. From these methods the best one will be chosen to be implemented. This will be discussed in the next chapter. After calculating the values of the parameters the research questions will be answered. In this thesis the focus will only be on power flow analysis and not on transient analysis. Finally the conclusions and recommendations will be given.

2.2 Main contribution

Researching the literature it is striking to conclude that there are not many studies done for islands like Aruba compared to big countries. When integrating new technologies from a big country, there is always the question if it can be integrated on an island. And if the technology that is studied in the big country can be treated the same way on an island. This thesis will make a link from the studies done in big countries and on Aruba. This link can also be used on other islands like Aruba.

One of the main objectives of this thesis is to know what the PV penetration can be without modification on a residential scale. In other words what steps need to be taken to get the answer of the main objective. A method for an island to know what their capabilities are on PV penetration on a residential scale. When looking into the literature it can be observed that there are residents that are studied after the integration of PV systems. There are also some ways to measure the impedance of the network in a resident area. The combination of both studies have not been thoroughly studied yet. In this paper the combination of both measuring methods and the translation knowing how many PV systems can be installed in the grid will be done.

For this thesis the privilege was given to do measurements that are not possible in most countries. Most energy distribution companies won't allow the grid to partly be taken off-line. The objective was to shut down some residents to do measurements. This way more reliable measurements could be done.

3 Literature research

In this chapter the main topics of interest, when integrating PV in the grid, are discussed. These following topics can be the limiting factors when integrating PV system into your grid. The topics are:

- Harmonic current injection from PV.
- Voltage rise effects

These topics could both effect the standards issued by the grid operator. Before these topics are discussed the standards of the grid operator will be discussed. After the standards are discussed the reason why the harmonic could limit the standard is mentioned. Finally the main limiting factor is discussed which is the voltage rise effect.

3.1 Standard on Aruba

Everyone who is connected to the grid of Aruba needs to comply to certain standards. But the grid also needs to comply to the standard made by the grid operator itself. These standards can be read in the "Aansluitvoorwaarden" [4]. Of all the rules and standards that are written in this document the most important ones for this thesis are the boundaries to which the voltage, frequency and power factor are defined. This is summarized in table 1.

Voltage	$127V$ from line to neutral and $220V$ from line to line
Frequency	$60Hz$
Power factor	0.9 for houses hotels business
Voltage fluctuation	$+/-4$ %

Table 1: Standards of grid operator

3.2 Harmonics

Modern electronic devices like power adapters, chargers, motors or inverters [5] create harmonics. This will cause distorted voltage and current waves. The harmonic currents generated by the inverter of the PV systems may lower the power factor of the power grid and affect the reliability and safety of the electrical equipments [6]. The relation between power factor and harmonics is given in formula 1[7]. The total harmonic distortion (THD) is also introduced in formula 1 and worked out in appendix A. The higher the harmonics the lower the power factor. This will affect the standard set by the grid operator.

$$PF \cong \frac{P_{avg1}}{V_{1rms}I_{1rms}} \frac{1}{\sqrt{1+THD^2}} \tag{1}$$

Here :

- P_{avg1} is the average power of the fundamental wave
- V_{1rms} is the rms value of fundamental voltage
- I_{1rms} is the rms value of fundamental current

A single inverter makes harmonics but it still complies with the IEC 61000-3-2 [8]. But it is possible that the inverters interact with each other in a grid with multiple inverters. All the capacitors and inductances in the grid interact and have a frequency response. This is called the resonance phenomenon. This resonance phenomenon has a resonance frequency. If one of the harmonics generated by the PV inverter corresponds with the resonance frequency, very high resonance voltages, damped only by the associated network and load resistances, will occur on the network voltage.
There is a residence in Holland where an investigation is done on resonance phenomenon. Despite the possibility of the occurring of the resonance phenomenon, the distortion level is still below the standard set by EN 50 160 that is used in Holland.[9]. Despite the resonance frequency there are methods that can suppress the injected harmonics effectively[5]. This is active filtering. In figure 1 a block diagram is shown of such a filter.

Harmonics won't be the limiting factor for the integrating of PV systems. As mentioned the problem of harmonics did not occur in a residence in Holland and if it did occur it could be removed by active filtering [10]. From here on no attention will be paid on harmonics and the voltage rise effect will be the limiting factor.

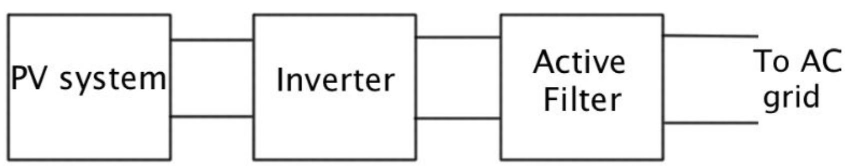


Figure 1: Example of Harmonic

3.3 Voltage rise effects

Voltage rise produced by solar PV resources in a distribution feeder is a result of offsetting the loads in the feeder by PV generation. Without PV or when the PV system is switched off, the voltage would drop along the feeder as shown in figure 2 line (A). This is because the transmission line has an impedance. And with the ohm's law (see equation 2) the voltage drop (V_{drop}) can be calculated between two houses. In reality the voltage drop over the transmission line won't be a straight line but a curved line. This will be explained in the chapter 5.4.

But for now let's assume it is a straight line.

$$V_{drop} = V_n - V_{n-1} = Z_n * \sum_{n}^{k} I_n \tag{2}$$

With PV, if all loads are perfectly balanced by PV generations at each Point of Common Coupling (PCC), then ideally no active power would flow through the feeder and the voltage profile would be nearly as in figure 2 line (B). However, if the PV generation exceeds feeder loads, especially at furthest end of the feeder, then power flows back from feeder to the upstream network and this causes the voltage to rise, as shown in figure 2 (C). In this scenario, voltage rise occurs due to the surplus power at the PCC of each PV connection.

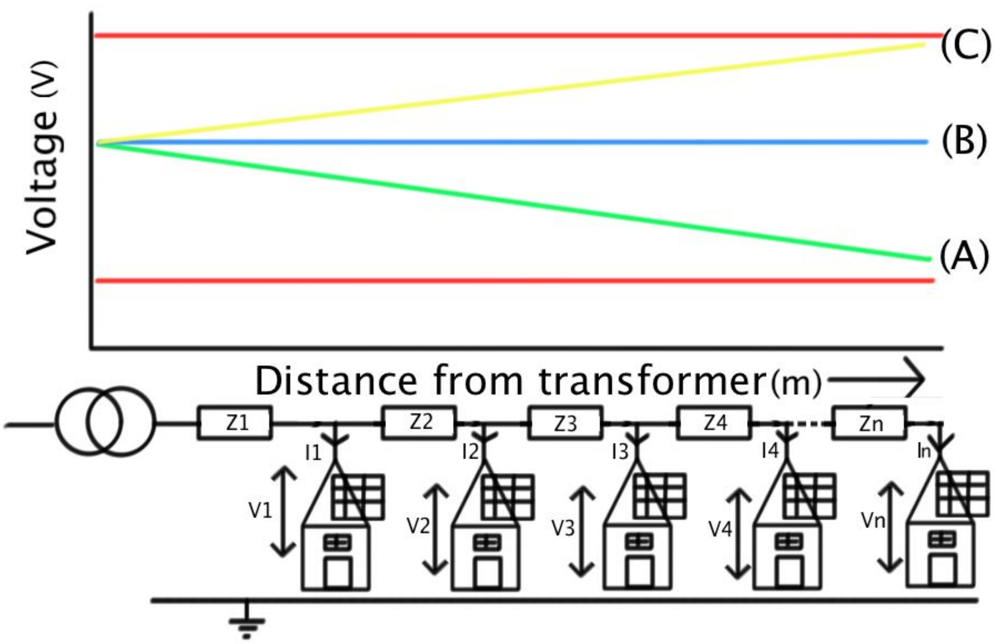


Figure 2: Voltage over length feeder

An extensive theoretical study [11] has shown that in German urban areas the increase of voltage due to reverse power flow is the limiting factor for penetration of PV on the LV grid. This is also the case of the following studies [12][9][13][14][15].

The maximum connectivity should ensure that the standards imposed by ELMAR are not violated. And from the previous paragraph we can conclude that the limiting factor is that the voltage may not rise above 132.08 and not below 121.92. See figure 3

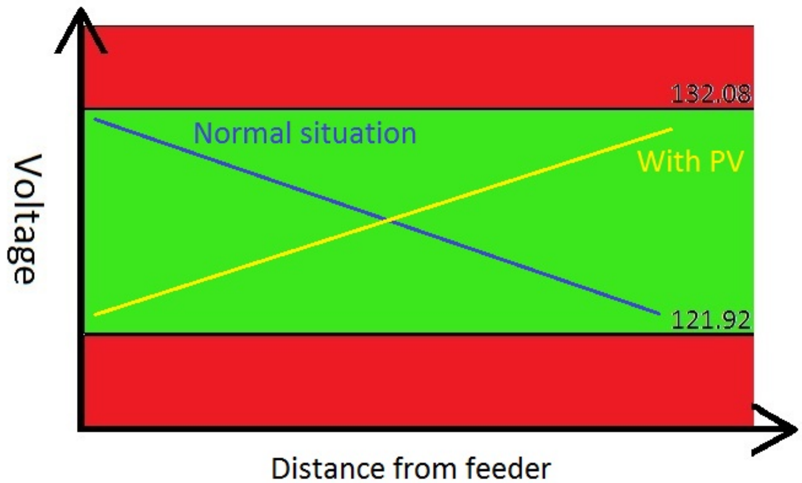


Figure 3: Acceptable voltage area

4 Approach

Knowing that voltage rise is the limiting factor when integrating Pv systems in the grid, it is good to know what the parameters are that cause this voltage rise. In this chapter the parameters that cause the voltage rise will be discussed. Also three ways to find the parameters is discussed.

4.1 The parameters

From the previous chapter it was concluded that voltage rise is the limiting factor. The voltage at the customer needs to be at a certain level and for that reason the PCC is chosen at the residents. This is the point were the house of the residence is connected with the transmission line. The voltage at the PCC needs to be between 132.08 and 121.92 volt. From the PCC to source of the voltage a whole grid is connected. The grid has a lot of resistances, capacitors and inductors. This all needs to be simplified as one. This would make the calculations much easier and better to work with. A Norton-Thévenin transformation would be the best solution for this. Because the voltage rise is the limiting factor the Thévenin transformation is chosen. See figure 4

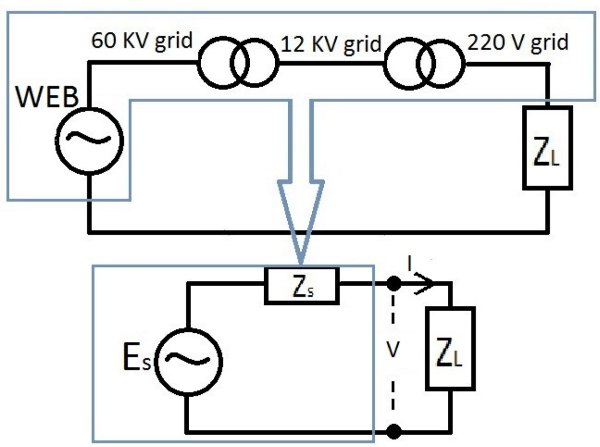


Figure 4: Thévenin circuit

There is only one location on Aruba which generates energy. This company is WEB. It makes electric energy by burning crude oil. From WEB there is a $60kV$ cable going to 7 substation around the island. And from those substations there is a $12kV$ line or cable going to the residential areas. And from the $12kV$ line through a transformer a $220V$ line goes to the residential area (see figure 9). The Z_s are the impedances from all the transformers and lines looking from the secondary side of the $12kV/0.22V$ transformer. Z_L in figure 4 is the impedances of the houses and the line.

4.2 Methods to measure Z_s

There are different ways to calculate the Z_s from figure 4. This all depends on the measuring possibilities that are available. Some cases the voltage may be to high and it is too dangerous to measure. Also it may be that to measure the impedance Z_s, a part of the grid needs to go off-line which is not acceptable for most grid operators. Here are three ways to measure Z_s:

- Multi-point method
- On load tap changer action
- Off-online method

4.2.1 Multi-point method

To calculate the Z_s we can use the multi-point method [16]. The method uses the Gauss-Newton algorithm. For a better understanding of the algorithm, we assume that the system side E_s and Z_s, shown in figure 4, are constant and the load side has some variations; therefore, applying KVL, the system equations for a set of measurement data at time 1, are as seen in equation 3. Time 1 is the time when the measuring starts.

$$E_s \angle \delta_1 = (Z_s \times I_1 \angle 0 + V_1 \angle \varphi_1) \tag{3}$$

Here :

- E_s is the source voltage. This is line to neutral voltage.
- δ is the angle between the source voltage and current.
- Z_s is the line impedance as mentioned in 4.1
- I_1 is the line current of time instance 1(and I_2 is the current of time instance 2 etc)
- V_1 is the line to neutral voltage of time instance 1(and V_2 is the current of time instance 2 etc)
- φ_1 is the angel between the voltage and current of time instance 1

Equation 3 has seven variables. Three variables are known (V, I and φ), and four variables are unknown (E_s, α and Z_s). The proposed method is to use the second set of measurements at time 2 as follows:

$$E_s \angle \delta_2 = (Z_s \times I_2 \angle 0 + V_2 \angle \varphi_2) \tag{4}$$

Time 2 is a few seconds to a few minutes apart from time 1. What important is that the $I, V, \angle\varphi$ are different for the two time instances. But still close enough that the assumption that E_s and Z_s are the same for the 2 time instances. If we synchronize the instant of measurements in order to have $\delta_1 = \delta_2$, and subtract 3 from 4, we will have:

$$Z_s \times I_2\angle 0 - I_1\angle 0 = V_1\angle\varphi_1 - V_2\angle\varphi_2 \quad (5)$$

Then we can calculate and from 6

$$Z_s = -\frac{V_1\angle\varphi_1 - V_2\angle\varphi_2}{I_1\angle 0 - I_2\angle 0} = -\frac{\Delta V}{\Delta I} \quad (6)$$

Using the calculated impedance and 3 or 4, we can get the solution for Z_s. The above method seems to be straight-forward. However, there is one piece of critical information missing, which renders the method unworkable. Equation 6 is based on the assumption that the two sets of phases are referred to the same reference time. Such a requirement, i.e., taking two consecutive waveform data that guarantees , cannot be met in reality. The main reason is that the power system frequency changes all the time. Therefore it becomes impossible to synchronize two consecutive shots by properly placing the sampling windows. In order to overcome this issue, the third set of measurements is added to the impedance estimation equations 3. Assuming that Es and Zs are constant during the measurements, for the third set of V, I, and φ , at time $t3$, we will have the same equation as 3 and 4.

$$E_s\angle\delta_1 = (Z_s \times I_1\angle 0 + V_1\angle\varphi_1)$$
$$E_s\angle\delta_2 = (Z_s \times I_2\angle 0 + V_2\angle\varphi_2)$$
$$E_s\angle\delta_3 = (Z_s \times I_3\angle 0 + V_3\angle\varphi_3 \quad (7)$$

Separating the real and imaginary parts of 7, we will have six equations and six unknowns which can easily be solved. Equations 7 has been solved in [17] using the iterative Newton-Raphson method.

4.2.2 On load tap changer action

This method uses the tap changing on a transformer to estimate the impedance [16]. Consider figure 5. A tap change is when a transformer changes its winding ratio. This is done in steps determined by the transformer designer.

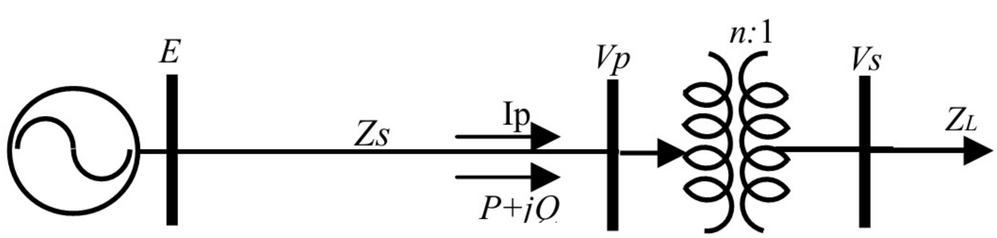


Figure 5: Tap change

The tap ratio is shown by n. Assume that there is a sudden change in load voltage. This can be due to higher energy demand or a disturbance. The on-load tap change(OLTC) transformer will try to restore the voltage by changing the tap ratio. This tap ratio change changes the load impedance seen from the OLTC primary side. So:

$$E = V_p + Z_s I_p \tag{8}$$

Taking the measurement before and after the tap changing action and using formula 9:

$$E_2 - E_1 = V_{p2} - V_{p1} + Z_s(I_{p2} - I_{p1})$$
$$\frac{\Delta E - \Delta V_p}{\Delta I_p} = Z_s \tag{9}$$

If is assumed that there are no changes in the source voltage than the ΔE goes to =0. Formula 9 changes into:

$$Z_s = -\frac{\Delta V_p}{\Delta I_p} \tag{10}$$

This method can not be used on Aruba. This because on Aruba, on a residential scale there is not an on-load tap-changing option. This is only possible on the $12kV$ line (see figure 4). The grid operator doesn't have a mobile measuring device to measure the $12kV$ line on a safe way. On a residential scale there are only transformers which taps switches need to be manually changed while the transformer is off-line.

4.2.3 Off-online method

This method also uses the Thévenin circuit from the previous paragraph (see figure 4). It can simply be shown that:

$$E_s = V + IZ_s \tag{11}$$

The extra information that is available is that the grid can partly be disconnected from the grid. The grid looking from the point where de grid has been disconnected will look like figure 6. For the calculation of Z_s all the houses of the measured residence is disconnected.

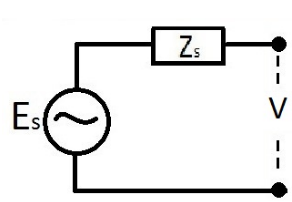


Figure 6: Equivalent circuit without load

Because there is no load Z_L from figure 4 the current is zero $I = 0$. And using formula 11 it may be assumed that $E_s \cong V$. This way it is known what E_s is. Taking measurements at two different time instants with few minutes apart it may be assumed that E_s is constant during the measurement moment. One time instant needs to be when the load is connected and one time instant needs to be when the load is disconnected. Now rewriting equation 11 the calculation of Z_s is pretty simple (see equation 12).

$$Z_s = \frac{E_s - V_m}{I_m} \tag{12}$$

This method is the most simple and accurate method. For that reason it is used to measure the Z_s on Aruba.

4.3 Evaluated methods for measuring Z_L

In this section two methods are described how to get the Z_L from figure 4. First the method is described where calculations are used to calculate the impedance of the line. Second the method is described how Z_L in gotten from measurements.

4.3.1 Calculating Z_L

In figure 7 an equivalent circuit of the neighborhood is drawn. Here the impedance of the transmission line(Z_L) of the neighborhood is divided into different sectors. These sectors depend on how many houses a neighborhood may have.

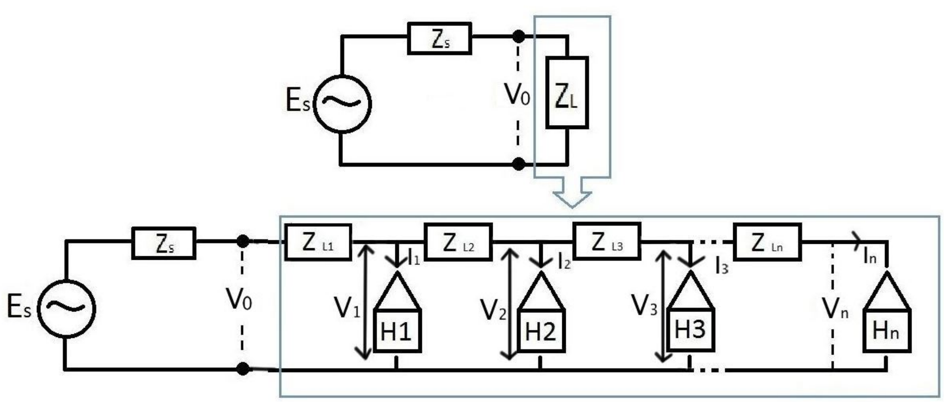


Figure 7: Model of neighborhood

To calculate the impedance of the whole transmission line the resistance, inductance and capacitance of the line needs to be calculated. By knowing how the resistance, inductance and capacitance is connected with each other the impedance of the whole line can be calculated. First the formulas for the individual components are given. The formulas for the resistance [18] is:

$$R = \rho \tfrac{l}{A}$$
$$\rho(T) = \rho_0[1 + \alpha(T - T_0)] \tag{13}$$

Here:

- ρ is the electrical resistivity
- A is surface of the wire
- l is the length of the wire
- T_0 is the temperature at room temperature
- T is temperature
- α is temperature coefficient of resistivity

The inductance of the wire [18] is:

$$L = 2l[2.303 \log(4l/d - l + \mu/4 + (d/2l))] \tag{14}$$

Here:

- l is length of cable
- d is the diameter of the wire
- μ is the permeability of the material

The capacitance of a wire is a little bit more difficult to calculate. This is because the environment around the wire has a big impact on the wire. But assuming that the ground is the only effect, then the formula looks like [18]:

$$C = \frac{\pi \varepsilon l}{\ln(\frac{2d}{r})} \tag{15}$$

Here:

- l is the wire length
- ε is the permitivity of air
- d is distance from wire to ground
- r is radius of wire

Now all the components of the line is known the impedance of the whole line can be calculated. For this an equivalent circuit is drawn (see figure 8). The resistor and inductance are in series and the capacitance is parallel to the resistor and inductance. Using formula 16 the impedance of the line can be calculated.

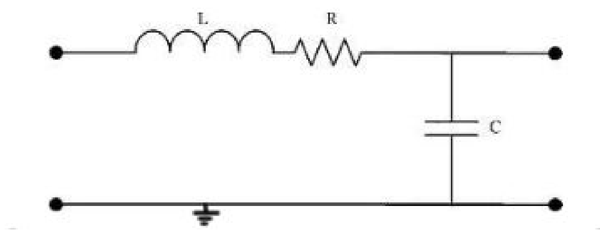


Figure 8: Equivalent circuit line

$$Z_L = \frac{1}{\frac{1}{R+Z_{inductance}} + \frac{1}{Z_{capasitor}}} \tag{16}$$

4.3.2 Measuring method

For load impedance (Z_L) calculation there is an extra measurement taken. This measurement is taken at the last house of the network. Let us call the voltage measured at the last house V_{13}. This is the house furthest away from the transformer. The voltage at the at the transformer on the secondary side is V_0. This also counts for the currents I_{13} and I_0. See figure 7.

To calculate the Z_L's from the two measurements is not possible because the energy usage from each house can be different. The different usage per house will result in different values at V_n. For example if we assume that $Z_{L1} = Z_{L2} = Z_{L3} = Z_{L4}$. If house n=1 is using all the power, than the voltage drop will be three times lower than when house four is using all the power. To get Z_L of the transmission line all the houses connected to it need to be switched off except for the last house. The house furthest away from the transformer. This way the Z_L can be perfectly measured and calculated with formula 17.

$$Z_L = \frac{V_0 - V_{13}}{I_0} \tag{17}$$

5 Results

5.1 Results for Z_s

In this section the calculations for Z_s for a neighborhood are discussed. First an overview will be given of the electric grid in Aruba. After that, the reasons for selecting the measured neighborhood are explained. Finally the calculations for Z_s are given with a conclusion.

5.1.1 Electric grid Aruba

The electric grid of Aruba has one producer, namely WEB(Water en Energie Bedrijf). From there the electricity flows to a three-phase transformer which transforms the voltage to 60 kV. This transformer changes the tap while being on-line. This way it regulates the voltage at 60 kV. From this transformer, cables run to seven substations. Here the voltage is transformed from 60 kV to 12 kV. The transformers at the substations also change the tap while being on-line to ensure a constant 12 kV. From these substations, transmission lines run to the transformers for the neighborhoods. These transform the 12 kV voltage to 220 V which is supplied to the households. See figure 9

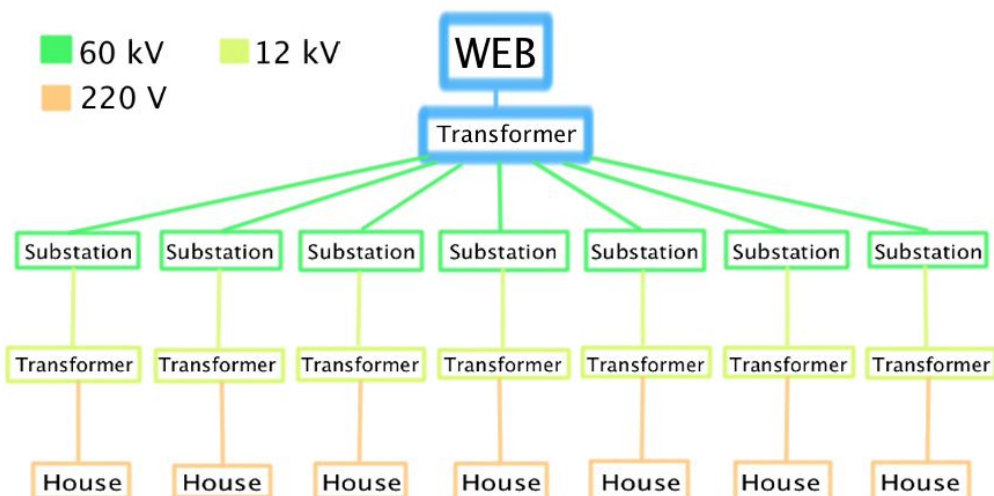


Figure 9: Simple model grid Aruba

5.1.2 Grid Area

To measure all the areas in the grid would be arduous and inefficient. In order to reduce the size of the study, a grid area has been selected to represent the

Aruban grid as a whole. First the amount of houses connected to a rated power transformer is illustrated in figure 10. It can be seen that about 8000 houses are connected to a $75kVA$ transformer, thus it can be assumed that a typical Aruban household is most likely to be connected to a $75kVA$ transformer.

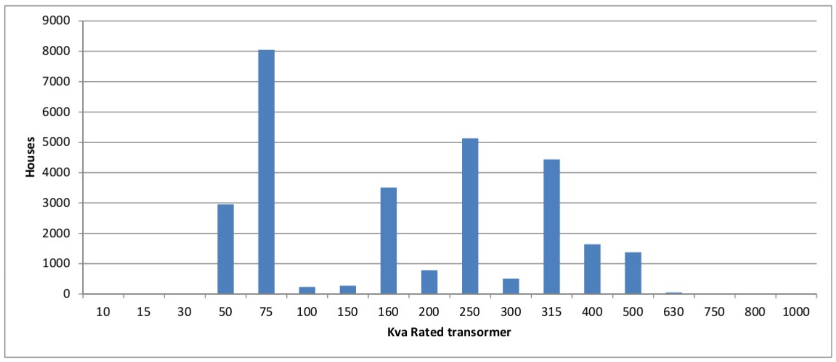


Figure 10: Amount of houses connected to a rated kVA transformer

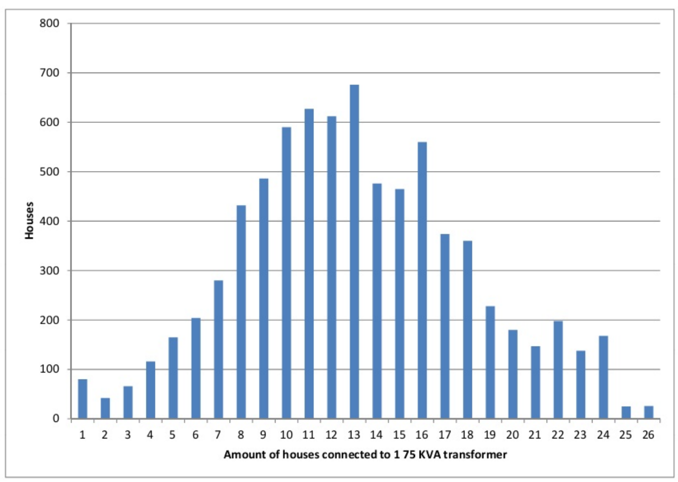


Figure 11: Amount of houses connected to a $75kVA$ rated transformer with an amount connection to it

Next the amount of houses connected to this transformer is plotted in figure 11. It can be seen that a transformer of $75kVA$ that is connected with thirteen houses is the most common grid configuration. For this reason a $75kVA$ transformer with thirteen houses connected to it will be measured. The selected neighborhood for the measurement is in Palmbeach(see figure 12). It is a neighborhood of thirteen houses on the north side of the island. For the rest of this thesis the term ”neighborhood” refers specifically to the Palmbeach neighborhood.

Figure 12: Overview Palmbeach

5.1.3 Measurement

The measurement is made with Elitepro. It measures the RMS value of the three-phase voltages, currents, and power factors of the three lines. For specification see appendix B. It takes a variety of measurements ranging from a period of a few hours to a whole day, with data points every second. This way there are enough data points to make a valid calculation. During the measurement period all the houses(Z_L) are disconnected one by one. This way there is no load on the cable and no voltage drop because no current is flowing, so the flowing situation will be valid (see figure 6). This way the E_s can be measured during the measurement period.
The Elitepro is connected just beyond the transformer. This can be seen in figure B.

5.1.4 Impedance transformer

For calculating the impedance of the transformer the information of the transformer is needed. This can be found on the transformer itself. In table 2 the information on the plate is given. For an actual image of the plate see appendix B.

Power	75 kVA	Type	TSC
	HS(primary side)		LS(secondary side)
Voltage	12726		230
Voltage	12423		230
Voltage	12126		230
Voltage	11817		230
Voltage	11514		230
Current	3x3.57		3x188
Short-circuit voltage	4.24%	Year build	1995
Total weight	565 kg	Frequency	50

Table 2: Information on transformer plate

From this information plate, the impedance can be calculated. The impedance test of the transformer is done via a short-circuit test. The secondary side of the transformer is short-circuited and a voltage is put on the primary side. From this test the short-circuit voltage can be measured. This can be found in table 2. With the short-circuit voltage the impedance can be calculated on the secondary side with the following formulas.

$$N = \frac{U_{1rated}}{U_{2rated}} \tag{18}$$

$$I_{rated} = \frac{S_{rated}}{U_{rated}\sqrt{3}} \tag{19}$$

$$Z_{transformer-primary-side} = \frac{u_k(\%)U_{rated}}{I_{rated}\sqrt{3}} \tag{20}$$

$$Z_{transformer-secondary-side} = \frac{Z_{transformerprimaryside}}{N^2} \tag{21}$$

5.1.5 Calculation

From the measurements a graph of the voltages and the currents of the total period is made (see figure 13). Here it can be seen that while the current is zero the voltages jumps. This is due to a tap change on the $12kV$ line. Due to this fact, there will be two calculations made per phase; one calculation before the tap change, and one after the tap change.

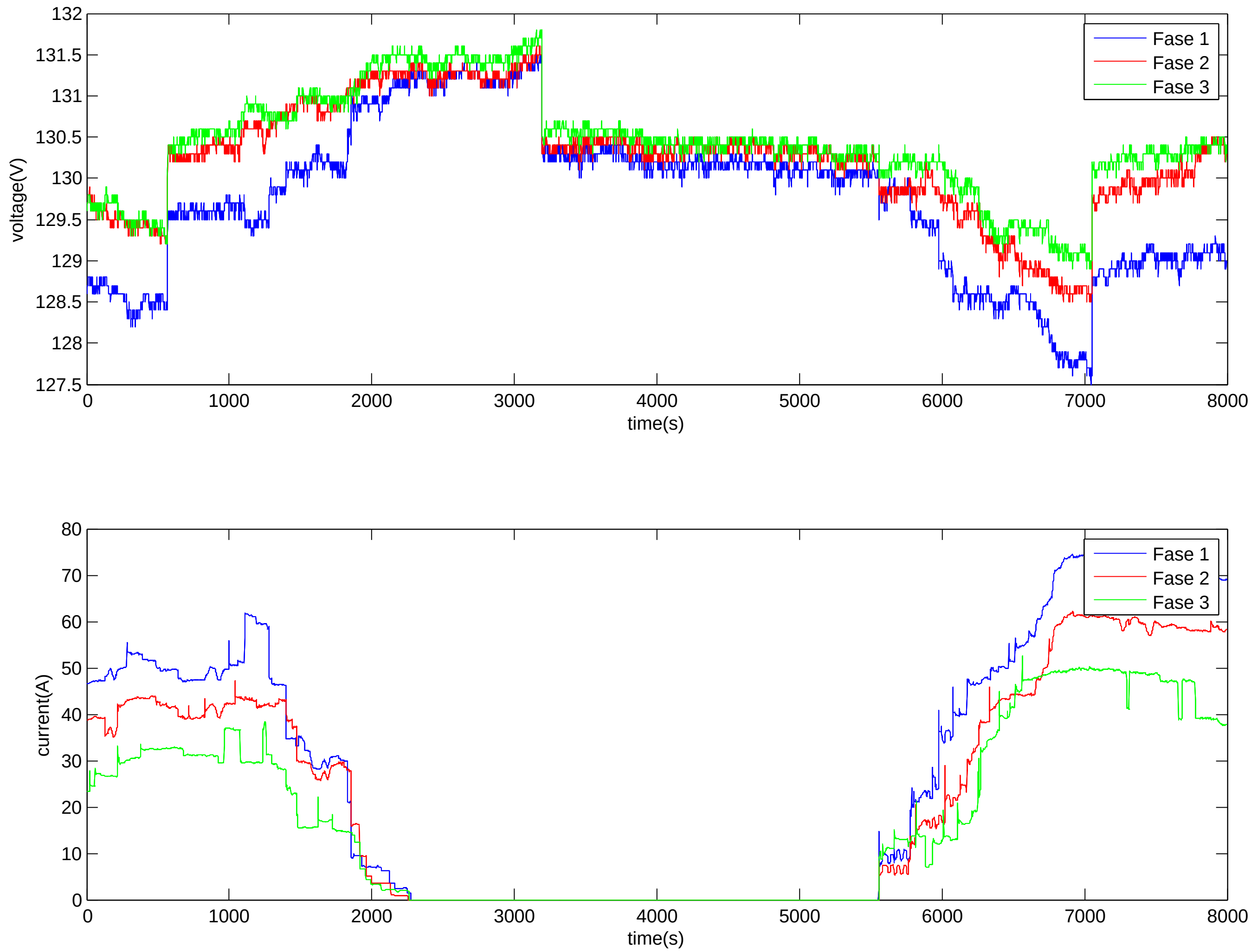


Figure 13: Voltage and current at measurement

The assumption is made that for this measurement the E_s(see figure 13) is constant before and after the tap change. This is why the average can be used for the value of E_s . This can be seen in figure 14 where two averages lines are drawn for each phase. These averages are used to calculate the impedance(Z_s)

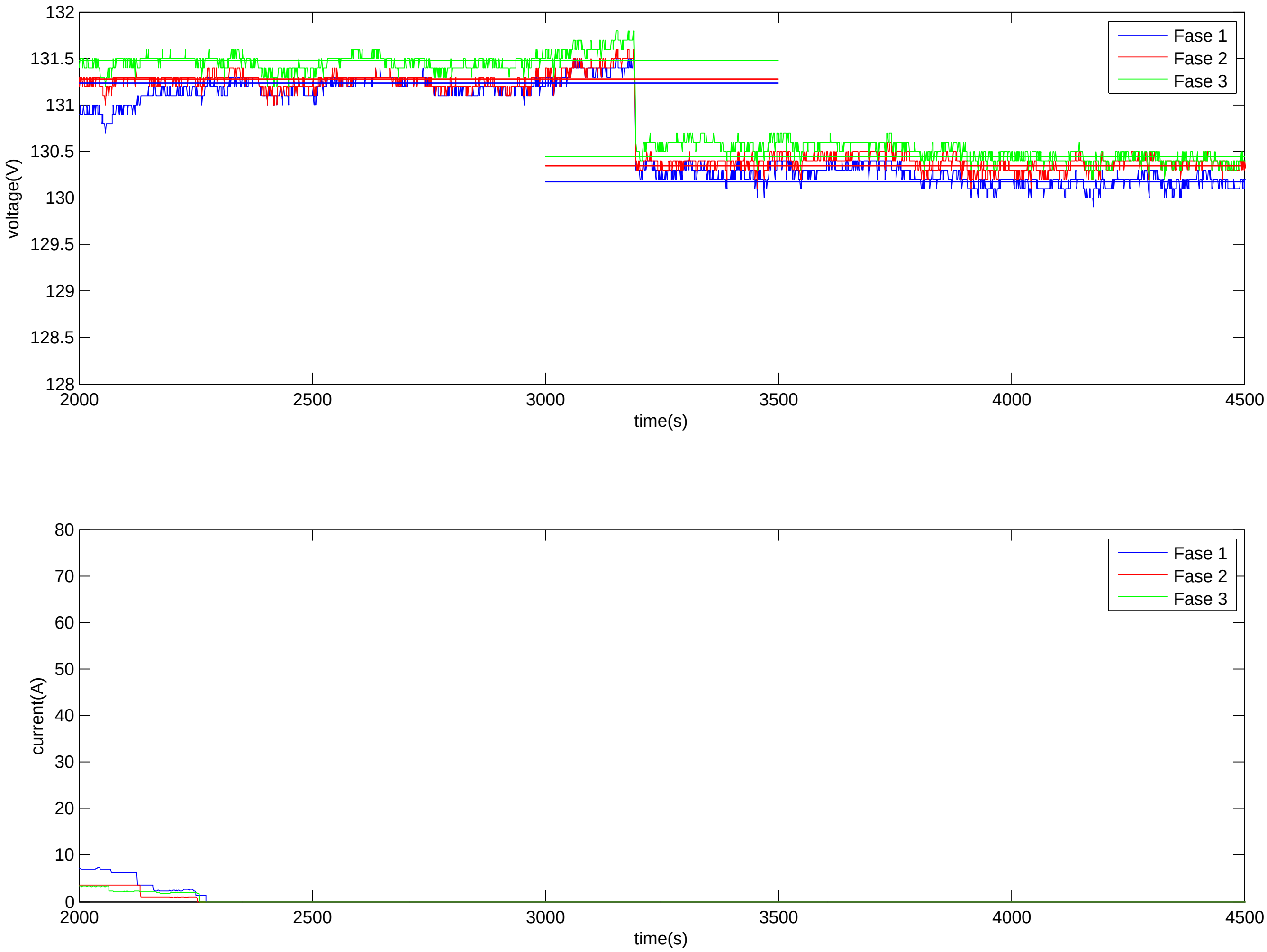


Figure 14: Voltage and current at measurement

With formula 12 the Z_s for each second is calculated and put in a graph. This can be seen in figure 15. The impedance of the transformer is calculated and also shown in the graph. This to show that the impedance of the grid is almost the same as the impedance of the transformer. For all the calculated impedances see appendix C.

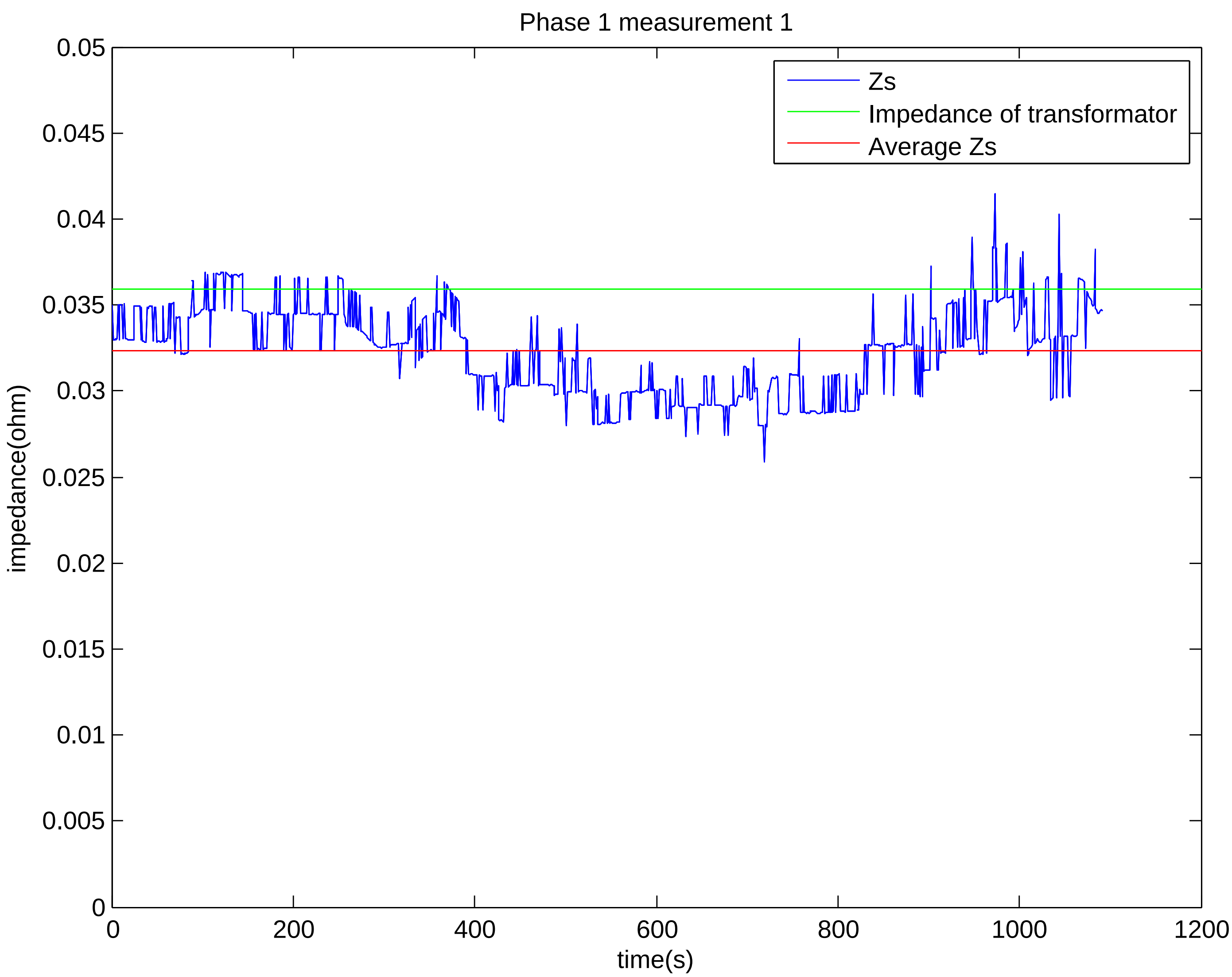


Figure 15: Impedance of measurement

5.2 Calculation of Z_L

For the calculation of Z_L the formula from paragraph 4.3.1 is used. For ease of reference the formula 13 is rewritten as one formula. This can be seen in formula 22.

$$R = \rho_0[1 + \alpha(T - T_0)]\frac{l}{A} \tag{22}$$

The answer for the area that is measured can be seen in the table below.

Parameter	Value
ρ_0	1.75×10^{-8}
T	318 Kelvin
T_0	293 Kelvin
α	0.00393
l	142 meter
A	$50mm^2$
R	6.2×10^{-2}

Table 3: Resistivity

The inductance of the wire is:

$$L = 2l[2.303\log(4l/d - l + \mu/4 + (d/2l))] \tag{23}$$

Parameter	Value
l	142 meter
d	9.1 mm
μ	1
L	.338 mH

Table 4: Inductance

Here we assume that the capacitance is between the wire and the ground.

$$C = \frac{\pi\varepsilon l}{\ln(\frac{2d}{r})} \tag{24}$$

Parameter	Value
ε	8.854×10^{-12} F/m
r	9.1 mm
l	142 meter
d	7 meter
C	6.14×10^{-10} Farad

Table 5: Capacity

The total impedance of the measured line can then be calculated. First an equivalent circuit of the line is drawn (see figure 8).

As seen from figure 8, the capacitance does not play a big role in the impedance of the whole line in the load flow simulations. This is just the impedance of the resistor and the impedance of the inductance in series. The impedance of one phase of Palmbeach is calculated in formula 25.

$$Z_R = R = 5.6 \times 10^{-2}\Omega$$
$$Z_L = \omega L = 2\pi f L = .127\Omega$$
$$Z_{line} = \sqrt{Z_R^2 + Z_L^2} = .135\Omega \tag{25}$$

5.2.1 Measurement of Z_L

To determine the Z_L there are two measurements available. The measurement at the mast, namely V_0, and the measurement at the house furthest from the transformer V_{13}. From the mast to the penultimate house of the series, all of the houses were disconnected so that only the last house remained connected. This meant that all the current went through the transmission line to the last house. The following picture illustrates this situation.

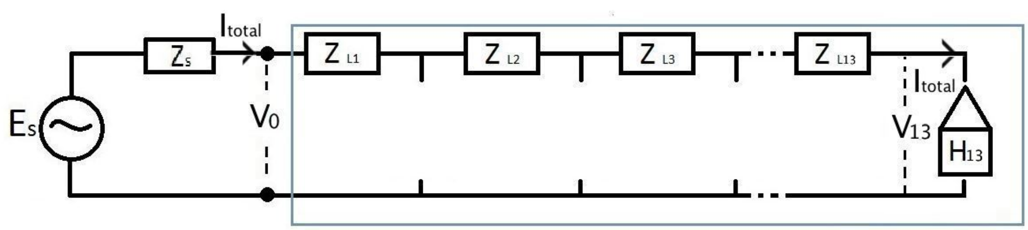


Figure 16: Transmission line measurement

Using the formula 17 we get the impedance of one phase of the transmission line. In figure 17 the impedance can be seen for a specified period of time. The average impedance and calculated impedance are also shown in the graph. The calculated impedance is derived from formula 25. It can be concluded that the calculated value is the same as the measured value.

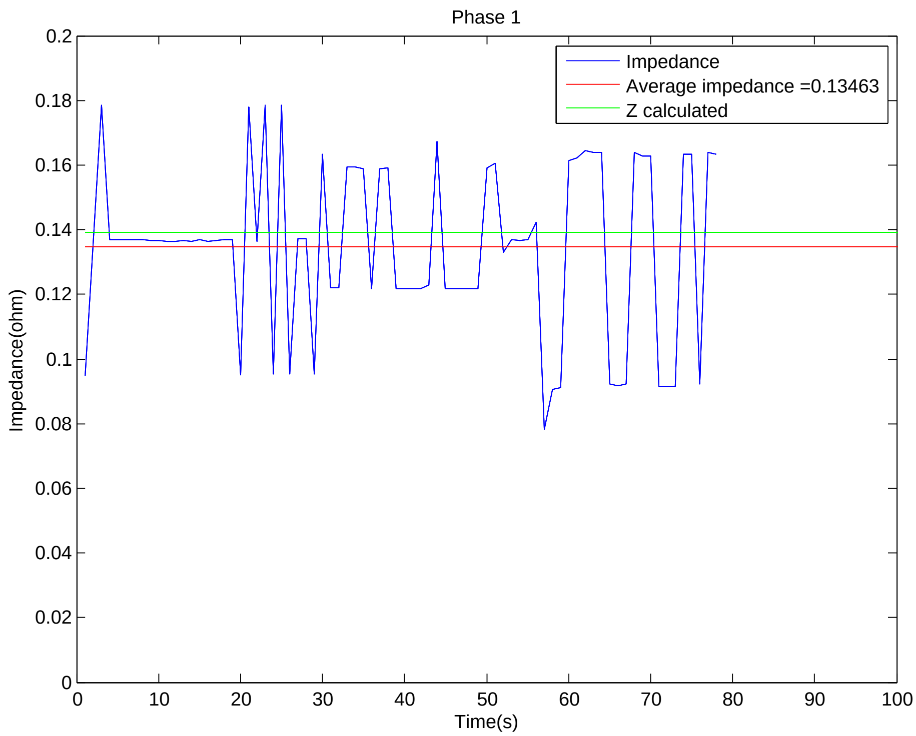


Figure 17: Transmission line measurement

5.3 Model in ETAP

Elmar uses ETAP as the software for the calculation of grid load-flows. This is the reason a model was made of the area that was measured in ETAP. This software also has the possibility to integrate solar panels to the model. It has an option to get live input from the current situation and simulate the load-flow. This option has a lot of potential when the grid is filled with solar panels in the future.

In figure 12 an overview of the neighborhood is given. For this neighborhood a model is made in ETAP (see appendix D). This model will be compared with the values derived from the measurements. The settings of the transformer and lines in ETAP can be found in appendix D

To validate the fact that the parameters are well chosen, five measurements are chosen and compared to the values ETAP gives. The three phases are plotted for different currents. The red column is the measured voltage and the blue column the data received from the ETAP model(see figure18). It can be concluded that the values are well chosen.

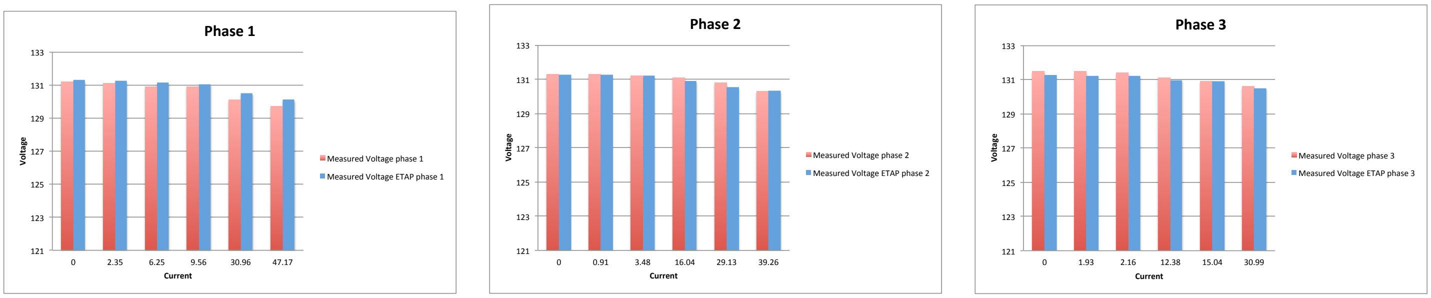


Figure 18: ETAP compared to measurements

For the modeling of the transmission lines the same method is used as for the transformer. The current is chosen when only the last house is connected to the transformer. This way any significant voltage drop is caused only by the current drawn by the house furthest away from the transformer. The current per phase is filled in ETAP and compared with the values from the initial measurement. The comparison graph can be seen in figure 19. The ETAP model confirmed the measured values.

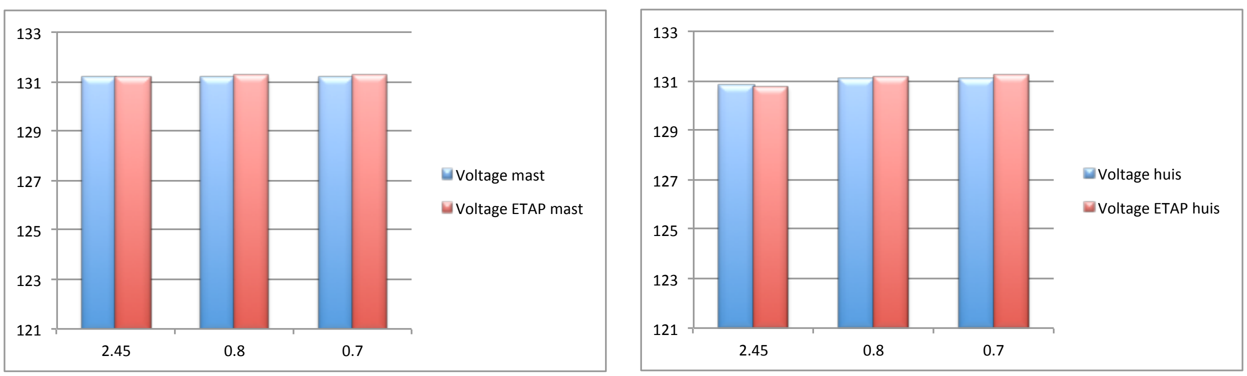


Figure 19: ETAP compared to measurements

5.4 Possible percentage of solar power in the Grid

In this chapter one of the main questions is going to be answered, namely "What is the current PV penetration level on a residential scale". For this question certain assumptions are made and more than one answer is possible. This is why a few scenarios will be explored.

First, as concluded from the literature research, the voltage rise effect would be the bottle neck. This means that the line to neutral voltage may not exceed $132.1V$ and may not be lower than $121.9V$. The parameters that cause the voltage to rise are the current and impedance. From the approach chapter, a method is used where the grid is modeled as a Thévenin circuit (see figure 4 and 7).

From chapter 5 it can be concluded that the impedance of the grid looking from the low voltage side of the transformer is the impedance of the transformer itself, and the impedance of the lines is the resistance and inductance of the line.

For the Palmbeach neighborhood measurement area, the following assumptions are made to calculate the maximum solar power penetration.

- Every house uses the same amount of energy.
- The power over the phases is balanced.
- The distance between each house is the same, which means that the total length of the line divided by the total number houses equals the distance between the houses.
- Each house generates the same amount of solar energy.
- The initial secondary voltage of the transformer can be chosen freely.

Figure 20 is made to visually depict these assumptions. In this figure all I_n and Z_n are the same. All houses and PV systems consume and generate the same energy. V_0 is the voltage of the transformer at the secondary side and can freely be chosen.

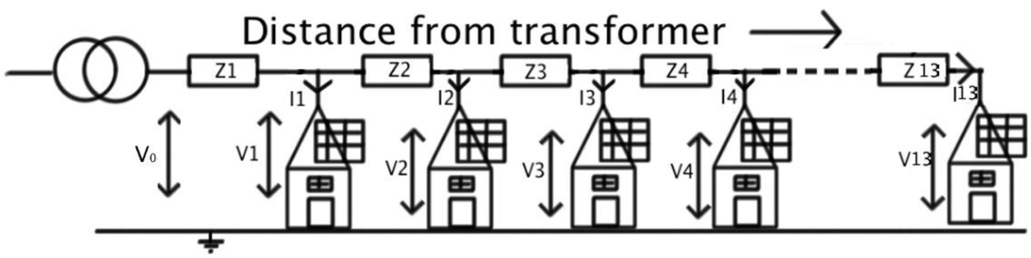


Figure 20: Assumption illustration

The first step is to calculate the first two assumptions. For this the total measuring period is visualized(figure 21). Here the voltage, current and power per phase is visualized. The total power of all the three phases is also visualized. The average, minimum and maximum power consumption is calculated from the information from figure 21 which can be seen in table 6. The Palmbeach neighborhood has 13 houses so the average, minimum and maximum consumption per house is:

$$P_{average} = \frac{21578}{13} = 1660W$$

$$P_{minimum} = \frac{8403}{13} = 646W$$

$$P_{maximum} = \frac{34377}{13} = 2644W$$

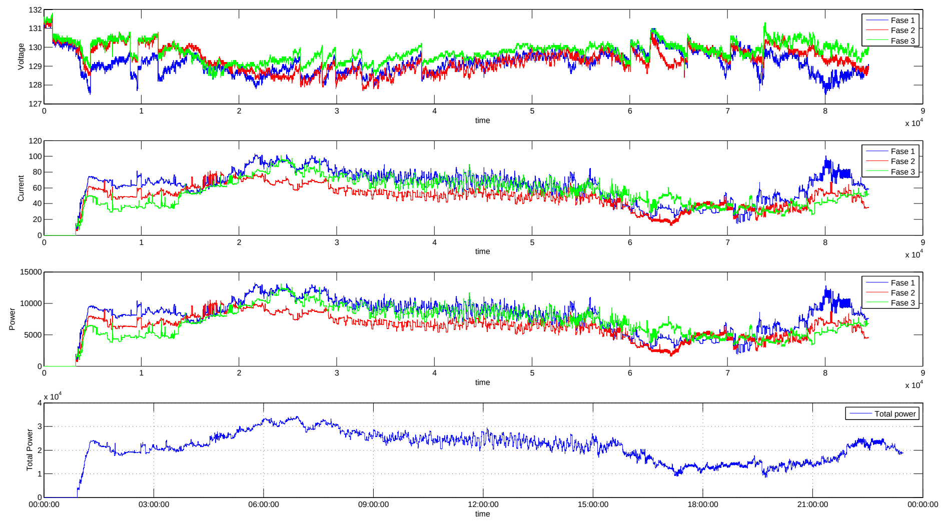


Figure 21: Total measuring period voltage, current, power per phase and total power

Maximum Power consumption	$34377W$
Minimum Power consumption	$8403W$
Average Power consumption	$21578W$

Table 6: Measured neighborhood information

From the power consumption per house, the current per house per phase can also be calculated. This is done with the assumption that the voltage per phase is the nominal voltage. This is done with the following formula:

$$I_{average-per-phase-per-house} = \frac{P_{average}}{3*V_{nom}} = \frac{1660}{3*127} = 4.36A$$

$$I_{minimum-per-phase-per-house} = \frac{P_{minimum}}{3*V_{nom}} = \frac{646}{3*127} = 1.70A$$

$$I_{maximum-per-phase-per-house} = \frac{P_{maximum}}{3*V_{nom}} = \frac{2644}{3*127} = 6.94A$$

With the rest of the assumptions the calculation of the maximum solar penetration of the Palmbeach can be calculated. The boundary is that the voltage is between $132.1V$ and $121.9V$. This means that during the day when there is sun and the PV system generates power, the voltage may not exceed $132.1V$ with the minimum power consumption, and that during the night the voltage may not be lower that $121.9V$ when using maximum power and no solar power. The voltage over the transmission line will be calculated step by step starting from the transformer going to the last house. First the total current per phase is calculated during the night. During the night the peak power is used so the $I_{maximum-per-phase-per-house}$ will be used. This is $I_{total} = I_{maximum-per-phase-per-house} * 13$. The voltage drop over the transformer is calculated with formula 26 and the impedance of the transformer from paragraph 5.1.4.

$$V_{0-drop} = I_{total} * Z_s \tag{26}$$

The voltage per house is calculated with formula 27. Here n is the number of the house when looking from the transformer. For the house closest to the transformer $n = 1$. And k is the number for the house furthest away from the transformer which is 13 for the Palmbeach neighborhood. Here the Z_{ln} is the line impedance calculated in 4.3.2 divided by 13 houses. The voltage drop over the 13 houses($V_{drop-houses}$) is calculated and added to the voltage drop over the transformer(V_{0-drop}) and added to the minimum line voltage to get the source voltage(E_s) (see equation 28). This way the last house(V_{13}) has the minimum voltage when the maximum power is consumed.

$$V_n = V_{n-1} - Z_{ln} * \sum_{n}^{k} I_n \tag{27}$$

$$E_s = V_{0-drop} + V_{drop-houses} + 121.9V \tag{28}$$

Now that the minimum source voltage(E_s) is known, the maximum solar penetration can be calculated. This is done by adding generated power to the consumed power per house. Because the minimum power consumption is during the day, the minimum power is used:$P_{house} = P_{minimum} - P_{solar}$. With formula 29 and 27 a loop is made in matlab where P_{solar} is increased until the maximum voltage is reach at one of the houses(V_n).

$$V_0 = E_s - I_{total} * Z_s \tag{29}$$

The voltage profile over the transmission line can be seen in figure 22. Every star(*) in the graph is a house(n). This means that the first * in the graph is V_1 in figure 20. The maximum power that can be delivered for the measured neighborhood is $11850W$. This means that every house in the neighborhood may have a PV system with rated power of $11850/13 = 911W$. This is 55 % of the average power consumed by the measured neighborhood.

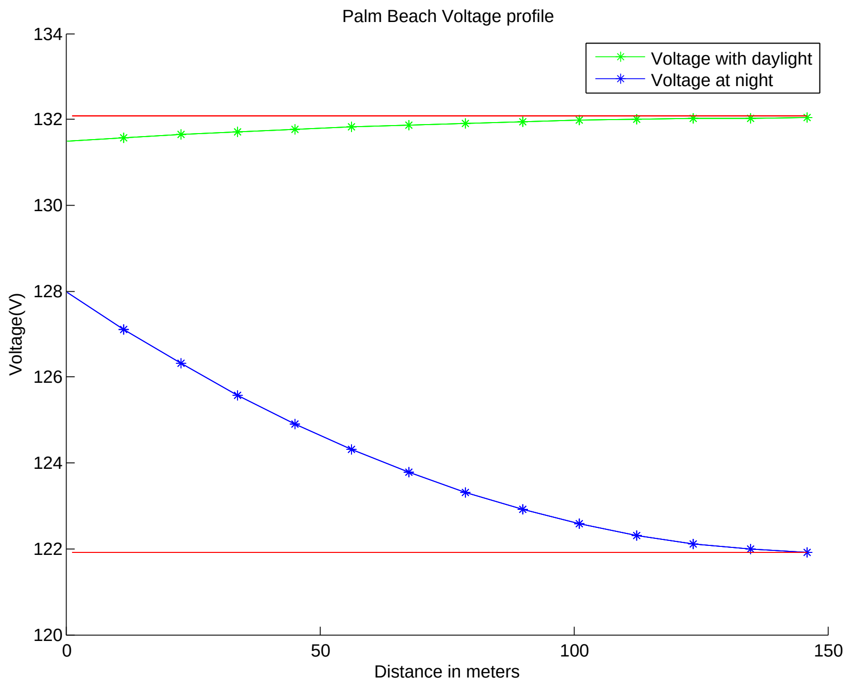


Figure 22: Voltage profile Palmbeach

This situation is only accurate if all of the assumptions are valid, however, this is not realistic. For that reason two further scenarios are discussed below to get a better feel of the actual situation. First of all, the tap on the transformer has fixed values. The transformer has five taps. The open voltage of the transformer per tap can be seen in table 7. The tap chosen for the two scenarios is tap ♯2. If it is taken that only the last house in the measured neighborhood has a PV system - that is, when house 13 from figure 20 has the only PV system - then a maximum of $7250W$ can be installed. The calculation is done in the same way as outlined above, but now only the last house has a PV system. If the calculation is repeated, but this time assuming only the first house(house 1) has solar panels, then a maximum of $14990W$ can be installed. The voltage plots and table of the two situations can be seen in figure 23 and table 8.

Tap ♯1	134.74V
Tap ♯2	131.29V
Tap ♯3	128V
Tap ♯4	124.89V
Tap ♯5	121.91V

Table 7: Tap voltages of transformer

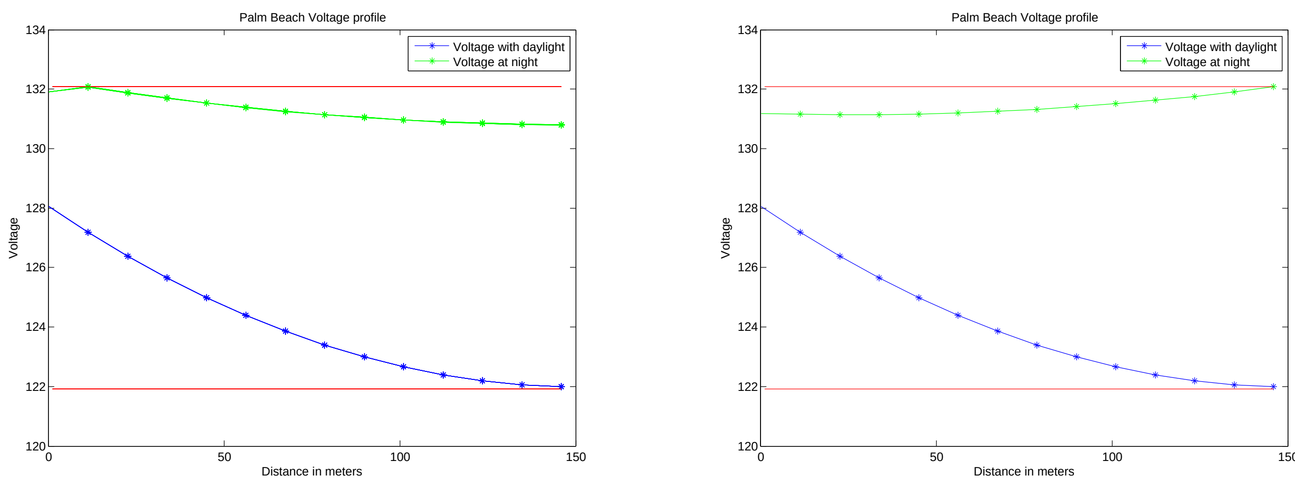


Figure 23: Solar panel installation for first house (left) and last house (right)

Situation solar power at the end of the line	maximum of 7250W	34 % of average power
Situation solar power at the beginning of the line	maximum of 14990W	69 % of average power
Situation where solar power is distributed over all houses	maximum of 11850W	55% of average power

Table 8: Overview situations

5.5 Model in Matlab

A model is made in Matlab where the voltage profile of the neighborhood is plotted. This is because the ETAP model does not visualize the voltage in one click. With the Matlab model it is clearer what the status is and how much more solar power can be integrated. Also the Matlab program can easily be used and no license is required to use it. See figure 24 for a screen shot. The same calculations as discussed in paragraph 5.4 are used in this program.

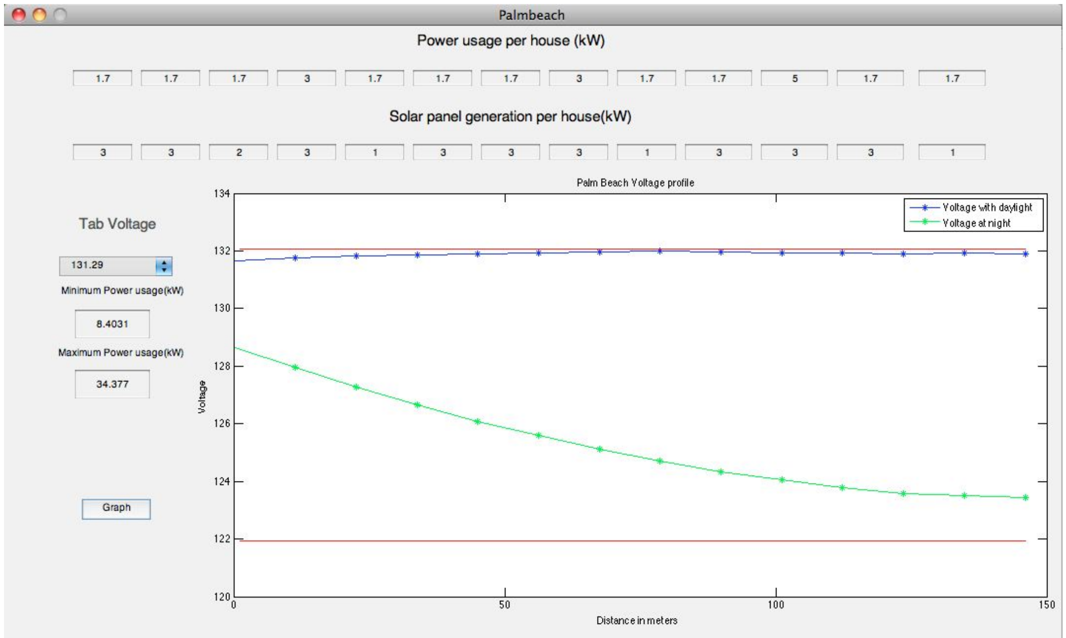


Figure 24: Matlab voltage profile plotter

In the top row the power usage per house is entered. The row below shows the power generated by the solar panels. To the left of the graph area, the tap voltages can be chosen. Below that the information of the neighborhood maximum and minimum power usage is shown.

6 Future possibilities

In this section the future possibilities for increasing the PV penetration is discussed. First the potential of reactive power is discussed. Second the option of changing the tap of the 60/12 kV transformers is explored. Finally the impact of integrating one EV into the grid is discussed.

- Reactive power
- Automatic tap change
- Electric vehicles

6.1 Reactive power

In this section options are discussed regarding how to improve the PV penetration. First a brief explanation is given about what reactive power is, and how an inverter can deliver this power. Finally a brief explanation is given as to what the potential of delivering reactive power to the grid is.

6.1.1 Reactive power and real power

Many electrical devices require reactive power from the grid for proper operation. Induction motors need it for generating a magnetic field which transmits torque to the rotor. Power electronic equipment like chargers need it to generate a DC voltage. Their grid current is not in phase with the grid voltage. Reactive powerflow results in additional grid currents and therefore they cause additional power losses on power lines and transformers [19]. The additional losses mean more costs for the grid operator. For a better understanding of reactive power see appendix E. If reactive power is produced locally in the neighborhood then less current needs to be transported. This advantage means less losses which is attractive for the grid operators. Reactive power is also interesting because there is no voltage limit that limits the amount of power that can be transported. The limit is the amount of power the transformer can transport [19]. This is around the rated power of a transformer.

6.1.2 Increase of solar power due to reactive power inverters

The inverters can be programmed to deliver reactive power and active power. It can do this by changing the phase angle between the voltage and the current of the grid. There are different types of control systems to control the phase angle [20] [21]. In this paragraph it will be assumed that the phase angel can be freely chosen.

To calculate what the impact of reactive power control is on the amount of PV systems that can be integrated into the grid, two further assumptions are made. The assumptions can be seen below.

- Solar power from a neighborhood can only generate reactive power for the neighborhood itself and not for neighboring neighborhoods. This assumption is based on the idea that most neighborhoods will have their own PV system and would generate their own reactive power. If reactive power needs to be transported to neighboring neighborhoods, the advantage of reactive power is not completely used.
- It will generate reactive power when voltage levels reach a critical level.

First the amount of reactive power that the Palmbeach neighborhood consumes will be visualized. This can be seen in figure 25. On the x-axis the time in seconds is shown, and on the y-axis the total reactive power of all the three phases. Also the maximum, minimum and average reactive power can be seen the figure 25.

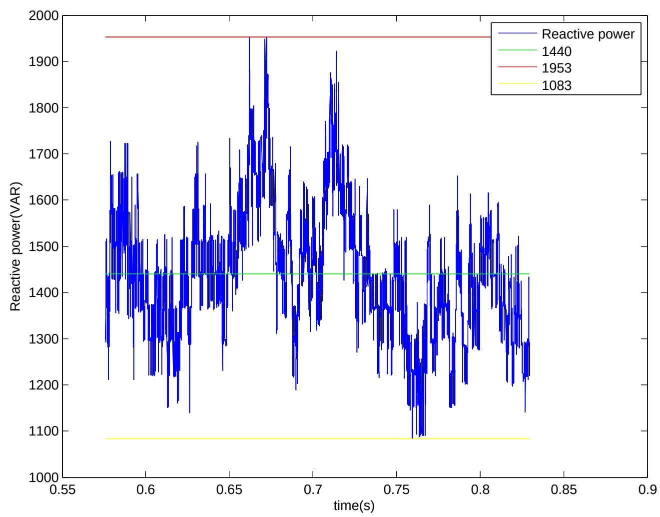


Figure 25: Reactive power Palmbeach

In table 8 it can be seen how much solar power can be installed if only real power was integrated in the grid. From figure 25 it can be seen that the minimum reactive power that can be added to the grid is $1083VAR$. In table 9 the extra $1083VAR$ is added. With reactive power inverters there is a $1083VAR$ increase of total solar power that can be integrated. The reason that the minimum reactive power is chosen is that no complex algorithm or measurement system needs to be used. If the average or maximum reactive power would be used there will be a moment when more reactive power is produced than can consumed. If this is true for all the residents of Aruba, then the economic advantage of reactive power will fall.

Configuration	Real power	Reactive power	Apparent power
Solar power at the end of the line	7250 W	1083 VAR	7330 VA
Solar power at the beginning of the line	14990 W	1083 VAR	15029 VA
Solar power is distributed over all houses	11850 W	1083 VAR	11899 VA

Table 9: Overview situations

6.2 Automatic tap change

In this section a tap changing action on the 12 kV line is discussed to maximize the amount of PV systems that can be integrated in the grid.

6.2.1 12 kV grid

As mentioned in the paragraph "Electric grid Aruba" the grid consists of a 60 kV, 12 kV, and 220 V line (see figure 26). The power flows from WEB to the houses in the conventional way. Once PV systems are integrated into the grid, power will flow from 220 V grid to 12 kv line back to 220 V line, and possibly through the 60 kV line. A transformer ensures that voltage on a line stays between marginal values by changing taps.

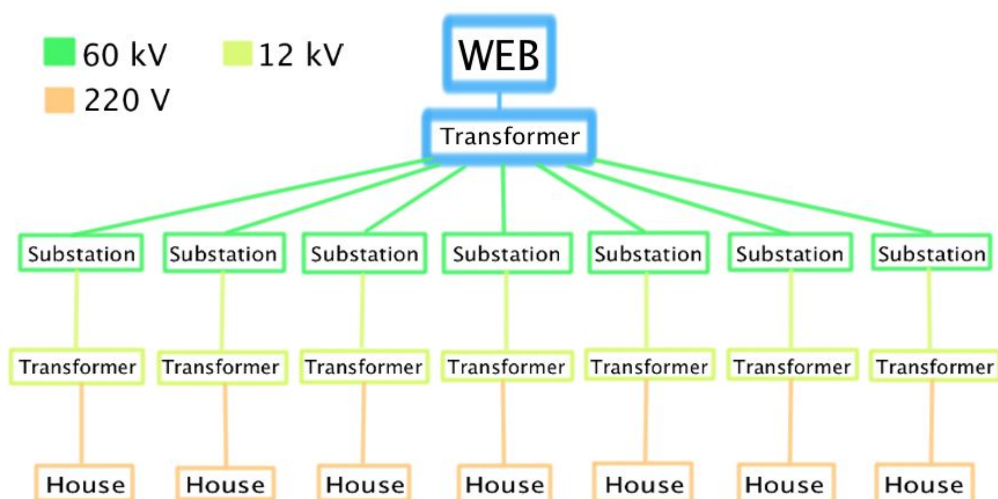


Figure 26: Simple model grid Aruba

6.2.2 Tap changing method

The transformer 60/12 kV changes the taps while they are on-line. The 12/0.22 kV transformer has a fixed tap and can only be changed if the transformer goes off line. Because the limiting factor for integrating PV systems is voltage, a tap changing method is developed. During the day the PV system will increase the voltage of the grid. During the night the PV systems doesn't produce power so the voltage will drop. The "tap changing method" is to change the tap of the 60/12 kV transformer during the day to decrease the voltage, and to increase more power for the PV system. During the night it changes the tap again to increase the voltage (see figure 27).

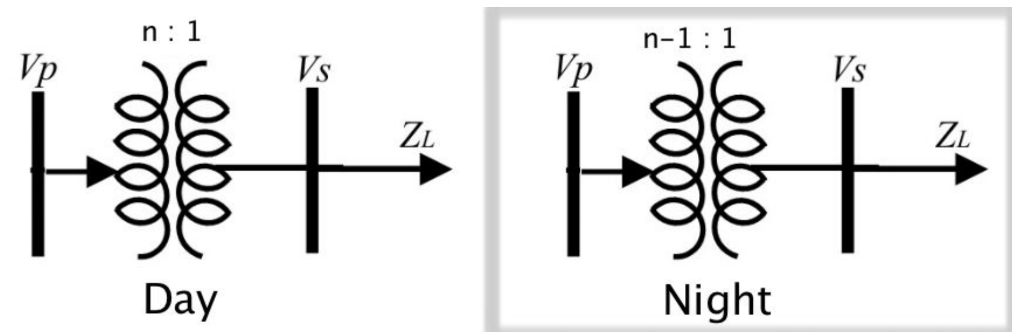


Figure 27: Tap change voltage profile

6.2.3 Increase of solar power due to tap change method

From figure 28 it can be seen that the voltage of all the three phases jumps. In this figure it jumps twice. This happens because a tap change is carried out on the 60/12 kV side transformer. The average voltage of a jump is $1.1V$ per tap change.

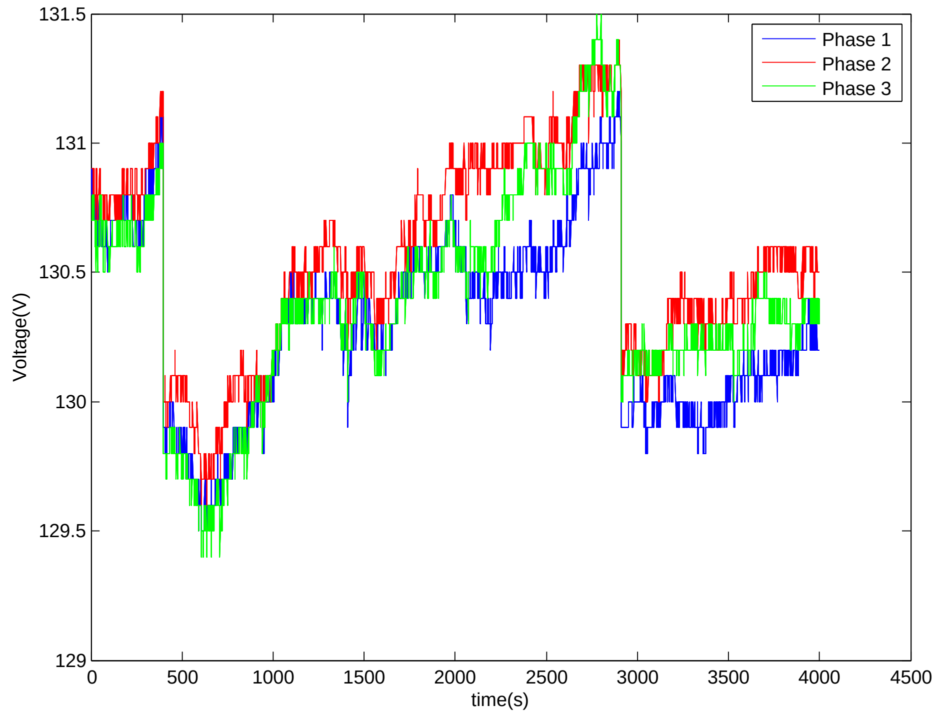


Figure 28: Simple model grid Aruba

If using this method together with the maximum calculated power derived in paragraph 5.4, the following situation occurs. The voltage during the day will be lowered by $1.1V$. This means that more power can be produced before it reaches the maximum voltage. In figure 29 it can be seen how the voltage profile is over the line using the same assumptions as in paragraph 5.4.

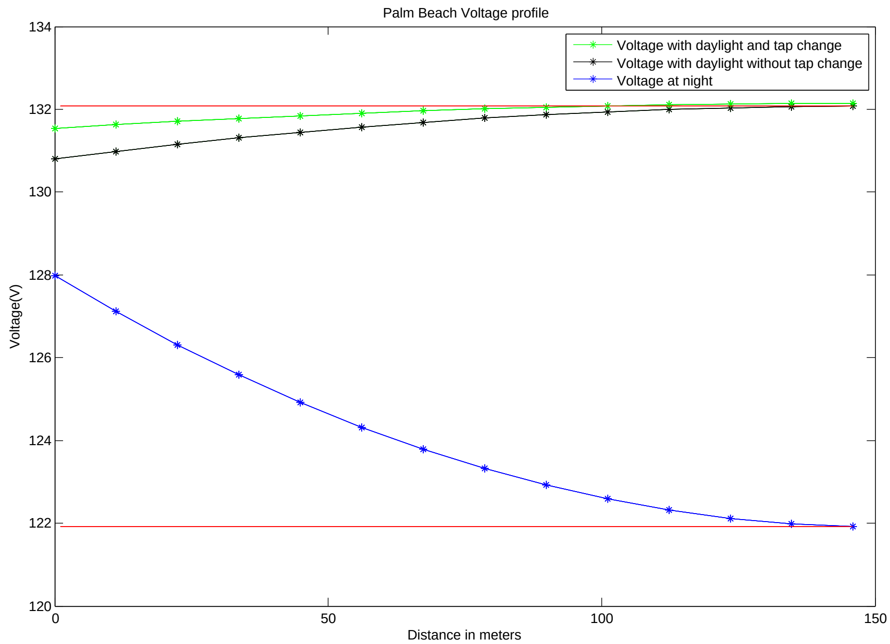


Figure 29: Voltage over line with tap change

The voltage profile in black demonstrates what happens when the tap change method is implemented. The green profile shows the voltage profile without a tap change. In blue is the voltage profile during the night. The situation above shows the ideal situation. Now some more realistic scenarios will be considered. The same situation will be outlined as in table 8 but with the tap changing option. This can be seen in table 14

Situation	Maximum power	Percent of average power	with tap change	Percent of average power
Solar power at the end of the line	$7250W$	34 %	$9870W$	46%
Solar power at the beginning of the line	$14990W$	69%	$24240W$	112%
Solar power is distributed over all houses	$11850W$	55%	$15670W$	73%

Table 10: Overview situations

6.3 Electric vehicles

In this section the option of integrating electric vehicles(EV) will be discussed. There will not be an in-depth analysis because that in itself is a large enough subject to be explored in a final thesis. Only optimal conditions will be discussed to gain an idea of what the integration of EV can do. Firstly the solar radiation on a clear day will be discussed. After that the amount of power going into a EV and the limitations of it will be explored. Finally an estimation of how EV can increase the amount of PV systems in the grid will be considered.

6.3.1 Solar radiation on Aruba

Aruba's geographical coordinates are 12°30N, 69°58 W. It is between the equator and the tropic of cancer. This means that there are two days every year when the sun is directly above Aruba with the maximum solar radiation per square meter. The solar radiation will be calculated based on this optimal condition. The formula used is formula 30. This is a simplified version of the real solar radiation.

$$I_{radiation} = 1.353 \times (0.7^{\frac{1}{cos(\Theta)}})^{0.678} \tag{30}$$

Here:

- $I_{radiation}$ is the energy per square meter (W/m^2)
- Θ is the angel between the sun and the earth. $\Theta = 0$ is when the sun is at its highest point directly above the earth.

The solar radiation on Aruba has a maximum of 1062 watt per square meter. This can be seen in figure 30. The standard for measuring PV systems is AM 1.5 and $1000W/m^2$ at the temperature of 25 degrees Celsius. For the calculations it is assumed that a 1000 W rated PV system will produce 1000 W if the solar radiation is $1000W/m^2$. With this assumption the maximum that a PV system on Aruba will deliver is a power of $1.062 \times PV_{ratedpower}$.

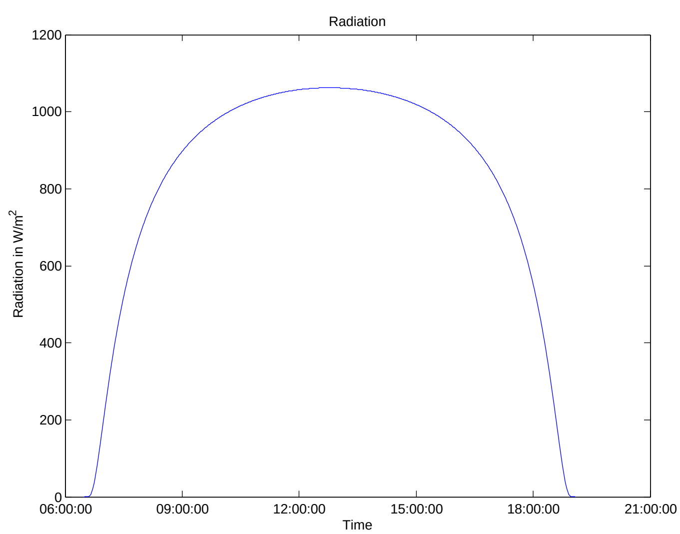


Figure 30: Radiation during most radiated day

6.3.2 Power and energy of EV

There are different types of EV's on the market with different batteries all with different capacities. For this calculation the average capacity of the top ten most popular EV cars is taken. The list of these cars can be seen in table 11. The average is taken for the calculation.

Car model	Capacity battery in kWh
Toyota Prius Plug-in	4.4
Renault Twizy	7
Peugeot 3008 Hybrid4	1.1
Tesla Roadster	53
BYD e6	48
Toyota Prius	2
Nissan Leaf	24
Vauxhall Ampera	16
Chevrolet Volt	16
MINI Electric	40
Average	21.15

Table 11: Overview EV capacity

For the charging of the EV there are limits. These limits are set by the chargers or the grid operator. The standard for charging EV can be found in the SAE J1772. There are two methods that can be integrated in the neighborhood. This can be seen in table 12. For the calculation of the integration of EV, method 2, 16 A will be used. This because the standard of the grid operator on Aruba is per group per house 16 A.

Charge Method Nominal Supply	Voltage (Volts)	Maximum Current	Maximum Power
AC Level 1	120 V AC, 1-phase	12 A	1.44 kW
	120 V AC, 1-phase	16 A	1.92 kW
AC Level 2	208 to 240 V AC, 1-phase	≤ 80	3.52 kW

Table 12: Overview EV charging method

6.3.3 Increase of solar power due to EV

In this section a few scenarios will be outlined exploring how the EV can increase the PV penetration in the grid. There are many configurations possible, however to put it in perspective the scenarios outlined in paragraph 5.4 will be considered with only one EV. The assumptions made for the calculations are:

- All assumptions as outlined in 5.4
- The solar radiation follows figure 30

- The EV battery is if half full and connected to the grid
- The EV starts charging when the voltage reaches its maximum
- The EV battery has a capacity of 21.15 kWh
- The maximal charging capacity is 3.52 kW

The maximum solar penetration may not exceed 3.52 kW above the calculated value of paragraph 5.4. This because the charger cannot consume more power than the PV system can deliver or the voltage will reach the maximum value.

$$P_{max-from-paragrap-5.4} + P_{charger} = P_{maxsolarpanel} \tag{31}$$

The charge of the battery is now looked at. This is done by looking at the total solar radiation. If the power from the PV system is higher than the level that the grid can accept (if the voltage exceeds the limit), then the charger will start charging so the maximum voltage will always be kept. If the battery is full, the charging will cease. The surface area of graph 31 must therefore be equal to the total charging capacity of the EV.

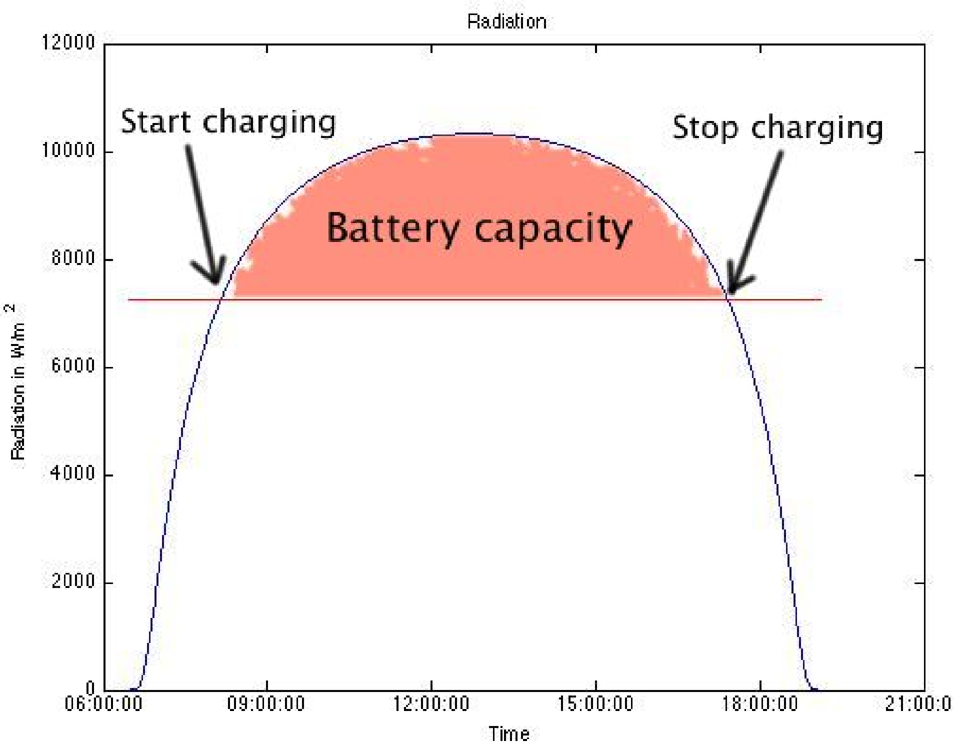


Figure 31: battery capacity

From these calculations it is shown that the bottle neck for the amount of solar panels that can be integrated in the grid, is the capacity of the battery. The battery is full before the maximum charging capacity of the charger is reached. As in paragraph 5.4 table 14 shows how one EV will increase the solar penetration if charging at the first house and last house looking from the transformer. See table 14.

Situation	Maximum power	Percent of average power	with EV	Percent of average power
Solar power at the end of the line	$7250W$	34 %	$9720W$	45%
Solar power at the beginning of the line	$14990W$	69%	$17490W$	81%

Table 13: Overview situations

7 Conclusion and recommendations

In this section the conclusions from the study are given and recommendations are made.

7.1 Conclusion

The main questions that this thesis sought to answer were:

- Where PV penetration levels currently lie on a residential scale.
- How can ELMAR N.V. move beyond that point by adapting the electrical network locally.

The answer to the first question was answered through a series of subquestions. Firstly literature research was carried out to ascertain what has already been researched. Before the literature review some boundaries needed to be set. These boundaries are set by the grid operator of Aruba (ELMAR). The main boundaries are:

- Voltage of 127V line to neutral and 220V from line to line with an voltage swing of +/− 4%.
- Power factor not lower than 0.9 for houses hotels business.

From the literature research one main issue arouse that can limit the penetration of a PV system. The limit is:

- Voltage rise effect

After establishing what the limit factor would be for the penetration of the PV system, the parameters for this limit were determined. The parameters that needed to be ascertained were the impedance of the grid and the transmission line (see figure 4). Once these parameters were established, a method for calculating and measuring the parameters was needed. For the parameter Z_s an off line method was developed (see 4.2.3). For the Z_L formula a measure and calculating method was used (see 4.3). The result of the off line method is that the impedance of the grid Z_s is determined by the transformer. The impedance of the line is mostly determined by the inductance of the line and partly by the resistance. A neighborhood was selected to represent the whole island. The assumption was made that if the maximum PV penetration for this neighborhood is calculated, that it will generally be a good representation for the PV penetration on Aruba. Three scenarios were then explored which represented the minimum, maximum and average PV penetration. The results can be seen in table 14. It must be said that this is not the percentage of energy that a PV system will deliver, only the maximum rated power of the PV system that can be installed in the neighborhood.

Minimum	$7250W$	34 % of average power
Maximum	$14990W$	69 % of average power
Average	$11850W$	55% of average power

Table 14: Overview situations

For the second part of conclusion, future possibilities are discussed. The three possibilities that have the most potential for increasing the PV penetration are:

- Reactive power
- Automatic tap change
- Electric vehicles

An overview of all the possibilities are summarized in table 15. For each possibility three scenario's are given. For the meaning of these scenarios see 5.4. Also a percentage of average apparent power that the neighborhood uses is given.

Configuration	Real power	Reactive power	Apparent power	Percent of average apparent power
Reactive power				
Solar power at the end of the line	7250 W	1083 VAR	7330 VA	34%
Solar power at the beginning of the line	14990 W	1083 VAR	15029 VA	70%
Solar power is distributed over all houses	11850 W	1083 VAR	11899 VA	55%
Tap changing method				
Solar power at the end of the line	9870 W	0	9870 VA	46%
Solar power at the beginning of the line	24240 W	0	24240 VA	112%
Solar power is distributed over all houses	15670 W	0	15670 VA	73%
EV				
Solar power at the end of the line	9720 W	0	9720 VA	45%
Solar power at the beginning of the line	17490 W	0	17490 VA	81%

Table 15: Overview situations

In its current state, the grid can handle approximately one PV system of 50% of the average apparent power usage. This is not much compared to the future plans of the government. For that reason the recommendation is to implement the option which has the best results. This is the implementation of 'automatic tap changing'. It has the highest potential and will help Aruba to take one step closer to reach the goal of being fully sustainable. Reactive power and EV can certainly help to improve the PV penetration. But these solutions alone will make a small impact.

8 Future recommendations

- More research needs to be made for the integration of EV. It has a high potential if a significant number of EV are integrated. But by their very nature, EV are mobile, so the question is whether they could still make a big and reliable enough difference to the PV penetration on Aruba.
- There needs to be a change in the regulations by the grid operator to further increase PV penetration. If the voltage swing increased by a half of one percent then it could swing by 1.3 V more and could have the same effect as the 'automatic tap change' which only increases the voltage swing by 1.1 V.
- Reactive power should be studied, but more from a economic point of view. If reactive power was locally produced then electric losses would be reduced, which in turn would mean reduced financial losses.

A Appendix

Here the total harmonic distortion is worked out:

$$THD = \frac{V_{2th}^2 + V_{3th}^2 + V_{4th}^2 .... + V_\infty^2}{V_{fundamental}^2} = \frac{\sum_{i=2}^{\infty} V_i^2}{V_{fundamental}^2}$$

$$THD = \frac{I_{2th}^2 + I_{3th}^2 + I_{4th}^2 .... + I_\infty^2}{I_{fundamental}^2} = \frac{\sum_{i=2}^{\infty} I_i^2}{I_{fundamental}^2} \tag{32}$$

B Appendix

In this section the practical side is shown, how the measurement is done in real life, what the specifications of the measuring system is and also the information plate of the transformer. Finally the impedance graphs for different transformers is shown.

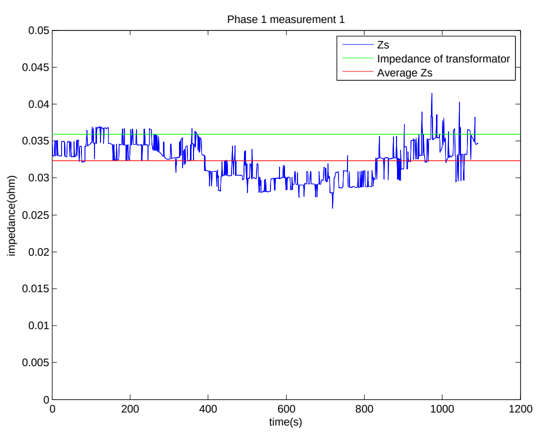
Figure 32: Measurement in mast

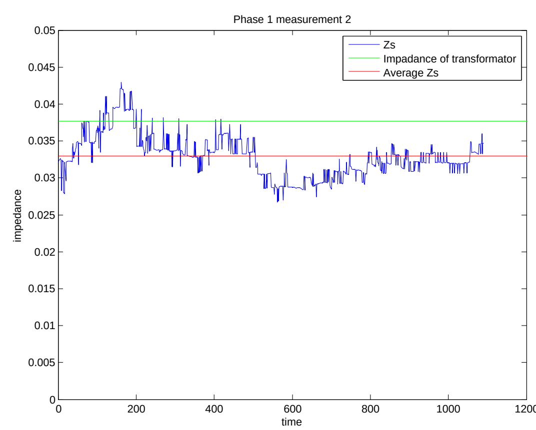
Measurement Type	True RMS using high-speed digital signal processing (DSP)
Line Frequency	DC/50/60/400Hz
Waveform Sampling	12 kHz
Channel Sampling Rate(internal sampling)	200 samples/cycle at 60Hz,240 samples/cycle at 50Hz,30 samples/cycle at 400Hz
Data Interval	approximately 14,400 measurements, The choices are 1, 3, 15, 30 seconds 1, 2, 5, 10, 15, 20 and 30 minutes
Accuracy	Better than 1 % (<0.5% typical) for V, A, kW, kVAR, kVA, PF

Table 16: Specifications Elitebox

Figure 33: Transformer information plate

C Appendix





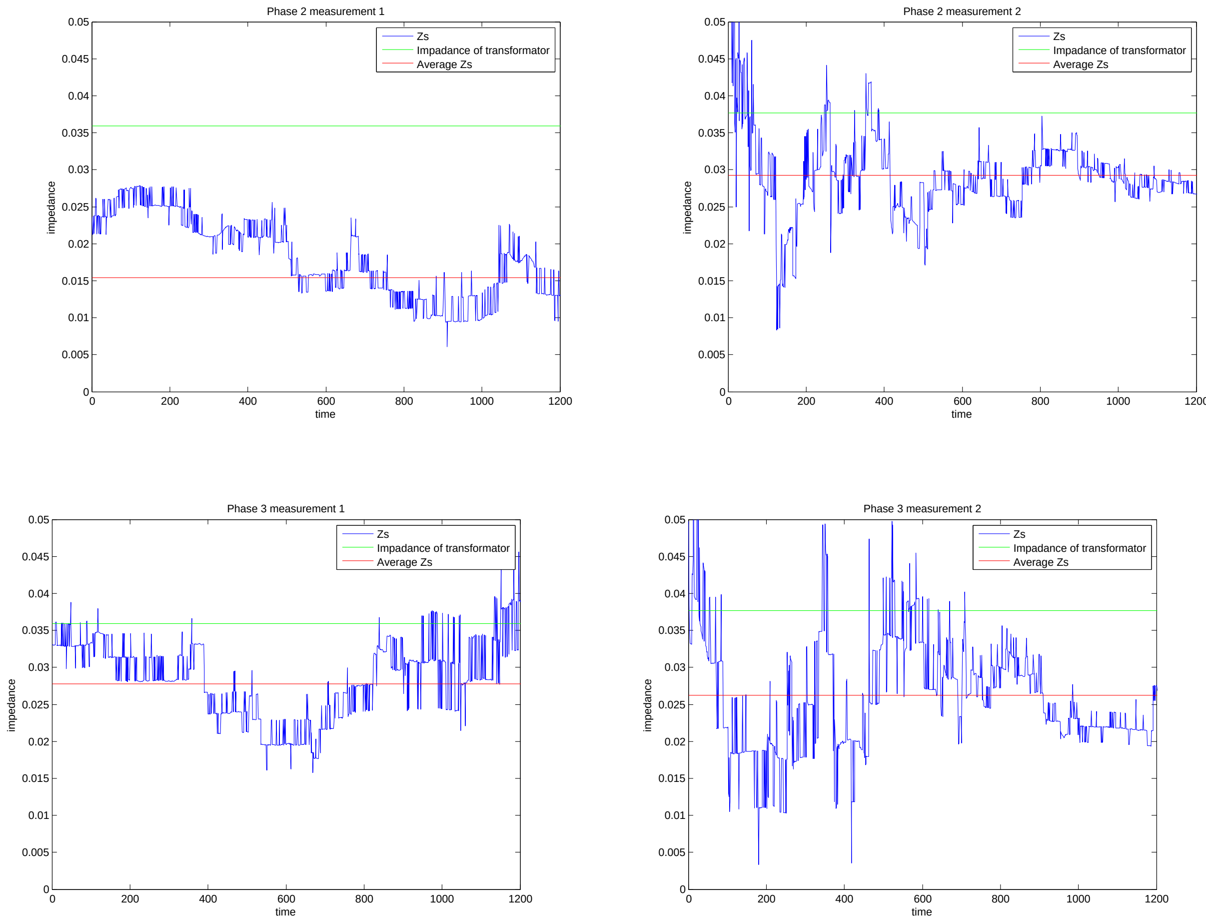


Figure 34: Impedance of 75 kVA transformer

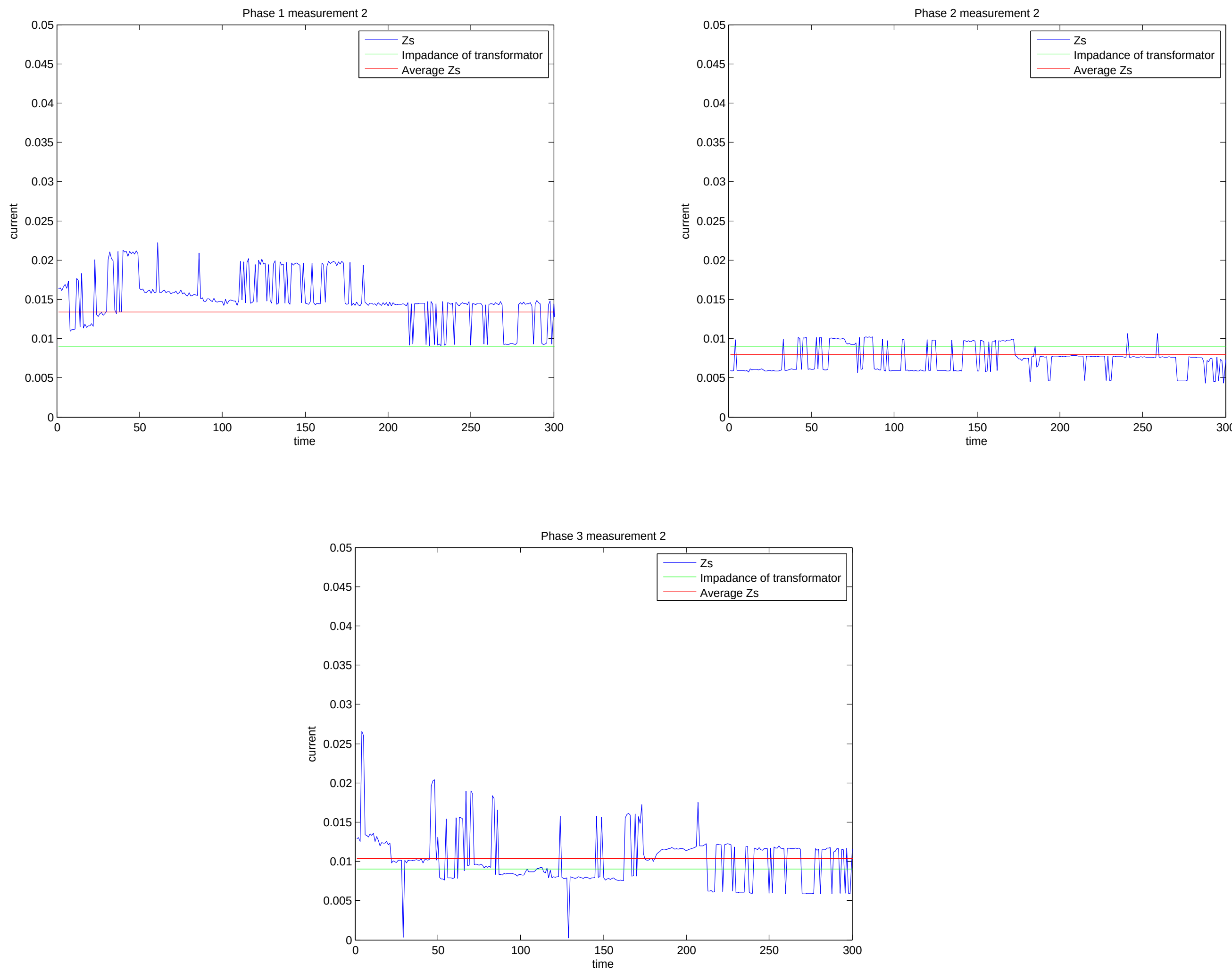


Figure 35: Impedance of 250 kVA transformer

D Appendix

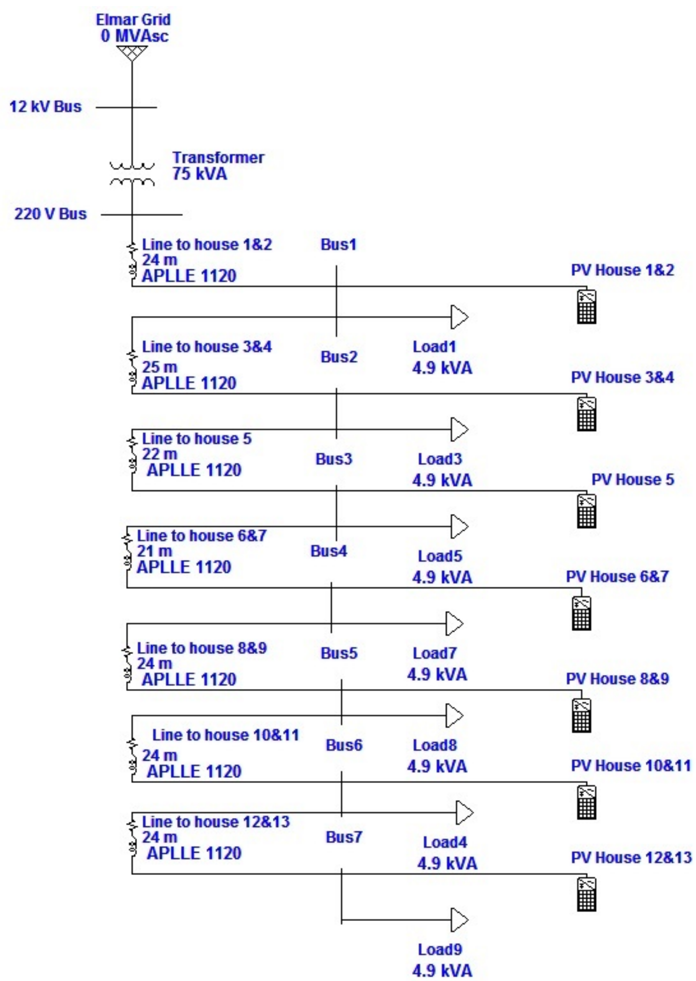


Figure 36: ETAP model Palmbeach

To model the transformer the right parameters need to be filled in to get the right model. For the parameters the information from the transformer is filled. This information can be found on the transformer plate (see 33).The information that isn't on the transformer plate is the X/R ratio. For this the button "Typical X/R" is selected. An example is given in the figure 37.

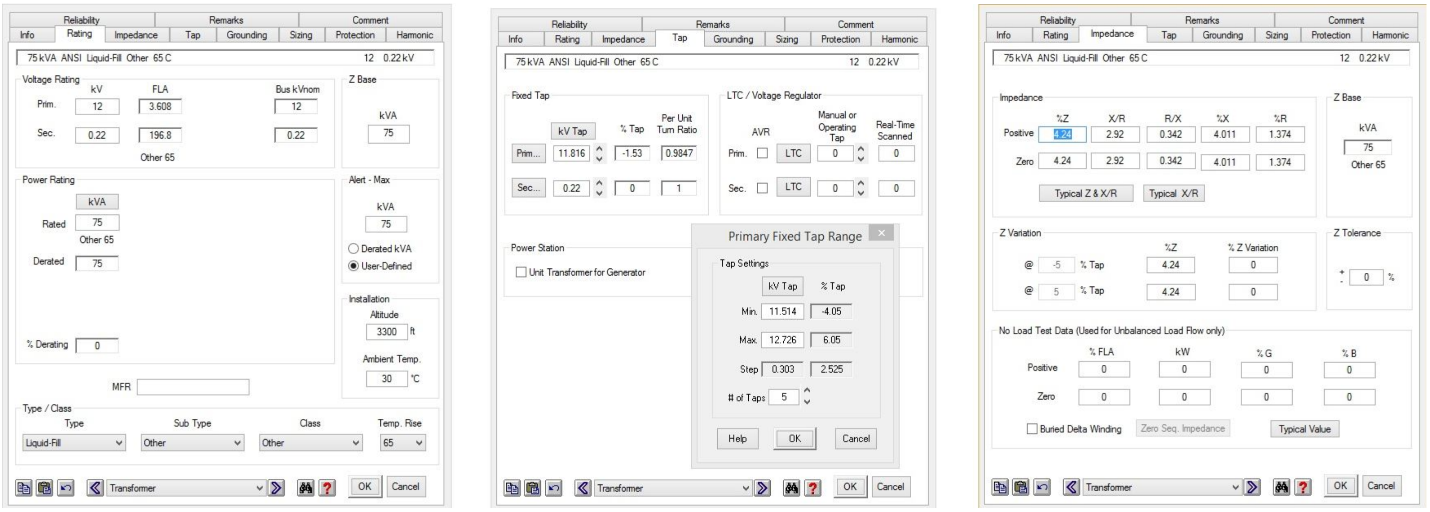
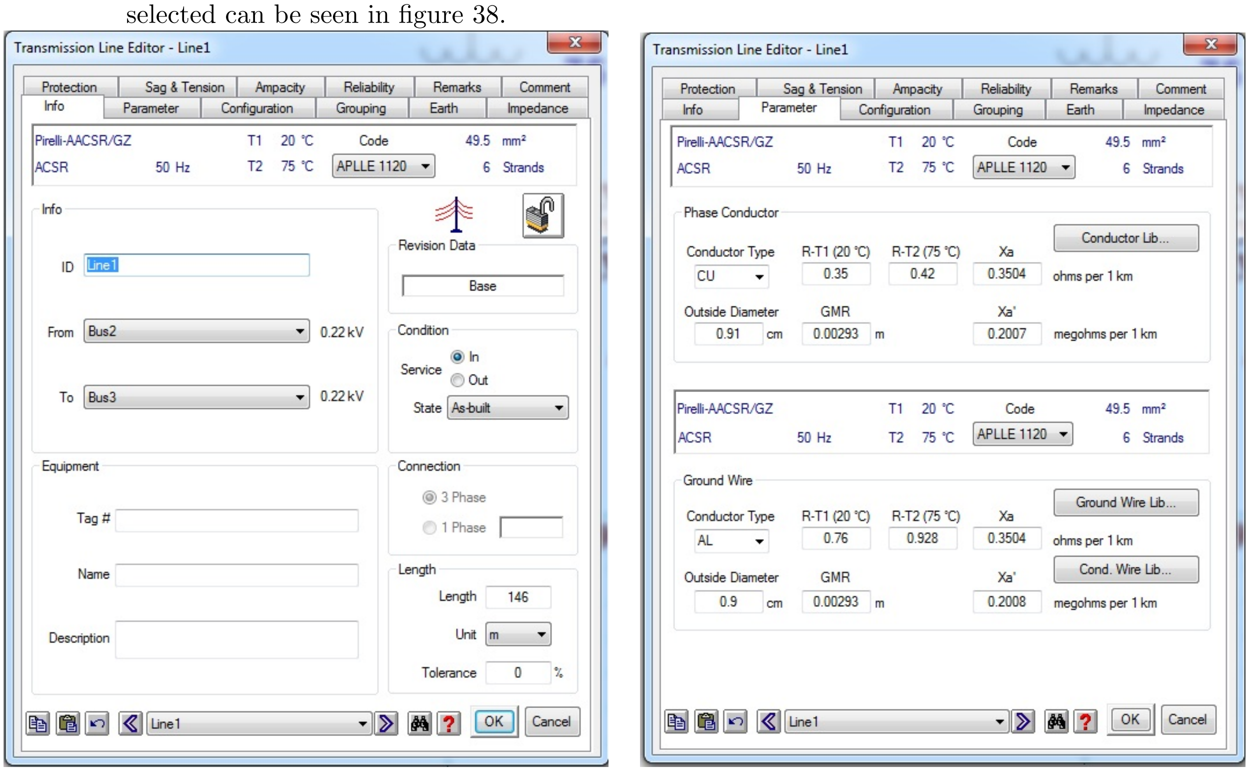


Figure 37: ETAP transformer settings

The line parameters have been chosen from the data sheet. The parameters selected can be seen in figure 38.



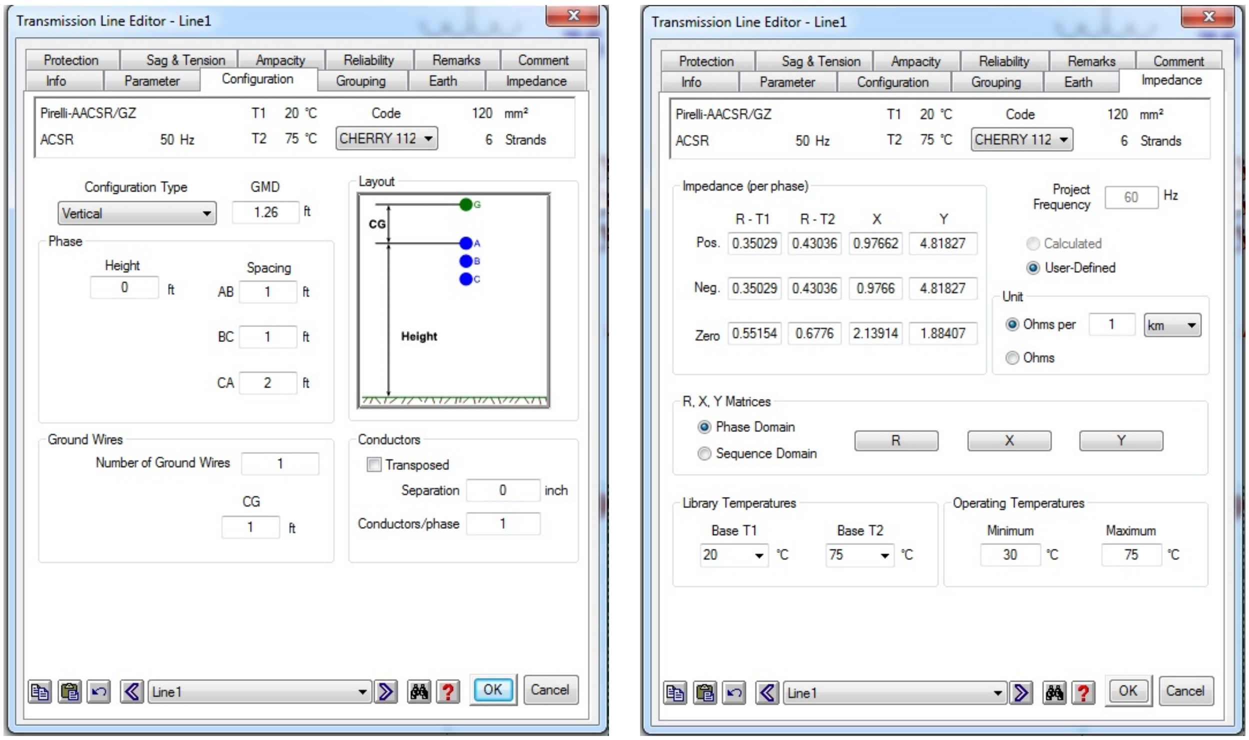


Figure 38: ETAP line settings

E Appendix

If there is a phase shift zero between the voltage and current, than there is only real power. If there is a phase shift of 90 degrees that there is only reactive power. From figure 39 it can be seen that there is a phase shift between the current and voltage. For this example there is reactive power and active power. The power is mostly positive but sometime negative. The negative part is due to reactive power. If the reactive power is zero, and the real power is constant, than the current is less and less losses are made over the grid lines. This is the reason that grid operators don't like reactive power. Also the customer only pay for the real power and not for the reactive power.

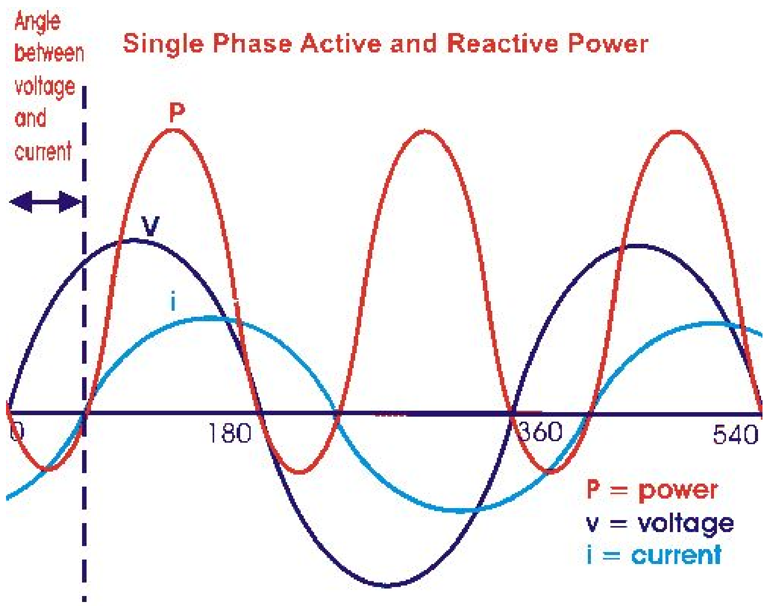


Figure 39: Reactive and real power

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