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Probability of islanding in utility networks due to grid connected photovoltaic power systems

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Task V
Grid Interconnection of Building Integrated
and Other Dispersed Photovoltaic Power Systems

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PROBABILITY OF ISLANDING IN UTILITY NETWORKS DUE TO GRID CONNECTED PHOTOVOLTAIC POWER SYSTEMS

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FOREWORD

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) which carries out a comprehensive programme of energy co-operation among its 23 member countries. The European Commission also participates in the work of the Agency.

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D agreements established within the IEA, and, since 1993 its participants have been conducting a variety of joint projects in the applications of photovoltaic conversion of solar energy into electricity.

The members are: Australia, Austria, Canada, Denmark, European Commission, Finland, France, Germany, Israel, Italy, Japan, Korea, Mexico, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

This report has been prepared under the supervision of PVPS Task V by

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in co-operation with experts from the following countries:

Australia, Austria, Denmark, Germany, Italy, Japan, Mexico, Portugal, Switzerland, the United Kingdom and the United States

and approved by the PVPS programme Executive Committee.

The report expresses, as nearly as possible, an international consensus of opinion on the subjects dealt with.

SHORT ABSTRACT AND KEYWORDS

This report summarises the results on a study on the probability of islanding in power networks with a high penetration level of grid connected PV-systems. The results are based on measurements performed during one year in a Dutch utility network. The general conclusion is that the probability of islanding is virtually zero for low, medium and high penetration levels of PV-systems.

Keywords: Utility power network, Islanding, High penetration level of PV-systems, probability, risk analysis, grid connected.

SUMMARY

Many international forum discussions have been dealing with ‘Islanding’. Islanding is when a disconnected part of the power network is sustainable powered by the connected PV-systems or other embedded generators for a period of 5 or more seconds.

A general conclusion of these discussions was that views on the subject are very polarised. On the one hand, the islanding phenomenon is considered such a rare or improbable event that it does not merit special consideration. On the other hand, the mere theoretical possibility of unintentional islanding, confirmed in laboratory experiments, is sufficient for individuals to have great concerns over the possibility of islanding. The reality probability lies somewhere between the two extremes. An important issue here is the lack of any real data on how often and for how long islanding can occur in practice and the associated risk of occurrence. An important observation in the discussion about islanding is that the discussion is based on “personal feelings” and/or “intuition”, which make the discussions even more difficult.

Various theoretical studies have been made to determine how often islanding can occur in a real power network. Disadvantages of these theoretical studies are the assumptions made to simplify the analysis. The results of these studies are therefore often disregarded.

In the Netherlands, an intensive study was made in an attempt to help the discussion and to provide real numbers on how often and for how long islanding can occur in a distribution network. This study is to measure the loading of a representative residential area together with the power produced in a PV-system. The measurements (active and reactive power) were taken every second for two years and stored in a computer for off-line analysis. The off-line analysis is possible due to the direct correlation between the loading of the network and the power produced by the PV-system. This analysis result in actual figures, which predict precisely how often and for how long islanding can occur in the residential area studied.

The main conclusions of this study are:

☞ The maximum PV-power in a power network for which balanced conditions never occur is approximately two to three times the minimum night load of the relevant power network.

☞ Balanced conditions and subsequently probability of islanding can not occur if PV-systems are installed on every house with a power rating of about 400 W_{peak} or less.

☞ The penetration level of PV-systems does not significantly influence how often and for how long balanced conditions between the load and the PV-systems occurs.

☞ Balanced conditions between active and reactive load and the power generated by the PV-systems do occur very rarely for low, medium and even high penetration levels of PV-systems.

☞ The probability of a balanced condition does not depend on the number of houses connected to a feeder.

☞ The probability of occurrence of a balanced condition in a low voltage power network is well below 1E-6 to 1E-5.

☞ The probability of encountering an island is virtually zero!

The overall conclusion of the work performed in this study is:

Balanced conditions occur very rarely for low, medium and high penetration levels of PV-systems. The probability that balanced conditions are present in the power network and that the power network is disconnected at that exact time is virtually zero.

Islanding is therefore not a technical barrier for the large-scale deployment of PV-system in residential areas.

1. INTRODUCTION

1.1 Why this study ?

Large centralised power generators supply the power network with electrical energy and are connected to the high voltage power network. This energy is distributed via the high, medium and low voltage networks to the loads. The design of the power network is based on this unidirectional power flow. Decentralised power generators have been growing in numbers and in popularity in the last years. These decentralised power generators are found in large industries and are mostly connected to the medium voltage power network. When comparing PV-systems with large and decentralised generators the following differences are found:

- Small in power rating
- Connected to the low voltage network
- Owned and operated by non-professionals
- Low cost
- Not controllable

For correct operation of the power network it is essential that the voltage, frequency and voltage waveform be kept within specified limits. These limits are clearly described in various power quality standards. Faults in a power generator or in the power network must be located and disconnected quickly to minimise the effect on the power quality of the network and to prevent damage in the network and/or generator. Every generator must be equipped with a protection device to disconnect the generator from the power network in case of a failure or when the performance of the network is outside the required limits. The basic protection devices for generators are over/under voltage protection and over/under frequency protection. For larger generators other, sometimes very sophisticated, protections are used.

Maintenance in a power network is another reason why every generator must be provided with a protection device. Maintenance must be carried out while a part of the power network is de-energised and safely grounded. The protection must detect whether the network is de-energised from the main supply side. With many PV-systems connected to a low voltage power network it is not feasible that every PV-system is manually disconnected before maintenance is performed.

When many PV-systems are connected to a low voltage power network it is possible for the power generated by the PV-systems to exactly equal the power consumed by the loads in that network. In this situation there is no power flow from the main supply at the distribution transformer. If the power transformer is disconnected it may be possible that the PV-systems maintain the voltage in the network feeding all connected loads. This situation is called islanding. An unintentional island is not acceptable by any power utility. Some utilities may be able to accommodate an intentional “Island Mode” operation, but only in exceptional circumstances, which is not relevant for residential areas.

Experiences with islanding conditions in power networks are internationally not reported. Countries with several decades of experience with high penetration levels of combined heat and power (CHP) and/or with large-scale integration of wind turbines have not reported any experience or incidents of islanding.

To prevent islanding different protection schemes have been developed. In some countries very complex protection schemes are mandatory, while other countries require a simple protection scheme. The additional costs for a complex protection scheme sometimes become significant especially for smaller PV-systems.

Many international forum discussions have not resolved the issue of different protection schemes for PV-systems. A general conclusion of these discussions was that views on the subject are very polarised. On the one hand, the islanding phenomenon is considered such a rare or improbable event that it does not merit special consideration. On the other hand, the mere theoretical possibility of unintentional islanding, confirmed in laboratory experiments, is sufficient for individuals to have great concerns over the possibility of islanding. The reality probability lies somewhere between the two extremes. An important issue here is the lack of any real data on how often and for how long islanding can occur in practice and the associated risk of occurrence. An important observation in the discussion about islanding is that the discussion is based on “personal feelings” and/or “intuition”, which make the discussions even more difficult.

Various theoretical studies have been made to determine how often islanding can occur in a real power network. Disadvantages of these theoretical studies are the assumptions made to simplify the analysis. The results of these studies are therefore often disregarded.

The Netherlands decided, in close co-operation with the international experts in the IEA-task 5 working group, to start a measuring programme to provide these numbers. This is an attempt to help the discussion and to provide real numbers on how often and for how long islanding can occur in a distribution network. The results of this work are described in this report.

A residential area with a high penetration level of PV-systems is not currently available. A few locations with a relatively high penetration level are available but these locations are not accessible for the required measurements or are not suitable due to some electrical constraints in the electrical layout of the network. A different approach was found to measure the loading of a representative residential area together with the power produced in a PV-system. The measurements were taken every second for two years and stored in a computer for off-line analysis. The off-line analysis is possible due to the direct correlation between the loading of the network and the power produced by the PV-system. This analysis result in actual figures, which predict precisely how often and for how long islanding can occur in the residential area studied. The residential area studied is representative of many residential areas in participating IEA countries.

1.2 Definition of islanding

Islanding is the electrical phenomenon in a section of a power network disconnected from the main supply, where the loads in that disconnected section are entirely powered by PV-systems and where the voltage and frequency are maintained around nominal values.

At the point of disconnection of an island it is essential that the active power and reactive power at the point of disconnection be very close to zero [2], [3] and [4]. The disconnection of the islanding must also happen without introducing a short circuit between the phases and/or between one phase and ground. Any fault forces the voltage to a very low value and all PV-systems will immediately switch off and islanding will not occur.

In the IEA task V working group it was decided that the lowest level of islanding is at the lowest switching point in the power network. This is at the fuses or disconnecting means in the low voltage cable or line close to the distribution transformer. In practice this means a few houses up to a few hundred houses connected to one distribution transformer.

Islanding is a balanced condition in a disconnected part of a power network where the load is sustainable powered by the connected PV-systems. A balanced condition of only a few seconds is not categorised as a sustainable power balance. Within the IEA task V working group a period of 5 or more seconds is treated as a possible islanding.

☞ Islanding is when a disconnected part of the power network is sustainable powered by the connected PV-systems or other embedded generators for a period of 5 or more seconds.

1.3 How to read and use this report

The methodology on how this study was conducted is described in chapter 2. This chapter explains how the measurements are made and how the data are analysed. The selected residential area where the measurements have been made is described in chapter 3. The measuring system and data logging system are described in chapter 4. The first analysis of the data to determine for what PV-penetration level islanding may occur is described in chapter 5. The methodology of the data analysis on how often and for how islanding occurs for the various PV-penetration levels is explained in chapter 6. Chapter 7 describes the results when analysing the data for active power balance only, while chapter 8 describes the results of the analysis for the combination of active power and reactive power balance. The probability of encountering an island situation is discussed in chapter 9. Final conclusions and recommendations are given in chapter 10.

The report is written in chronological order matching the stages of the work. Correct interpretation of the conclusions and recommendations is not possible without a thorough understanding of the methodology. We therefore suggest that this report is red chapter by chapter, and that the methodology described in chapter 2 is carefully studied.

To fully understand the contents of this report it is expected that the reader is familiar with the design, operation and behaviour of electrical power networks. Readers are kindly requested to interpret the information in this report very carefully as misinterpretations are easily made.

The report contains many figures and charts. Much effort has been made to produce figures and charts that are self-explanatory. The reader is guided through these figures and charts with as little as possible explanatory text.

At a few locations ‘rules of thumb’ are derived from the observations. These are identified as with the symbol ☞.

2. METHODOLOGY

The probability of islanding in a distribution network with a high penetration level of connected PV-systems is difficult to obtain because such a distribution system is not (yet) present in the world. A few residential areas are present in the world in which many PV-systems are installed but these systems are not suitable for an intensive programme of measurement to determine the probability of islanding because of technical constraints and/or organisational difficulties. To overcome these problems a special measuring system was developed to obtain information on how often and for how long islanding can occur in a distribution network without the need of many PV-systems.

This measuring and data logging system is designed on the idea to measure the load of all outgoing Bays of a distribution transformer and to simultaneously measure the power produced by a single PV-system. The load and power produced by the PV-system is time-correlated and offline data analysis is possible when logging the measured parameters on a computer system. The sample rate must be sufficient to capture the electrical phenomena of islanding. Islanding of distribution networks happens within the range of seconds. A suitable sample rate is therefore a 1-second interval. The loading of a power network and the power produced by a PV-system varies for the different seasons. Hence, the measuring time must be at least 1 full year to capture seasonal influences.

The power produced by a single PV-system will, by far, not be sufficient to equal the loading of the distribution network. Direct comparison of the data for the loading and the power produced by the PV-system is therefore not possible. When multiplying the power produced by the PV-system with a constant factor it is possible to vary ‘by calculation’ the penetration level of PV-systems connected to the power network. When comparing the actual load of the network and the increased PV-power, possible balanced conditions can be determined. This comparison can be repeated using different multipliers, thus varying the penetration level of PV-systems in the power network. Multiplying the PV-power does not introduce significant inaccuracies as the PV-power is based on actual measured data that have a direct time relation with the measured load of the network. The only assumption made is that ‘all PV-systems’ have an identical orientation towards the sun and that the power electric inverters have identical characteristics.

The multiplier can have any value to simulate low, medium or high penetration levels of PV-systems. A realistic multiplier value can be determined by looking at the available roof-space on the houses connected to the distribution network or can be determined by calculating the ratio between the load and the PV-power. The ratio is calculated for every measured sample over the year. The ratio that occurs most frequently is the ratio for which balanced conditions between the load and the PV-system occurs most frequently. The data can then be analysed by comparing the load with the power of the PV-system multiplied by the ratio found. This comparison can be repeated for lower ration values and for higher values, to obtain information about the occurrence of islanding for different penetration levels of PV-systems. This approach is made from an electrical perspective and the results must be evaluated how reasonable the used multiplier values are in terms of available roof surface for PV-systems.

The number of houses connected to one distribution transformer varies in different countries. Some countries use pole mounted transformers feeding a few houses, while large distribution transformers are used in other countries feeding up to several hundreds of houses. The residential area where the measurements are made must be acceptable for all those countries. The selected residential area in the city of Arnhem - The Netherlands, has 5 outgoing Bays and every phase feeds from 2 up to 82 houses. The measurements are made on an individual phase level. The analysis for balanced conditions for various penetration levels is made for every individual Bay and phase. It is important to include active and reactive power flows during the analysis. The measuring system is equipped to measure and log both active and reactive power of all outgoing Bays, phases and the PV-system.

Apart from PV-systems other small generators may be connected to low-voltage distribution networks. Examples are micro-combined heat and power installations that provide a house or a block of houses with warm water and space heating and producing electricity as a by-product. These generators are from the perspective of islanding very comparable. Such systems are becoming, or will be in near future, commercially available on the market. To make islanding studies for this type of generator possible, the speed of the wind and the ambient temperature parameters was be measured. These two parameters have a good correlation with the demand for space heating of a house. This report does not include the analysis for the probability of islanding for such generators.

The quantity of data obtained by the measuring and logging system is vast. In total 49 parameters are logged every second during 24 hours per day and night and for one whole year. The size of the data set is about 9 GB and it is analysed several times.

The evaluation of the data is made on the whole data set. Although, analysing the data set for a restricted number of samples is possible when using statistical techniques it was decided not to do so. When using statistical techniques the results may be disputable as people could argue about the statistical techniques used. To eliminate any discussions on how the analysis was made we decided to make the evaluations on the whole data set.

When comparing the load of the network with the PV-power multiplied by a constant factor two parameters can be varied. One is the constant multiplier with which the PV-power is multiplied. The second variable is the margin used when comparing the load of the network with the PV-power multiplied by the constant factor. This margin is very important as too small a margin gives a low number of balanced conditions, while too large a margin gives a high number of balanced conditions. In the analysis the margin can be set at any value: 2%, 5% or even 20%. The best and most realistic margin is difficult to determine as the margin represents the mismatch to be allowed between the active power and the reactive power for which an island can remain stable or becomes unstable. In an unstable island the voltage and/or frequency in the island goes outside the protection settings in each PV-inverter resulting in a disconnection of the PV-systems. The experience of experts in the field of network stability shows that a lack or surplus of even a few percent of active or reactive power in a network significantly effects the voltage and/or the frequency [3] and [4]. The evaluation of the data is made using a small margin but also for a large margin that is beyond from what is acceptable from an electro-technical point of view regarding power network stability. This is done not to make any pre-assumption that may result in discussion of the validity of the results of the study.

3. RESIDENTIAL AREA

3.1 General description of the residential area

A residential area is selected that is representative as a modern area with a good mixture of types of dwellings and inhabitants. The area is comparable with residential areas in various European countries. Also, a good match with residential areas for example in the US, Australia is present.

The selected residential area was discussed with the IEA Task V working group. The participating countries agreed that the selected area is a good or acceptable representation of a residential area in their countries. A general conclusion is that the selected area is not representative for densely populated multi-level housing estates, but high penetration levels of grid connected PV-systems are not possible for such a residential area. An overview of the selected residential area is given in figures 3.1 and 3.2.

Figure 3.1 Overview of the suburb “Rijkerswoerd” in the city of Arnhem – the Netherlands

The selected residential area is part of the new suburb “Rijkerswoerd” located south of the city of Arnhem in the Netherlands. The selected area was built in the early nineties. The selected area ‘electrically’ includes about 240 houses. Detailed information on the type of houses, inhabitant, appliances and energy consumption is given in chapter 3.2.

The Dutch electrical supply system has power transformers located at various locations in the suburb. Every power transformer feeds approximately 200 to 300 houses. Cables directly buried in the ground make all medium voltage and low voltage power connections between the power transformer(s) and between transformers and the houses. Detailed information about the electrical supply system is given in chapter 4 and [1].

Figure 3.2 Overview of the suburb “Rijkerswoerd” in the city of Arnhem – the Netherlands

3.2 Characterisation of houses and electrical loads

The dwellings in the selected residential area include several types of houses. The table 3.1 shows an overview of the type of houses and the percentage in the total number of houses in the residential area. The percentages are not the average for The Netherlands, as the selected residential area is a more up-market area with large houses. For the purpose of the study this is an ideal situation as high penetration levels of PV-systems are possible due to the large roof area and the inhabitants have a relatively high income.

Type of house	%	General characteristics
Apartment	5%	Apartment small 3-story flat normally occupied by 1 or 2 persons. Figure 3.2 - right-hand side.
Terraced	20%	House normally occupied by family of 2 to 4 persons. The houses are build together side-by-side. Centre of figure 3.2.
Semi-detached	70%	Family house normally occupied by family of 2 to 4 persons. Two houses are build side-by-side with gardens on the other sides. Figure 3.2 – Houses with the red tiles.
Detached	5%	Family house normally occupied by family of 2 to 4 persons. Every house has a garden on all four sides.

Table 3.1 Overview of types of houses in the residential area.

A questionnaire was submitted to all families in the residential area, requesting information about the energy consumption and patterns. The response to the questionnaire was 70%. The information below is taken from the questionnaire.

The number of inhabitants per house is given in figure 3.3. Most of the families have two or four persons. It is obvious that two children per family is very popular. The residential area is 8 years old. For most of the families it's their second house after marriage which means that the average age of the adults is about 35 to 40 years. The children are in the age of 3 to 17.

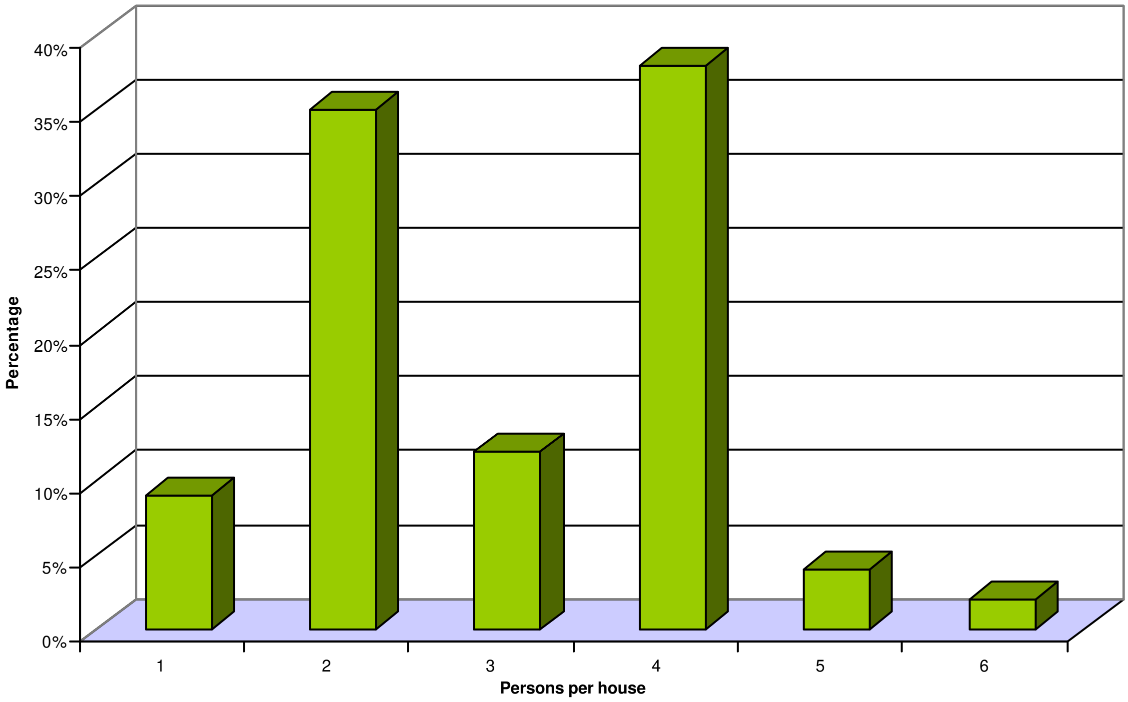


Figure 3.3 Number of persons per family in the selected residential area.

Nearly all houses have a washing machine and about 70% also have a tumble dryer. About 75% of the houses have a dishwasher. The energy consumption of these appliances is high and for this study it is important to have some understanding of when the inhabitants use these appliances. One of the questions in the questionnaire was when the different 'washes' are made.

Figure 3.4 shows the percentage of these 'washer' per hour of the day. Some differences are observed during weekdays and weekends. Washing on Saturday and Sunday is popular. Washing activities are most frequent in the late morning and early afternoon. The dishes are done after dinner. The peak at 23.00 hours originates from the double tariff-system. Low tariff (7 Euro-cent per kWh) starts at 23.00 hours. High tariff (11 Euro-cent per kWh) starts at 7.00 in the early morning.

Other large electrical appliances are not significantly present. The penetration level of air-condition units is nearly zero. A few houses have electrical cooking, but gas is mostly used. Space heating is always gas-fired. The average annual energy consumption per house in the Netherlands is 3.200 kWh.

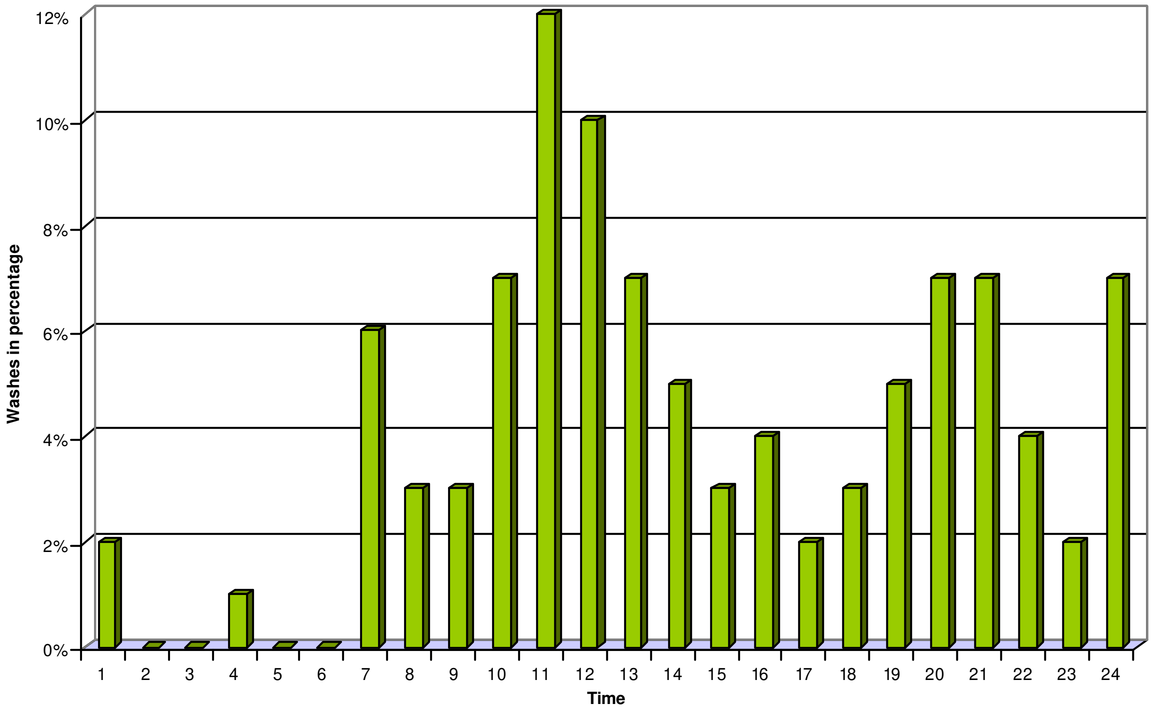


Figure 3.4 Number of washes (for clothes, dryer and dishes) during the day.

3.3 Electrical supply system

The medium voltage distribution system in the Netherlands is a three-phase 10 kV system. Distribution transformers are located between the houses and have an average power rating of 630 kVA. Every transformer feeds approximately 200 to 300 houses. The 10 kV distribution network is a meshed system but is operated in a radial configuration. Additional details on the typical configuration of the Dutch power network are given in [1].

The 230 Volt low voltage cables run from the distribution transformers through the streets. At every house a cable-joint is made to feed the energy into the house fuse-box. Every house is supplied with a three-phase voltage but normally only one phase is connected. The connection to every house is made in a sequential order: red – yellow – blue – red – yellow ect. This ensures a well-balanced loading of the distribution transformer. The low voltage cables are operated in a radial configuration. A very few houses have a three-phase connection for electrical cooking.

The low voltage cables have a nominal cross section of 240 mm^2 and have aluminium conductors. A separate neutral and ground conductor is fed into each house and is directly connected to the main grounded start point of the distribution transformer.

Figure 3.5 Power distribution cabinet with power transformer and low voltage busbar.

The low voltage busbar system in the selected residential area has 6 Bays. Table 3.2 shows the number of houses connected to each Bay. Bay 7 is the feeding point from the distribution transformer to the low voltage busbar system. Bay 1 is used for public lighting and is automatically switched on during the night. Clearly, this Bay has no relevance to the work described in this report. The phase voltage of the main busbar is measured together with the phase currents in every Bay (1 trough 7). Additional details of the measuring system are given in chapter 4.

Bay	**Houses connected phase Red**	**Houses connected phase Yellow**	**Houses connected phase Blue**	**Average houses per phase**	**Total houses connected to the Bay**
1	Public lighting for street lights is only active after sunset				
2	2	2	3	2,33	7
3	18	16	16	16,67	50
4	25	26	27	26	78
5	17	20	18	18,33	55
6	20	19	17	18,67	56
7	82	83	81	82	246

Table 3.2 Overview of houses connected to the Bays of the low voltage busbar system

One of the main reasons why this residential area was selected is that the number of houses connected to the different Bays varies significantly. Bay 2 supplies only a very few houses while the Bays 3, 5 and 6 supply approximately 50 houses. The Bay 4 includes some day-and night-care units for disabled persons. Every unit has 5 to 10 persons. The units have a relatively high day-loading profile, for washing and lighting. This effect can be seen in the analysis on the occurrence of islanding as described in the chapters 7 and 8. Bay 7 supplies the whole selected residential area of 246 houses and is the sum of the Bays 1 through 6.

Typical measured load profiles of the selected distribution network are included in the annexes 1 and 2. The annexes show the 5-minutes averaged load profile at the transformer level (Bay 7) and for a few houses in Bay 2. Annex 1 shows the load profile for July 15 – 1999 (minimum load) and annex 2 shows the load profile for December 15 – 1999 (maximum load). The load profile for Bay 2 shows sharp peaks in the power consumption. The switching on and off of an appliance is a relatively big change in the total power consumption as this Bay feeds only a few houses. Bay 7 includes 246 houses and the load changes are more averaged. The load profiles given in the annexes 1 and 2 are typical for a Dutch residential area and most probably also for central part and the northern part of Europe.

The power generated by the PV-system mounted on the roof of the transformer cabinet is also given in the annexes. The output of the PV-system is multiplied by a certain value to be in the same power range as the load. The multiplier used is the value as calculated in chapter 5.

The number of houses connected to every Bay of this distribution transformer varies significantly. This is important for various countries with a different configuration of the low voltage distribution system. For example, The United States frequently use pole-mounted transformers supping only a few houses (Bay 2 equivalent). This allows detailed analysis of the probability of islanding for various network layouts and conditions, by comparing the results for the individual Bays we can study the dependability of number of houses versus the probability of islanding.

4. TEST SETUP AND MEASURING SYSTEM

4.1 Test setup

The measuring system must log all electrical parameters of the residential area. The sample rate for the logging of the data must be sufficient to capture the rapid changes in the electrical loading of the network and to capture changes in the power produced by the PV-system. A study performed at KEMA some years ago revealed that a sample rate of 1 second is sufficient to capture these phenomena. This sample rate however results in a huge data flow for storage. Fortunately, modern computer and data logging systems can deal with this huge data flow. Figure 4.1 shows the schematic diagram of the distribution transformer, outgoing Bays and the location of the current and voltage sensors.

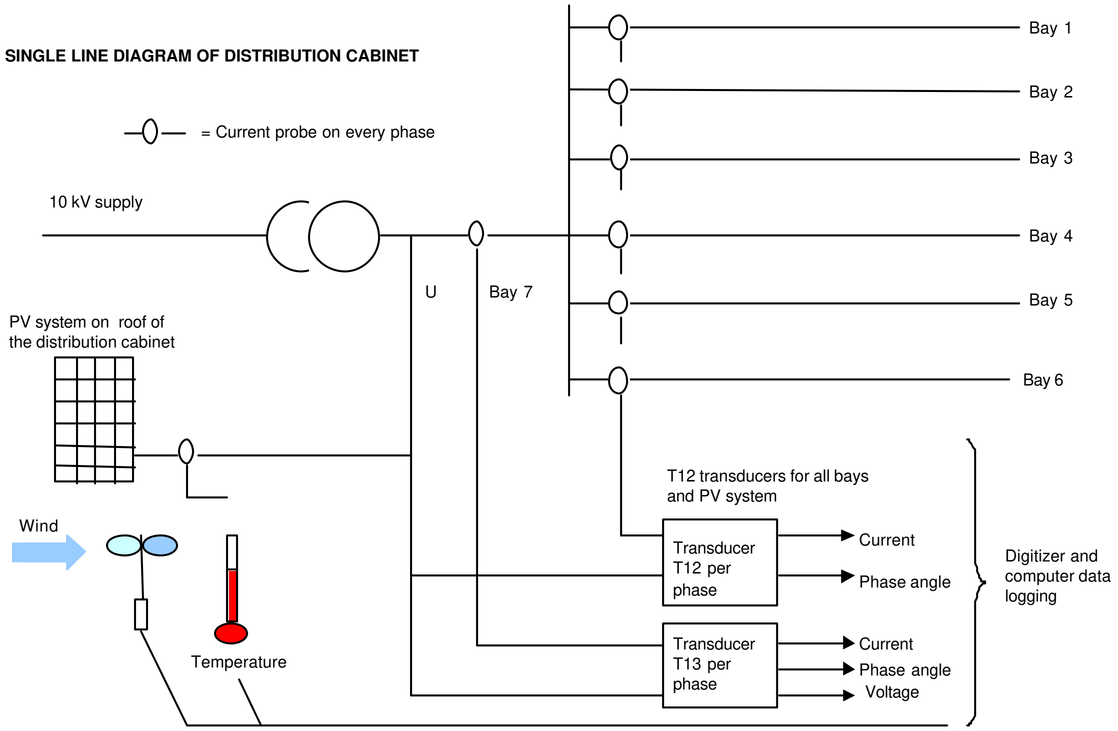


Figure 4.1 Schematic overview of the Bays and the location of the current and voltage sensors.

The measurement of Bay 7 is also used for verification of the integrity of the measurements of the Bays 1 through 6. The summation of the current in the Bays 1 through 7 must equal the current of phase 7. This check is made during the off-line data evaluation.

Every phase conductor of each Bay was equipped with a current probe. The phase voltage was measured at the low voltage busbar. The current and voltage was fed into a power transducer to determine the phase angle between the current and voltage. The transducers return a value in the standardised low-voltage 0 to 10 low voltage signal. The transducers are two-quadrant transducers to measure the positive and negative phase angle (import and export reactive power).

A PV-system was installed on the roof of the distribution transformer cabinet. The PV-system was a 100 W_{peak} PV-module in combination with a 100 W modern power electronic inverter. The PV-system was connected to one phase of the low voltage busbar. The current and voltage of the PV-inverter was fed into a transducer to determine the phase angle of the PV-inverter.

A wind-speed meter and a temperature sensor were also installed on the roof of the transformer cabinet. These values are not relevant for this research work but may be used in a later stage to determine probability of islanding for micro-combined heat power generators. The temperature and wind-speed have a relative good correlation with the heat demand of a house.

The outputs of all transducers were digitised using a multiple channel analogue-to-digital converter. The sample rate of the analogue-to-digital converter was set at 10 samples per second to prevent aliasing. From these samples the average was computed for obtaining the 1-second based data values. All measured parameters are taken at exactly the same time and have an ideal time correlation. Table 4.1 shows the electrical parameters that are logged at a 1-second sample rate.

Voltage	**Current**	**Phase angle**	**Others**
Phase Red Phase Yellow Phase Blue	Bay 1-7 / Phase Red Bay 1-7 / Phase Yellow Bay 1-7 / Phase Blue PV-system	Bay 1-7 / Phase Red Bay 1-7 / Phase Yellow Bay 1-7 / Phase Blue PV-system	Speed of the wind Temperature (both not used for this study)

Table 4.1 Overview measured and logged parameters

The 49 data values were taken every second and stored on the hard disk of a computer together with label for date and time. The measurements were taken for 24 hours per day. Every hour produces about 1 MB of data. Hence, 750 MB of data per month, 9 GB per year. The data was taken from the computer on a monthly basis and stored on CD Roms for off-line evaluation.

The measurements started on May 1st 1999 and continued till April 2001 (2 years). The evaluations for the probability on islanding have been made on the 1-year period from May 1999 to April 2000. A few comparable evaluations have been on the data set from May 2001 to April 2002. These evaluations did not show any significant change in the results.

In the period from May 1999 to April 2000 some errors occurred during the measurements. Some of these errors were due do some software problems and one error is due to a malfunctioning of the computer. The total time ‘missed’ by the data logging system is less than 2 weeks and is randomly scattered over the relevant period of one year. The 1999-European solar eclipse is unfortunately in such a gap in the data. The missing data was corrected during the off-line evaluation of the data values by normalising the results per month.

Figure 4.2 shows an overview of the measuring system. The clip-on current probes are connected to each outgoing phase. The current probes of the main supply between the transformer and the low voltage busbar are visible on the centre-left. The transducers (blue boxes) are mounted on a separate panel. The analogue-to-digital converter is installed on the lower-right corner of the panel. An insulation transformer is used for the power supply of the measuring system. The computer system for data storage is not visible.

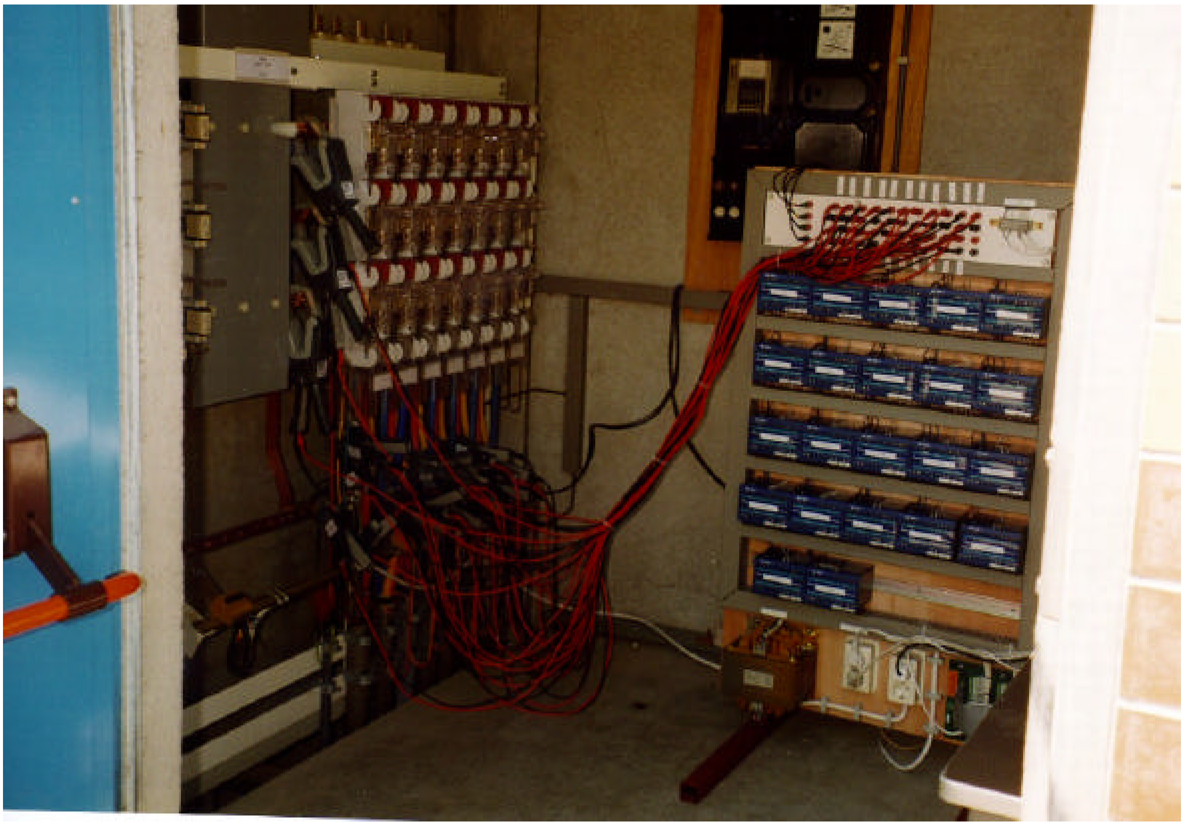


Figure 4.2 Overview of the test equipment, with the clip-on current probes, transducers and data acquisition system

Figure 4.3 PV-panel, wind and temperature sensors on the roof of the transformer cabinet.

Figure 4.3 shows the PV-system installed on the roof of the transformer cabinet. The PV-module is exactly oriented to the south. The speed-wind meter is installed behind the PV-system. The white cylinder mounted on the pole of the wind meter holds the temperature sensor.

4.2 General specifications of measuring system

The measuring system was specially designed for this purpose. All materials used are state-of-the-art of the shelf products. Some minor modifications have been made to the transducers for meeting a sufficient response time. A certified laboratory has calibrated all sensors and transducers. The overall accuracy of the measuring system is better than 3%.

Current probes

High accuracy single phase clip-on current probes with multiple secondary windings. The accuracy class is S1. Manufacturer is ABB.

- Type 1 0 – 500 – 1.000 – 2.000 Amp ⇒ 1 Amp used for Bay 7
- Type 2 0 – 100 – 200 – 400 Amp ⇒ 1 Amp used in Bays 1 through 6

Transducer

Transducers with voltage (230 V) and current (1 Amp) inputs and current and phase angle as outputs. The company Enerdis manufactured the transducers. The transducers have been slightly modified to obtain a response time better than ½ second. This introduces a small increase in the noise level that is filtered in the analogue-to-digital converter.

- Type T12 Input voltage (230 V) and current (1 Amp)
  Output 1 : 0 – 10 Vdc for current equivalent of 0 – 1 Amp
  Output 2 : 0 – 10 Vdc for phase angle equivalent of 0.5 Cap – 0.5 Ind
- Type T13 Input voltage (230 V) and current (1 Amp)
  Output 1 : 0 – 10 Vdc for current equivalent of 0 – 1 Amp
  Output 2 : 0 – 10 Vdc for phase angle equivalent of 0.5 Cap – 0.5 Ind
  Output 3 : 0 – 10 Vdc for voltage equivalent of 207 - 244 Vac

The type T12 is used for the Bays 1 through 6 and for the PV-system. Type T13 is used for the Bay 7. The total number of transducers is 19 for the T12 type and 3 of the T13 type.

PV-system

The PV-system is a single 100 W_{peak} PV-module manufactured by Shell Solar together with an inverter from NKF-electronics type OK4E-100. This NKF inverter is a modern power electric inverter with excellent performance characteristics at low and high levels of solar irradiation. The inverter has unity power factor. The solar panel is oriented to the south. The solar panel is mounted on the “Ecofys Console” and is not subject to shading effects.

Wind and temperature measuring system

The speed of the wind was mounted on a metal post of 1 meters. The temperature was measured with a calibrated PT-100 sensor. This temperature sensor was positioned in a white open cylinder and mounted on the foot of the wind meter. Both sensors are placed on the roof of the distribution cabinet. The values of the speed of wind and the temperature have been measured and stored on the data logging system. These data values are not relevant for this research work.

Data acquisition system

The analogue-to-digital converter is a standard computer IO-card. The card has 64 analogue input and several digital in- and outputs for control. Sampling time of the analogue-to-digital converter is 10 samples per second. The oversampling is used for filtering (moving averaging) of analogue signals to prevent aliasing.

Computer storage system

A computer system is used for data storage. The data from the data acquisition systems was taken every second. The data values were recalculated for obtaining the original primary levels for voltage and current using the ratio of the current probes and the conversion ratio of the transducers. The data values were stored in a data file on the hard disk together with a date and time label. A CD-writer was used for making the data available for off-line analysis.

5. RATIO BETWEEN LOAD AND PV-POWER

5.1 Methodology for the calculation

The PV-power was measured using a single 100 Watt PV-system. This power rating is by far insufficient to equal the loading of the power network. To determine for what PV-power balanced conditions occur we need to study the ratio between the load and the power produced by the PV-system. This is calculated by determining the ratio between the PV-power and the power in every phase of every Bay. In other words how big should the PV-system be to equal the power consumed in the power network. The ratio varies as the loading of the power network and the output power of the PV-system varies in time. The ratio is calculated every second using the equation (5.1):

$$Ratio = \frac{P_{load}}{P_{pv}} \tag{5.1}$$

For example, for a load of 10.000 W and a PV-power of 50 W the ratio is 10.000 / 50 = 200. Hence, if 200 PV-systems had been installed in the power network the power taken from the transformer would have been zero. This situation is then a possible islanding condition. If in the next second, the loading of the network increases to 10.150 W and the power of the PV-system remains at 50 W then the ratio becomes 10.500 / 50 = 210. This calculation can be repeated for every second during the whole year.

In an attempt to reduce the computing time to acceptable levels, the load current and PV-current was used instead of the active power. This assumption may be made since the power factors of both the PV-system and the loading of the network are relatively constant. Also, the ratio is an indication about possible penetrations levels for which islanding may be relevant. Equation (5.1) now becomes:

$$Ratio = \frac{I_{load}}{I_{pv}} \tag{5.2}$$

This calculation was made for every second during the whole year. The time frame for the calculation was always from 7.00 hours in the morning up to 21.00 hours in the evening. The calculation was only made for a PV-current equal of above 30 mA (equals 6 W).

All ratio values were sorted in uniform groups for obtaining a frequency distribution chart. The x-axis contains the categories of the ratio, the y-axis how often a certain category occurs. The y-axis value therefore equals time in seconds.

5.2 Maximum Ratio between load and PV-system

The value of the ratio between the load of the network and the PV-power is high at a low irradiation level and a high network loading (Winter). A high irradiation level and a low loading of the power network results in a low value for the ratio (Summer). This effect on the ratio is clearly visible in figure 5.1. This figure shows the frequency distribution chart of the ratio for every month of Bay 7. The summer months have a very distinct peak while the winter months have a less distinct peak. The peak of the ratio moves to high values for the winter months. The y-axis is graduated in seconds.

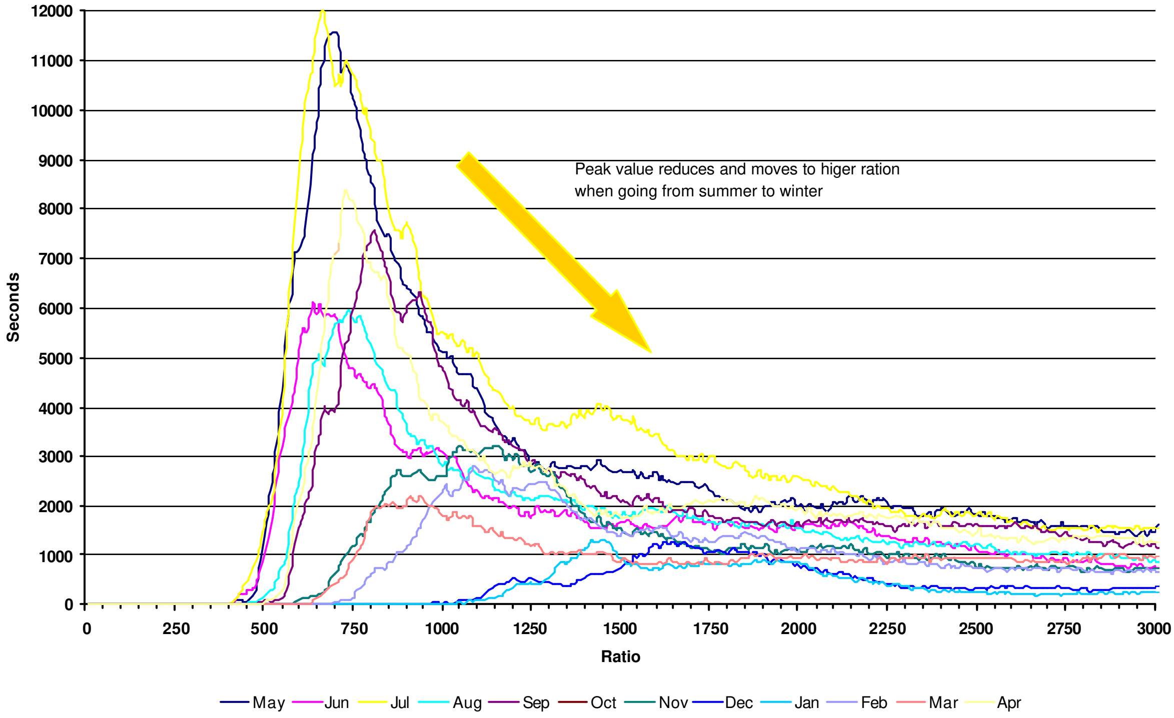


Figure 5.1 Frequency distribution chart for the ratio per phase and per month for Bay 7

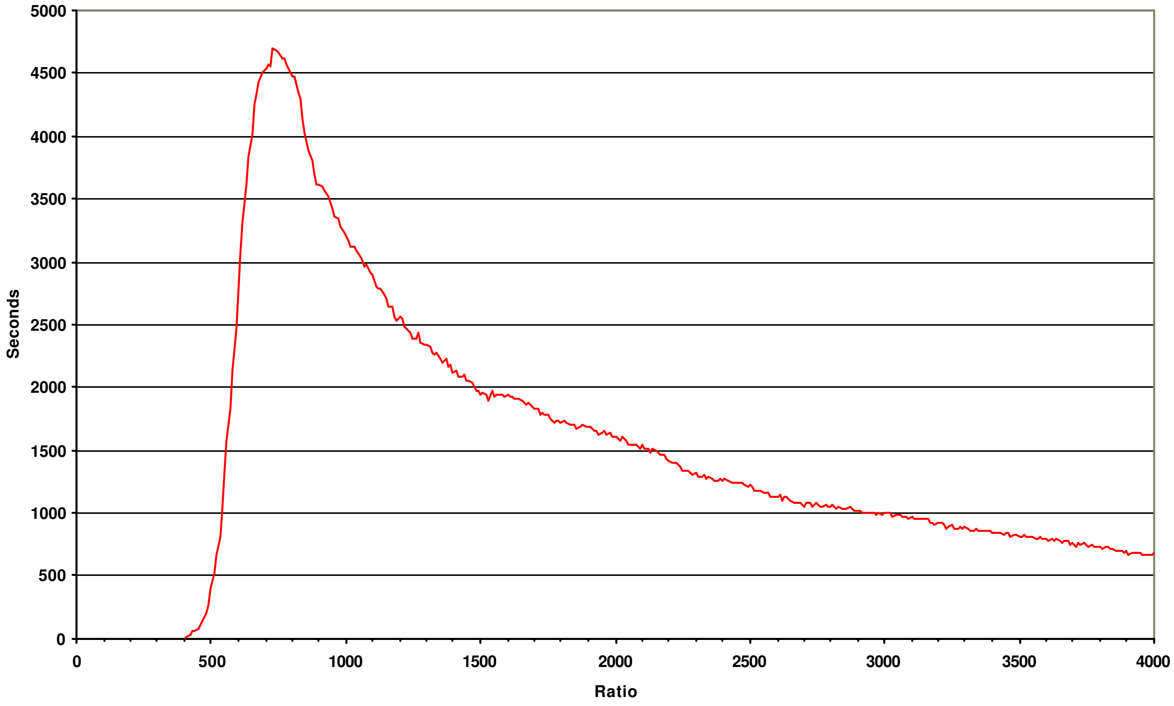


Figure 5.2 Frequency distribution chart of the ratio per phase of Bay 7 for the whole year.

The summation of the ratio for all months is given in figure 5.2. The figure shows a clear peak at a ratio of 740. The shape of the distribution chart shows a steep ramp from zero to the peak value and a smooth tail beyond the peak. This shape is very typical for all other Bays as shown in annex 3.

The peak values of the ratio as given in annex 3 are listed in the fourth column of table 5.1. The equivalent PV-power per house is calculated for the peak ratio value using the average number of houses per Bay (2^{nd} column – see table 3.2). This value is calculated by the peak value of the ratio multiplied by 100 W_{peak} for the PV-system, divided by the average number of houses per Bay. The calculated average for all Bays is 913 Wpeak.

Bay	Total houses in Bay	Houses per phase (average)	Peak at ratio	Equivalent PV power per house in Wpeak
2	7	2,33	20	858
3	50	16,67	110	660
4	78	26	350	1346
5	55	18,33	150	818
6	56	15,67	140	893
7	246	82	740	902
Average PV power on every house				913

Table 5.1 Overview of peak ratio value for the Bays and equivalent PV-power.

The equivalent PV power in table 5.1 must be interpreted as the PV power to be installed on every house in the whole residential area for which balanced current conditions between the PV-power and the loading of the power network occurs most frequently. It is noted that these values refer to an evaluation based on current criteria only and 1 second based (see equation 5.2). For this peak value of the ratio it is not necessarily true that islanding will occur most frequently. The ratio is calculated per individual second using currents while the probability of islanding must be considered on an evaluation of active and reactive power and for the time that the matching condition remains stable for at least 2 seconds as is discussed in chapters 6, 7 and 8. The value however gives a good impression of the PV-penetration level for which islanding can be expected. The equivalent PV-power is for Bay 4 slightly higher when compared to the other Bays. This can be explained as Bay 4 feeds a few day- and night-care units for disabled persons. The day load of these units is relatively high. Hence, more PV-systems are required to meeting the load.

A graphical presentation of table 5.1 is given in figure 5.3. From this figure it may be concluded that the peak of the ratio is almost linear with the number of houses per Bay. Hence, the results obtained by this evaluation may be interpreted as valid for a Bay with a few houses up to a large area up to about 250 houses. This is an important conclusion, because the number of houses connected to one distribution transformer or feeder various in different countries.

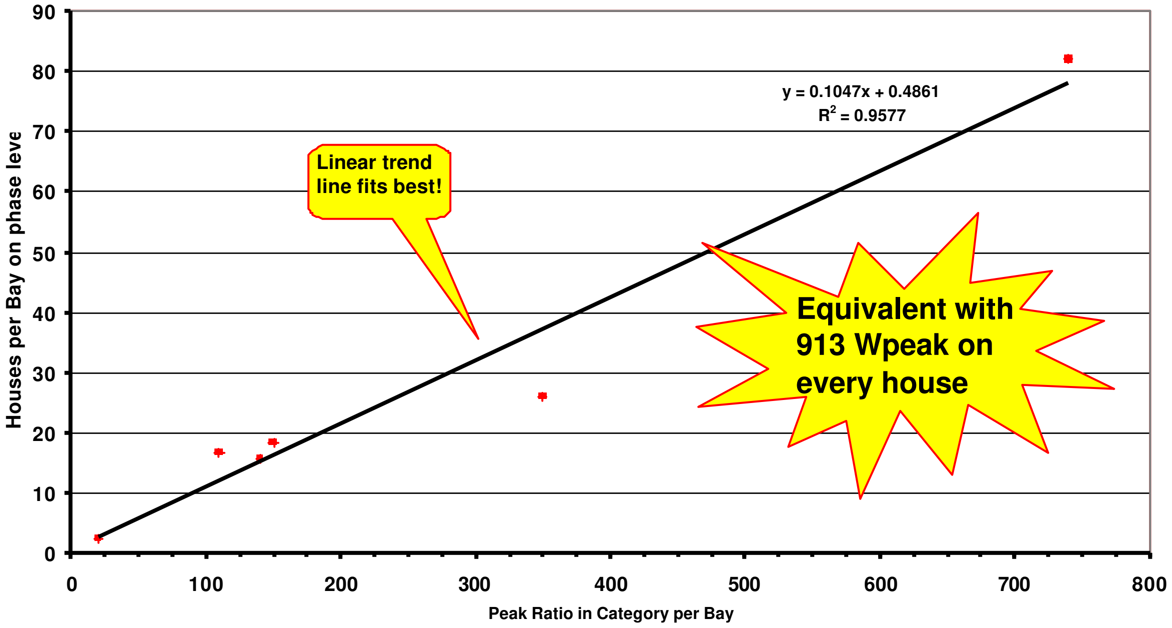


Figure 5.3 Peak factor of the ratio versus number of houses per Bay.

5.3 Maximum PV level for which balanced condition does not occur

An important observation from figure 5.1, figure 5.2 and the graphs in annex 3 is that the ratio remains zero just before the peak value occurs. This means that there is always a certain amount of loading of the network. Hence, a certain amount of PV-power may be installed in the residential area for which balanced conditions (islanding) never occur. The second column of table 5.2 shows the ratio value for which the ratio is for the first time greater than zero. Like in table 5.1 this can be translated in an equivalent PV-power per house. For Bay 4 this value is slightly high due to the higher loading of the day- and night care units connected to that Bay.

Bay	First ratio greater then zero	Average houses in Bay and per phase	Max. PV power on every house where balanced conditions do not occur in Wpeak
2	10	2,33	435
3	50	16,67	300
4	160	26	615
5	60	18,33	327
6	50	15,67	319
7	400	82	488
		Average	413

Table 5.2 Overview of minimum ratio

The average for which balanced conditions do not occur is about 400 W_{peak}. A graphical presentation of table 5.2 is given in figure 5.4. The best-fit trend line is a power trend line. This trend line is however nearly linear. The residential area has 246 houses, hence balanced conditions do not occur even when a PV-system of 100 kW (˜ 246 x 400) is installed in that residential area. This value may be interpreted as a significantly high value.

☞ Balanced conditions and subsequently probability of islanding can not occur if PV-systems are installed on every house with a power rating of about 400 W_{peak} or less.

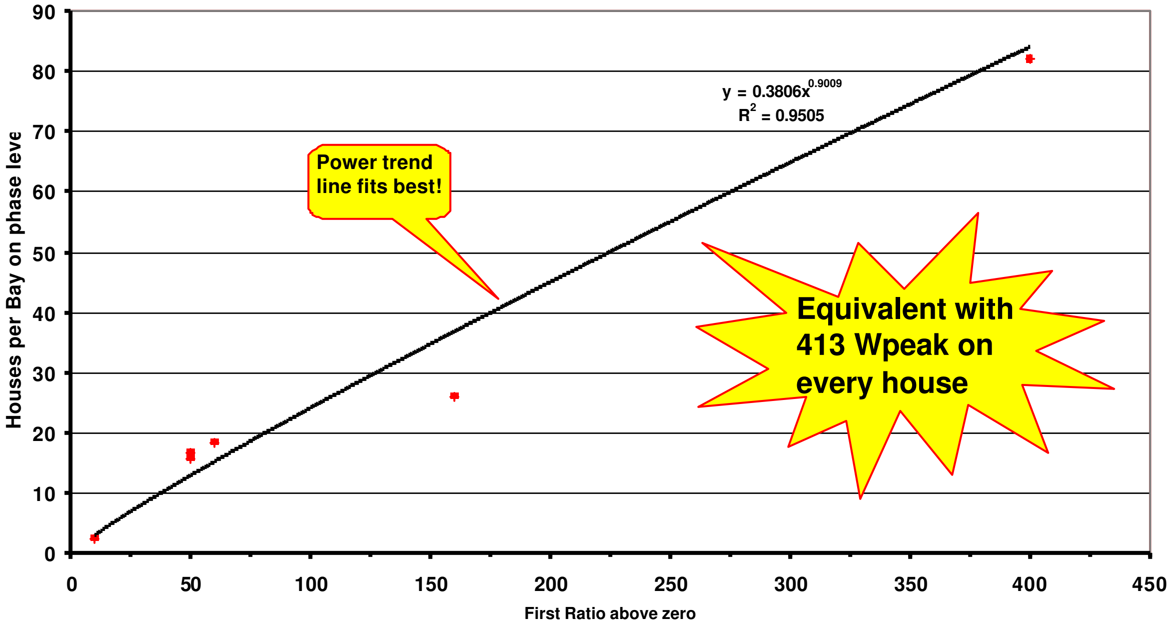


Figure 5.4 Minimum ratio versus number of houses per Bay.

The minimum PV-power for which balanced conditions can not occur can also be derived from the frequency distribution chart of active power. This chart is obtained by calculating the active power taken in every Bay for every second for every day and night during the whole year. The active power values are plotted in frequency distribution charts. Figure 5.5 shows the frequency distribution chart of the active power for Bay 7. The active power distribution charts for the other Bays are given in annex 4. The y-axis has the unit seconds, the integral under the curve equals the energy consumption.

Figure 5.5 shows that the power taken from the network in Bay 7 is always higher then 16.750 W. In other words there is always a certain minimum load of the network. With an average of 82 houses per phase we can calculate the power rating of a PV-system to be installed on every house for which the load is always higher. This value is 16.750 W divided by 82 houses and equals about 200 W_{peak} per house. This means that balanced conditions will never occur if every house in the residential area is equipped with a PV-system of 200 W_{peak} or less. The values for the other Bays are given in figure 5.6.

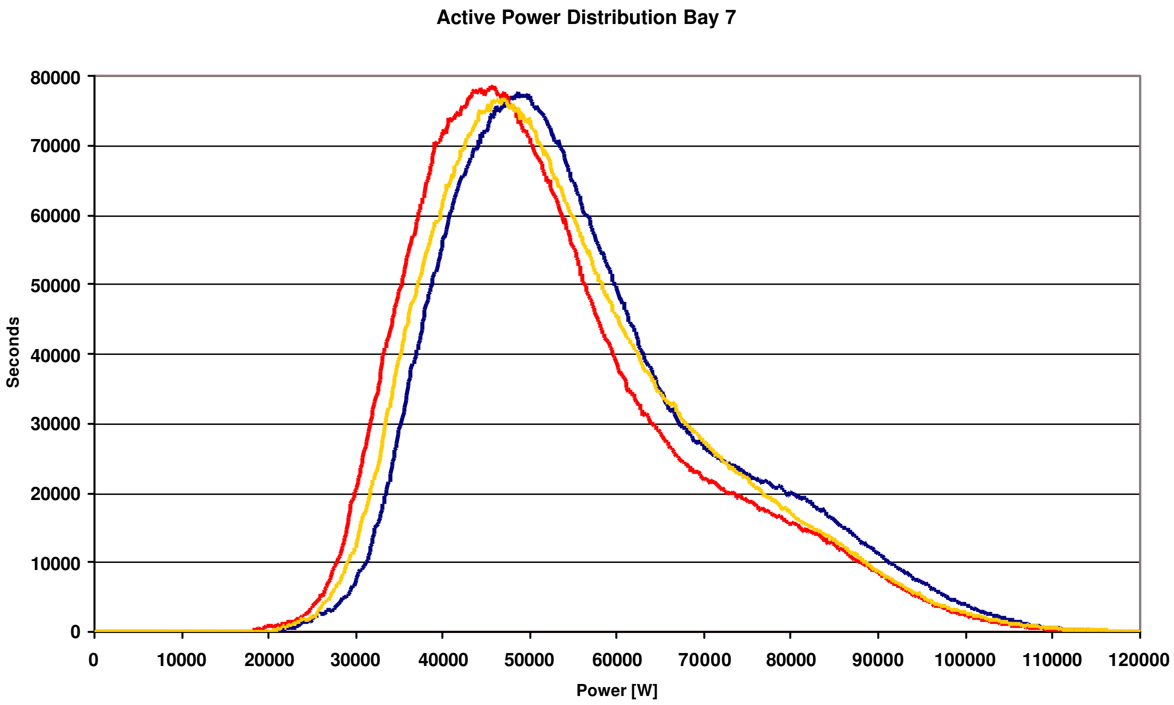


Figure 5.5 Active power frequency distribution for Bay 7 for phase red, yellow and blue

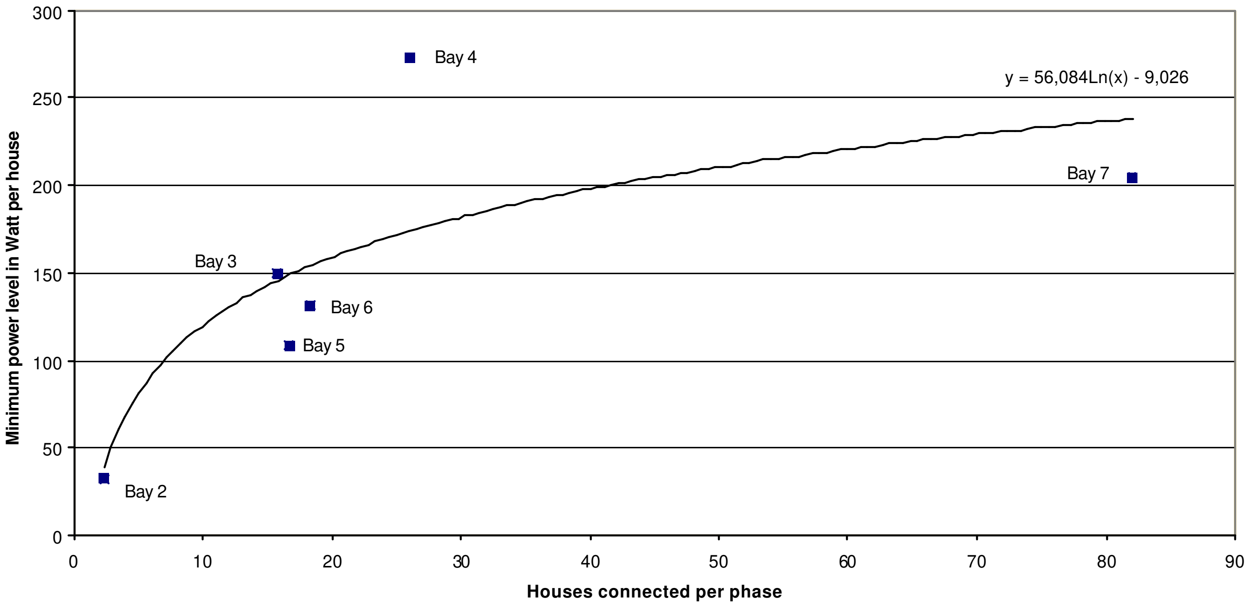


Figure 5.6 Minimum active power level versus number of houses connected to the phase

Figure 5.6 shows the minimum power in Watt per house as a function of the number of houses connected to one phase. The load of a Bay is never below this level. If PV-systems are installed in that Bay and the peak power of these systems remains below this minimum load level, it is guaranteed that balanced conditions (islanding) never occurs. An important observation is that the minimum power taken per house is not linear with the number of houses connected to the phase. A nearly linear relation is however observed for the minimum ratio in figure 5.4. This figure presents a analysis time frame from 7.00 to 21.00 hours. The data shown in the figure 5.6 is based on the day and night. From this it is concluded that the minimum loading of the network occurs during the night. For Bay 4 the minimum load level is relatively high when compared to the other Bays. This can be explained as Bay 4 includes several day- and night-care units for disabled persons. These units have a relatively high average loading due to the activities performed during the day, while certain activities like supervision are also performed during the night.

Bay 2 has only a few houses connected. Averaging of loads does not happen too much. The minimum load is about 30 Watt and is equivalent to a clock radio and some mechanical ventilation.

The trend line in figure 5.6 is a logarithmic curve. The minimum active power per house is relatively small for Bays with a few houses (Bay 2). For 20 or more houses connected to a phase the minimum power active power becomes about 150 W per house. For this power level balanced condition can never occur. This number is smaller when compared to the 400 W derived in table 5.2 and figure 5.4.This can be explained as the active power frequency distribution chart is calculated over a period of 24 hours per day and the minimum load happens during the night. The ratio in figure 5.4 is calculated only from 7.00 to 21.00 for which the minimum load level of the power network exceeds the minimum night minimum load.

☞ The maximum PV-power in a power network for which balanced conditions never occur is approximately two to three times the minimum night load of the relevant power network.

6. METHOD TO CALCULATE THE PROBABILITY OF ISLANDING

The measurements have been made using a single PV-system of 100 Wpeak. This power rating is too small for direct comparison with the actual load of the power network. The PV-power must first be multiplied with a certain fixed number before the comparison with the actual load of the network can be made. By this comparison we can determine how often and for how long balanced conditions are present. This is illustrated in figure 6.1. The values for the load and PV-power are based on the measured data but slightly modified for the purpose of the illustration.

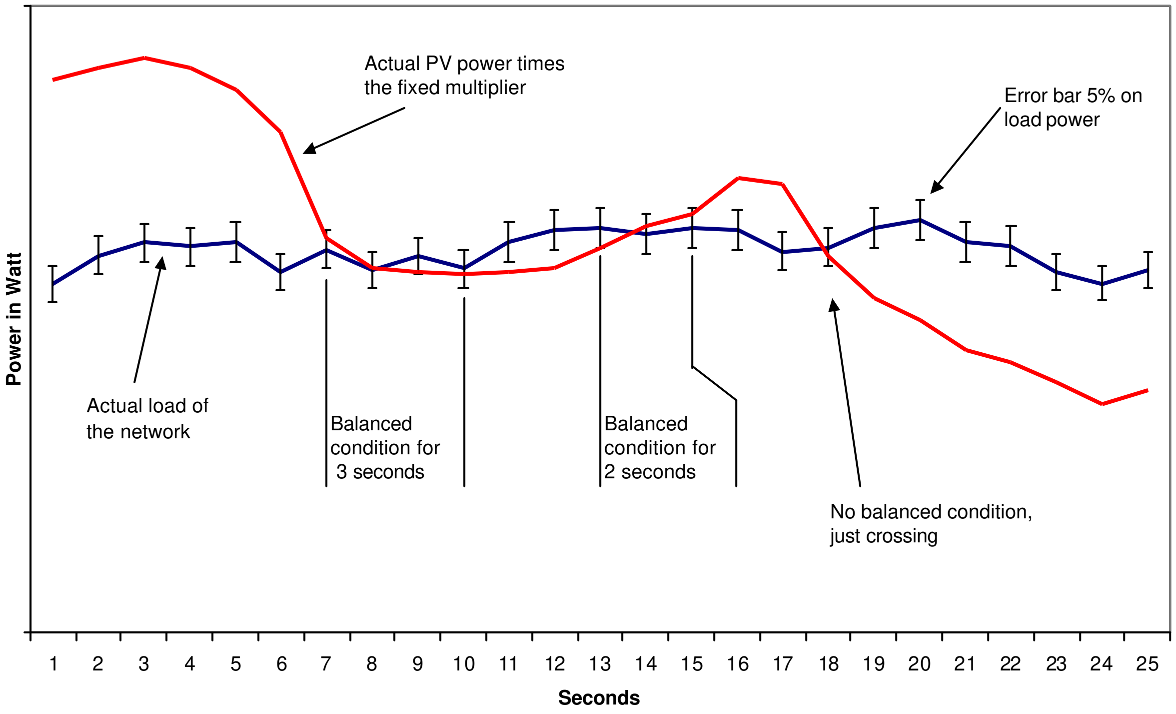


Figure 6.1 Illustration to show how often and for how long balanced conditions are stable.

The red line shows the actual power produced by the PV-system power multiplied by a certain fixed value. This multiplier is kept constant during the analysis of the whole year. The blue line shows the load of the network. If the PV power is within the 5% error bar of the load it is interpreted as a balanced condition. If this remains for the next second(s) it is then determined as a balanced condition. Figure 6.1 shows two possible-islanding conditions, one for 3 seconds and one for 2 seconds. The crossing of PV-power with the load line on the right hand side of the figure is not interpreted as a balanced condition.

This process of evaluation has two variables to simulate different conditions:

- Multiplication factor of the PV-power
- Error bar (margin) for with balanced condition is accepted or not

An analysis of the ratio between the PV-power and the load has been made in chapter 5. This analysis shows a clear peak ratio. One could expect that balanced conditions occur most frequently for this peak ratio. To evaluate this expectation and to determine the sensitivity of the multiplier used it was decided to perform the analysis for the following multipliers: 0.75x, 0.9x, 1x, 2x and 3x times the peak ratio. A multiplier with a value of 0.75 times the peak ratio presents a low PV penetration level, while 3x the peak ratio corresponds to a very high PV penetration level. The multiplier values used and equivalent PV-power assumed to be installed on every house is given in table 6.1. The equivalent PV-power on every house is calculated using the average number of houses per phase and Bay as given in table 5.1.

Balanced conditions cannot occur for a multiplier much below 0.75 x the peak ratio as indicated in table 5.2 - 4th column, e.g. for Bay 7 balanced conditions cannot occur for a multiplier value below 400.

Bay	0.75 x Peak Ratio Equivalent PV power per house	0.9 x Peak Ratio Equivalent PV power per house	1 x Peak Ratio Equivalent PV power per house	2 x Peak Ratio Equivalent PV power per house	3 x Peak Ratio Equivalent PV power per house
	Lower penetration levels		Peak value	Higher penetration levels	
2	15 64 Wp	18 772 Wp	20 858 Wp	40 1.716 Wp	60 2.575 Wp.
3	82,5 495 Wp	99 594 Wp	110 660 Wp	220 1.320 Wp	330 1.980 Wp
4	262,5 1010 Wp	315 1.211 Wp	350 1.346 Wp	700 2.692 Wp	1.050 4.038 Wp
5	112,5 613 Wp	135 736 Wp	150 818 Wp	300 1.636 Wp	450 2.454 Wp
6	105 670 Wp	126 804 Wp	140 893 Wp	280 1.786 Wp	420 2.679 Wp
7	555 677 Wp	666 812 Wp	740 902 Wp	1.480 1.804 Wp	2.220 2.706 Wp
7 total	166 kWp	200 kWp	222 kWp	444 kWp	666 kWp

Table 6.1 Overview of the multiplier used for different data analysis and the equivalent PV-power per house

The bottom row in table 6.1 shows total equivalent PV-power in the residential area (Bay 7 = 246 houses) These values are calculated as the equivalent power times 82 houses times 3 phases. From the values it may be easier to understand for what total PV-power the analysis are made. As described in section 5.3 islanding never occurs for a total PV-power of 100 kW.

The second variable is the margin used when comparing the load of the network with the power generated by the multiplied PV-system. In figure 6.1 an error margin of 5% is used. The selected error margins used for the analysis are given in table 6.2.

run	Margin for active power	Margin for active power	< combination >	Margin for reactive power
1	2%	2%	And	2%
2	5%	5%	And	2%
3	10%	10%	And	5%
4	15%	15%	And	10%
Results in chapter	7		8	

Table 6.2 Overview of the margins used for the calculation of active power and the combination of active power and reactive power.

A 2% margin is a strict margin, while a 20% margin in active power is assumed as to be very large. It is not expected that a power network will remain stable if a 10% or even a 20% mismatch of active or reactive power is present. The voltage must increase or decrease significantly for such a large mismatch and the over voltage or under voltage protection in the inverter will in practice trip and switch-off the inverter. This large margin is however used to gain information on the sensitivity on how often and for how long balanced conditions remain stable.

The margin used for the reactive power is slightly smaller in comparison with the active power as studies revealed a very high sensitivity of the stability of an islanding condition for even a very small mismatch in reactive power [1] and [2].

The total number of analyses: 5 different multipliers and for 4 margin values. Hence, 20 analyses for active power only and 20 analyses for the combination of active and reactive power. Every analysis is made for the full year keeping the multiplier and the margin(s) constant.

7. BALANCED CONDITIONS FOR ACTIVE POWER ONLY

The measured data has been analysed as described in chapter 6 by looking at the active power only. All balanced conditions per phase (Red, Yellow and Blue) and per Bay (2 trough 7) have been determined separately. Due to the large number of variables (offset, margin, phase and Bays) it is not possible to show all the results. The results presented in this chapter are carefully selected to show the most important observations.

This chapter shows the results of the analysis for balanced conditions when using the criteria for active power only. In a power network balanced conditions have to occur for both active and reactive power as described in chapter 8. The relevance of this chapter is to obtain a good understanding on the mechanism involved. Several graphs are given for Bay 2 - a few houses connected to one phase, and for Bay 7 with 82 houses connected to every phase. These two Bays are the outer limits.

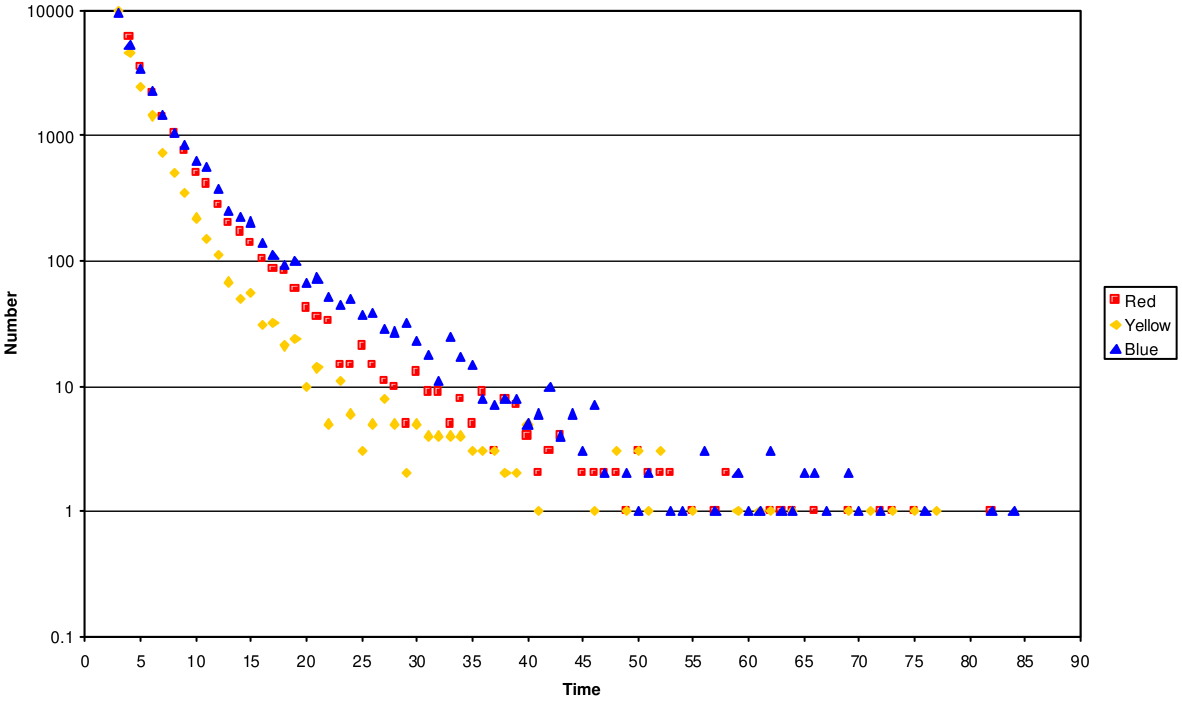


Figure 7.1 Number and time when balanced conditions are stable for Bay 2.

The figure 7.1 presents the number of balanced conditions and the time that the balanced conditions remain stable in Bay 2. The multiplier of the ratio is 1 and the margin used is 5% (see table 6.1 and 6.2). The graph presents the conditions for the phases Red, Yellow and Blue. The x-axis is the time that a balanced condition remains stable. The y-axis shows how often a balanced condition occurs over the whole year. For example, balanced conditions of 30 seconds occur 13 times for the Red phase per year. For the Blue phase this is 23 times and 5 times for the Yellow phase. Note that the y-axis has a logarithmic scale. The plotted points are always discrete values due to the 1-second based interval of the sampling.

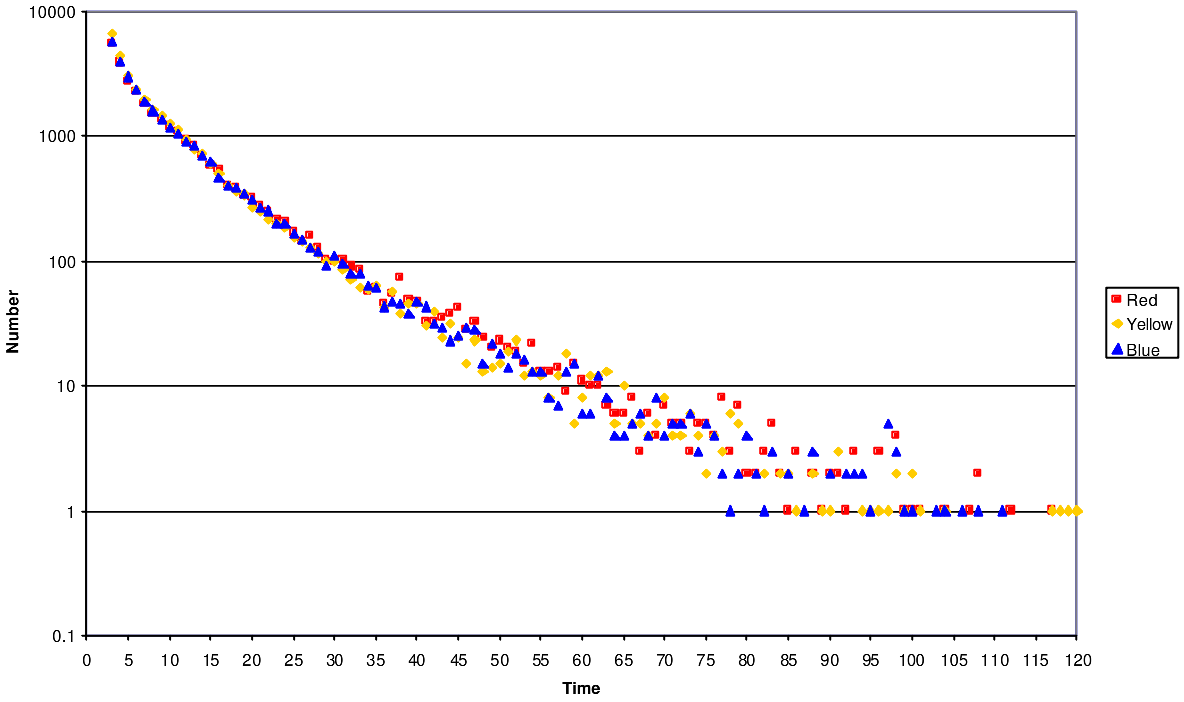


Figure 7.2 Number and time when balanced conditions are stable for Bay 7.

Figure 7.2 shows the balanced conditions for Bay 7. The multiplier used is 1 and the margin is 5%. The figures 7.1 and 7.2 show very little differences between the individual phases. This is also observed in the other Bays. The variation between the phase is for Bay 2 a little larger when compared to Bay 7. The number of balanced conditions and the time that balanced conditions remain stable is for Bay 7 higher. This is explained as Bay 2 has only 2 houses connected to every phase while Bay 7 has 82 houses per phase. The variation of the load is for Bay 7 more averaged.

For reasons of simplicity all other figures given in this chapter are given for the Red-phase only.

Figure 7.3 and 7.4 shows how often and for how long balanced conditions occur as a function of the margin between the actual load of the network and the power generated by the PV-systems. The graphs are calculated for a fixed value of the multiplier of 1 while the margin was varied between 2%, 5%, 10% and 15%. For the small margin of 2%, balanced conditions occur less frequently and the time that the conditions remain stable is, of course, smaller when compared a 5% margin. The difference between a margin of 10% and 15% are less significant. An important observation is that the all curves are similar and have their origin at approximately 10.000 balanced conditions for 2 seconds. The graphs for the Bays 3 though 6 do not show any significant change in this observation.

☞ The margin (allowable mismatch) between load and generated PV power significantly determines the number and duration of balanced conditions.

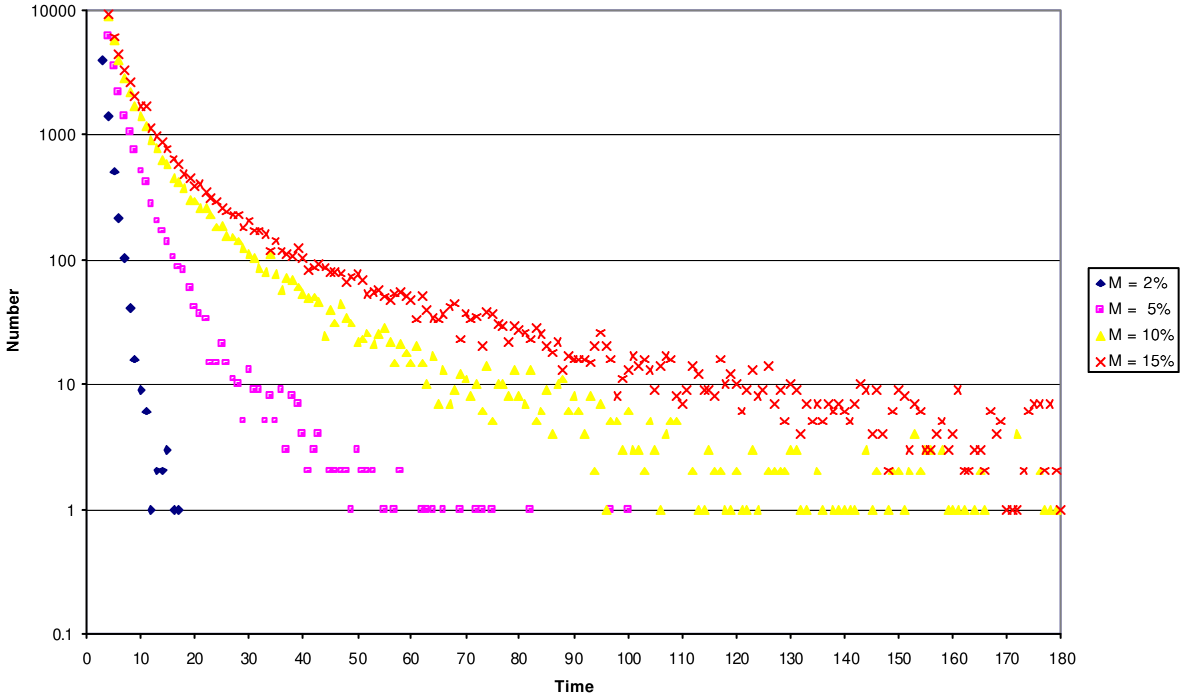


Figure 7.3 Balanced conditions for multiplier =1 and when varying the margin for Bay 2

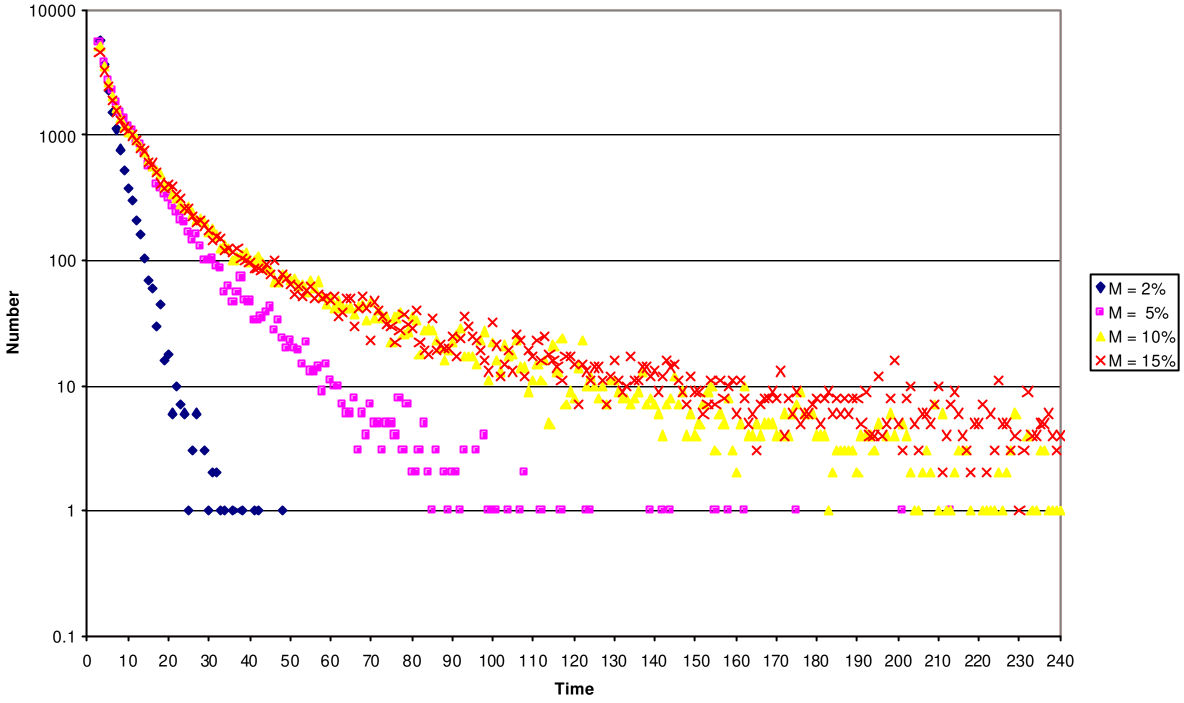


Figure 7.4 Balanced conditions for multiplier =1 and when varying the margin for Bay 7

The figures 7.5 and 7.6 show the relation between the number of balanced conditions when using a fixed margin of 5% and when varying the multiplier from 0.75 to 3 times the maximum ratio. These two graphs show the relation of the penetration factor of the PV-system versus how often and for how long balanced conditions occur.

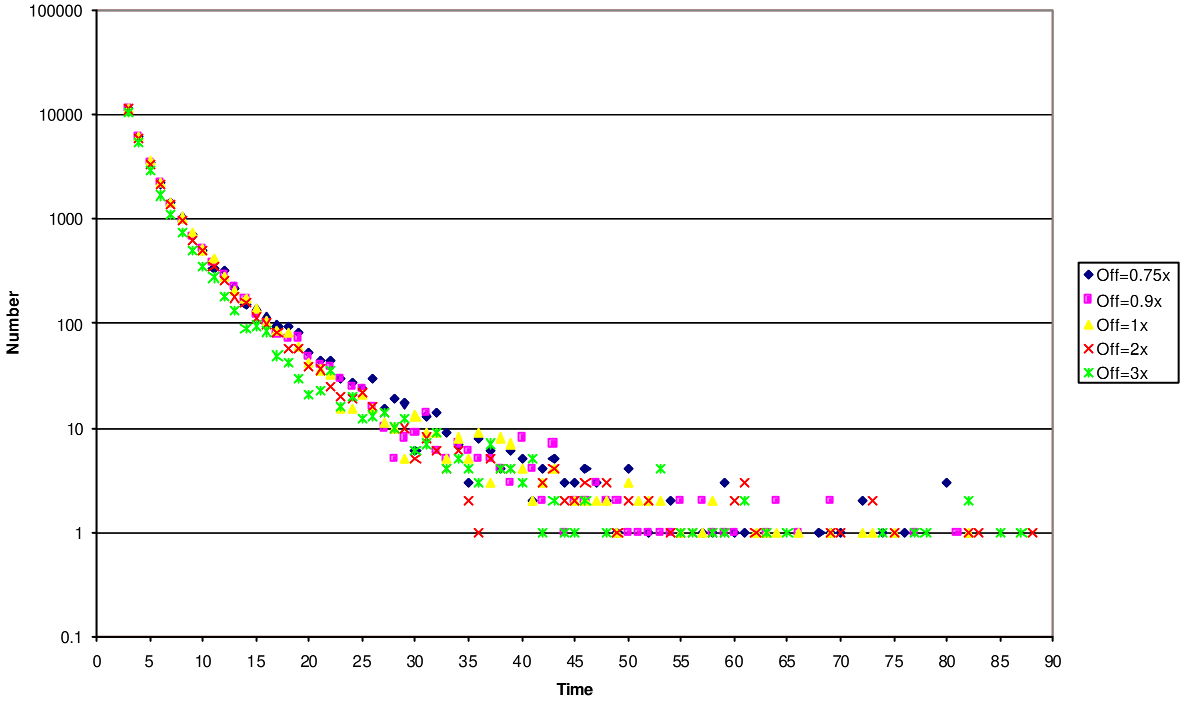


Figure 7.5 Balanced conditions for margin = 5% and when varying the multiplier for Bay 2

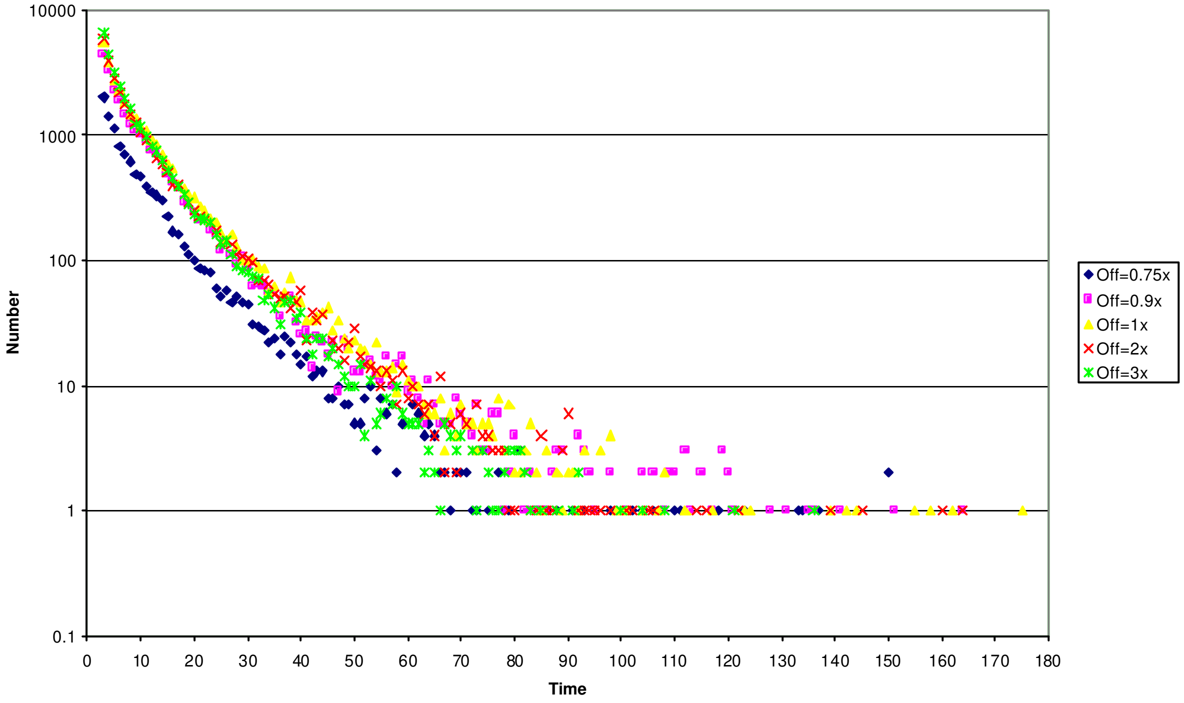


Figure 7.6 Balanced conditions for margin = 5% and varying the multiplier for Bay 7

Both figures show that the number of balanced conditions and time that these conditions remain stable does not significantly vary with the penetration level of PV-systems. This is also observed for the Bays 3, 4, 5 and 6. This is an important observation as the graphs of the ratio (chapter 5) suggest a strong relation between the ratio and the number is balanced conditions. The distinct peak in the ratio is not found in the graphs 7.5 and 7.6 and in all other

Bays. This means that the PV-power and load have many crossings not significantly dependable on the PV-power level as explained in chapter 6 and figure 6.1.

☞ The penetration level of PV-systems does not significantly influence how often and for how long balanced conditions between the load and the PV-systems occurs.

8. BALANCED CONDITIONS FOR ACTIVE AND REACTIVE POWER

Islanding in a power network is only possible when both the active and reactive power are balanced. The variation of the load in the network is given in the annex 4 (frequency distribution diagrams). The actual load varies over a wide power range due to the night and day loading and the seasonal influence. The reactive power consumption of the network varies over a less wide range as is shown in figure 8.1 for the three phases.

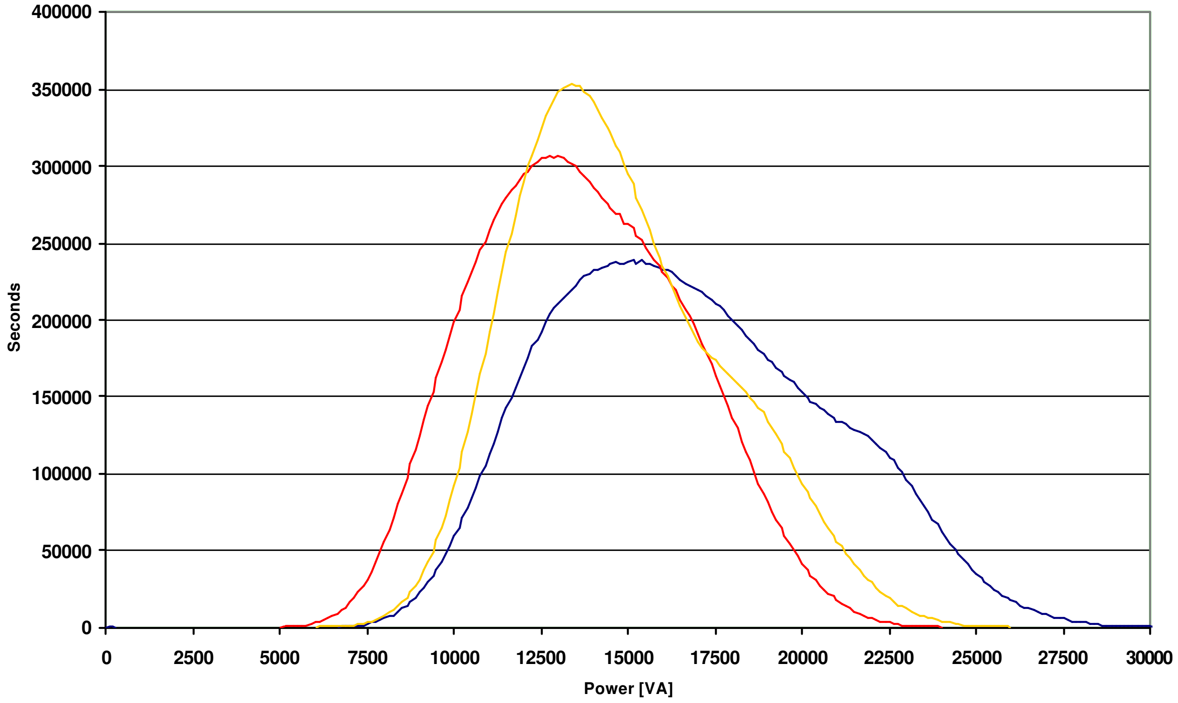


Figure 8.1 Frequency distribution diagram of the reactive power for Bay 7 per phase

Figure 8.1 shows the frequency distribution diagram of the reactive power consumption per phase for Bay 7. This diagram is determined analysing the measured data over the whole year and for 24 hours per day. For reference, the frequency distribution diagram of the active power of Bay 7 is given in figure 5.2 and in annex 4. Figure 8.1 clearly shows that the distribution network constantly needs a reactive power flow towards the loads.

☞ A power network always requires reactive power.

If balanced conditions occur, the reactive power requirement of the network must be supplied by the PV-inverters. The measured data was analysed and it appeared that the PV inverter could generate reactive power. Hence, probability of islanding may be present.

The data are analysed for balanced conditions for active and reactive power varying the multiplier and the margins as defined in the table 6.1 and 6.2. The results for a multiplier of 1x the peak ratio and a margin of 5% for the active power and a margin of 2% for the reactive power are given in figure 8.2 and 8.3. These figures may be compared with the figures 7.1 and 7.2.

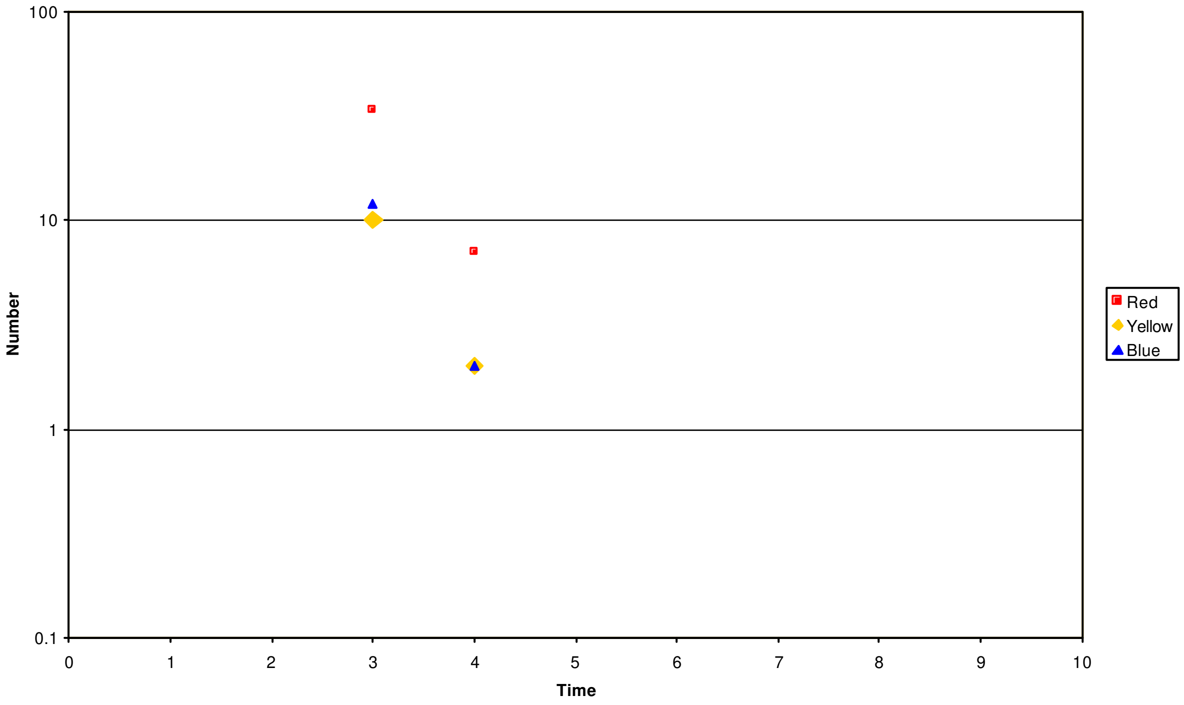


Figure 8.2 Number and time when balanced conditions are stable for Bay 2

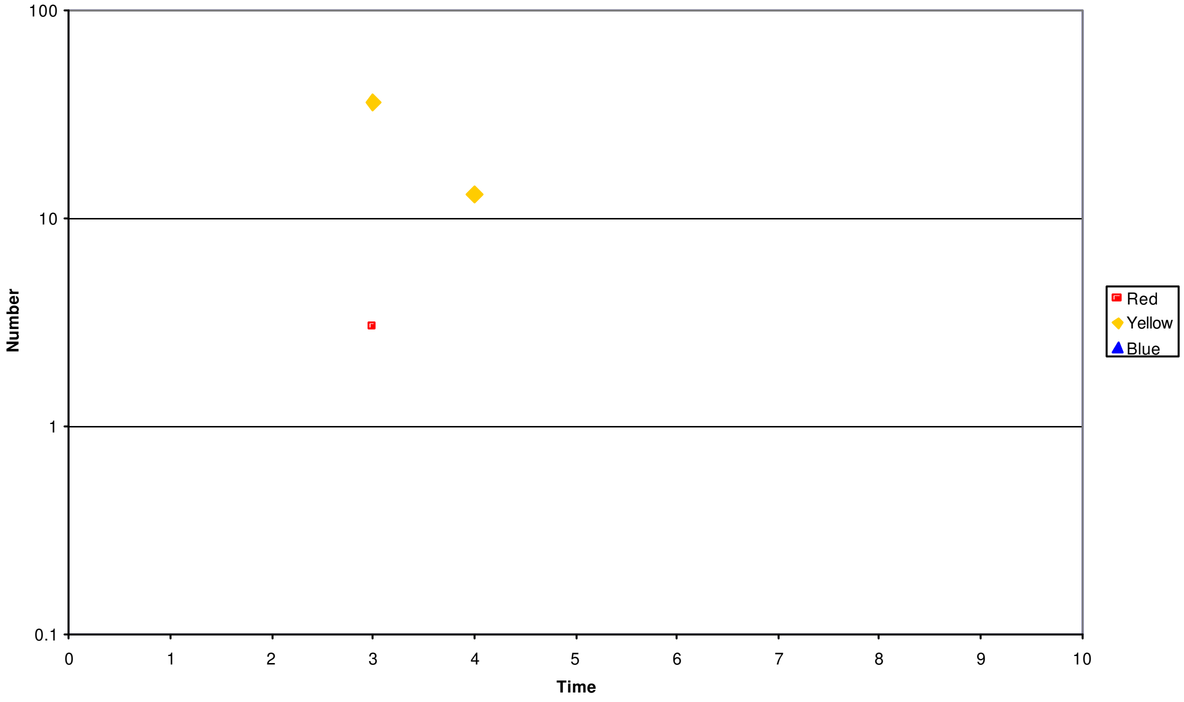


Figure 8.3 Number and time when balanced conditions are stable for Bay 7

The figures 8.2 and 8.3 show that the number and the time for which balanced conditions remain stable is very small. For Bay 2 only two balanced conditions occur of three and four seconds per year. For Bay 7 only two balanced conditions occur for the yellow phase one for the red phase and zero for the blue phase. From both figures it may be concluded that the probability of balanced conditions is (nearly) zero.

Figure 8.4 and 8.5 shows how often and for how long balanced conditions occur as a function of the margin between the active and reactive load of the network and the power generated by the PV-system. The graphs are calculated for the fixed value of the multiplier of 1x peak ratio while the margin was varied between 2% / 2%, 5% / 2%, 10% / 5% and 15% / 10%, where is x / y the margin for active power / reactive power. Reference is made to table 6.2.

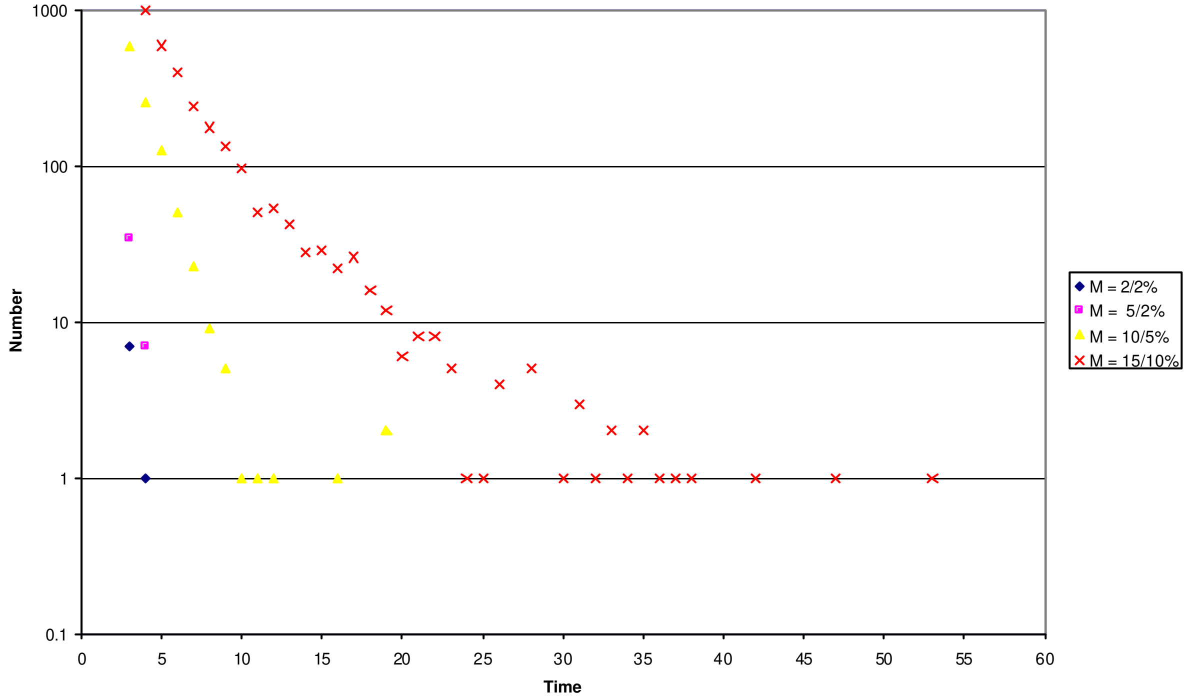


Figure 8.4 Balanced conditions for multiplier =1 and when varying the margin for Bay 2

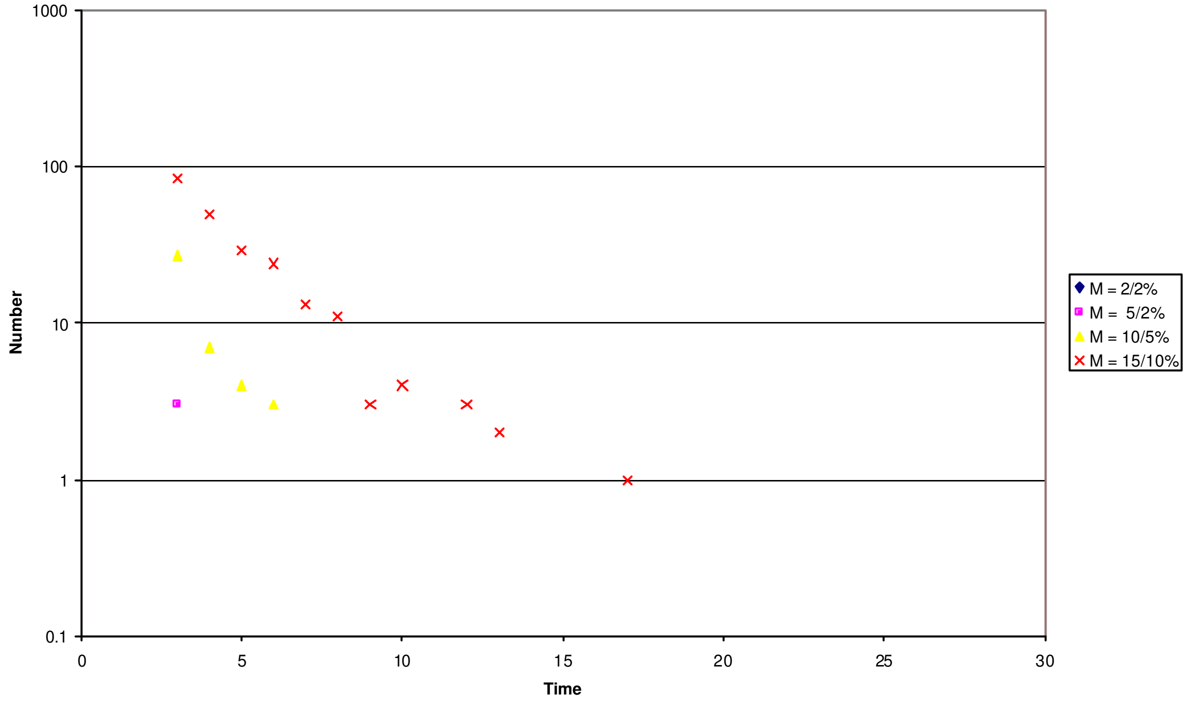


Figure 8.5 Balanced conditions for multiplier =1 and when varying the margin for Bay 7

The figures 8.4 and 8.5 show that balanced conditions occur more frequently for the large margins for active and reactive power. Balanced conditions for the smaller margins occur only a very few times and the time that the balanced conditions remains stable is also very small. Comparing these figures with the figures 7.3 and 7.4 it is observed that all figures show a significant relation with the margin; the smaller the margin the less balanced conditions. A conclusion also found and described in chapter 7.

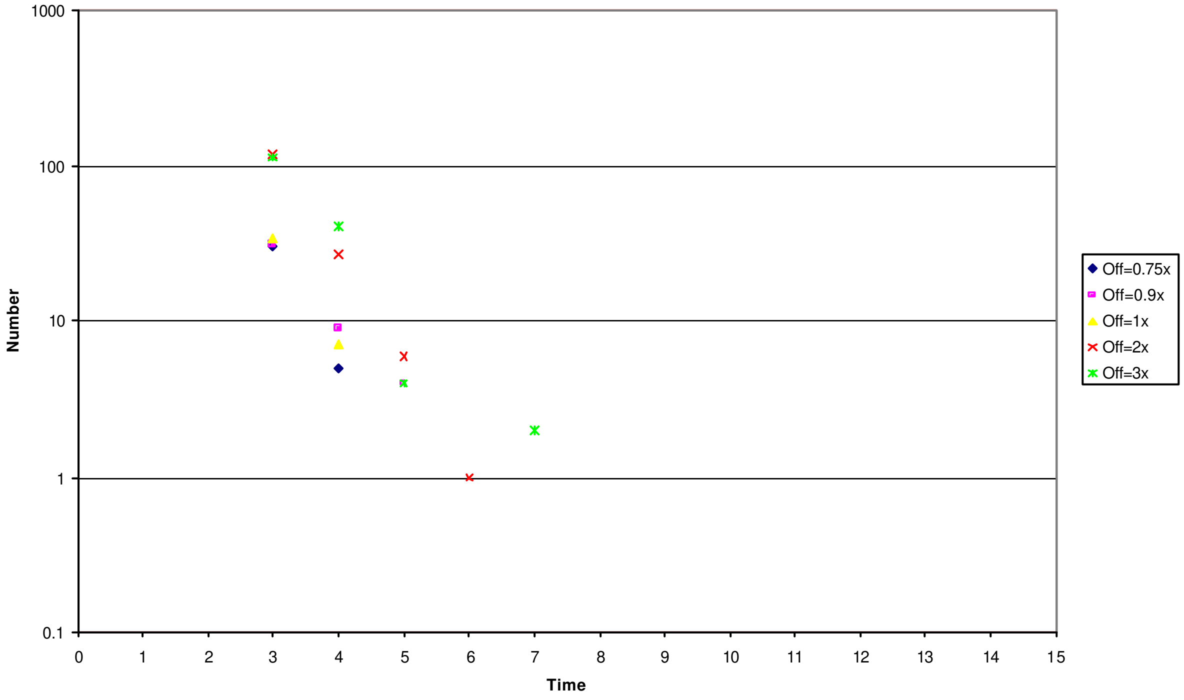


Figure 8.6 Balanced conditions for margin = 5/2% and when varying the multiplier for Bay 2

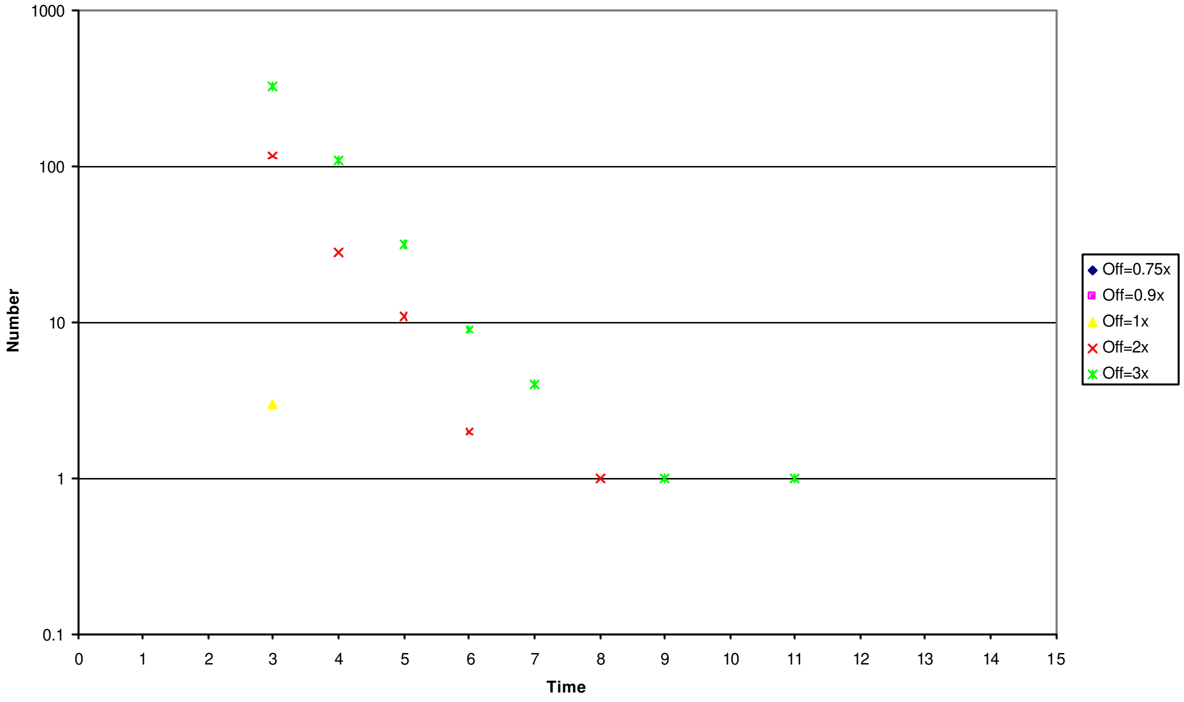


Figure 8.7 Balanced conditions for margin = 5/2% and when varying the multiplier for Bay 7

The figures 8.6 and 8.7 show the relation between the number of balanced conditions when using a fixed margin of 5% for the active power and 2% margin for the reactive power and when varying the multiplier from 0.75 to 3 times the peak ratio. These two figures show the relation of the penetration factor of the PV-system versus how often and for how long balanced conditions occur. From the figures it is concluded that this relation is not as significantly present as observed in chapter 7.

The balanced conditions for the other Bays are given in annexes 5 and 6. Annex 5 shows the balanced conditions for a fixed multiplier while varying the margin. Annex 6 shows the ratio for the balanced conditions for a fixed margin and a variable multiplier.

All figures in the annexes 5 and 6 show that balanced conditions do not frequently occur. A few balanced conditions longer than 10 seconds only occur for a large margin 15% of active power and 10% for reactive power. For all other smaller margins and penetration levels balanced conditions a few balanced conditions occur up to 10 seconds.

☞ Balanced conditions between active and reactive load and the power generated by the PV-systems do occur very rarely for low, medium and even high penetration levels of PV-systems.

By looking when the balanced conditions occur during the year, it was observed that these balanced conditions happen randomly over the late spring, summer and early autumn.

☞ Balanced conditions are randomly scattered over late spring, summer and early autumn

9. PROBABILITY AND RISK OF ENCOUNTERING AN ISLAND

9.1 Probability

The previous chapters describe the how often and for how balanced conditions could occur. Since the balanced conditions are randomly scattered over the year we can determine the probability of encountering a balanced conditions (island).

The probability of islanding is defined as the time that balanced conditions are present in relation to the total time that balanced conditions could occur. The total time for balanced condition is calculated as the sum of the number of balanced conditions multiplied by the time the balanced conditions remains stable.

$$\mathrm{Pr}\,obability = \frac{\sum number \cdot of \cdot balanced \cdot conditions \cdot x \cdot time}{relevant \cdot \mathrm{sec}\,onds \cdot in \cdot a \cdot year} \tag{9.1}$$

For example, the yellow phase in figure 8.2 has ten balanced conditions for 3 seconds and two balanced conditions for one for 4 seconds. Hence, the total time of balanced conditions is 10 x 3 + 2 x 4 = 38 seconds. The relevant seconds in a year that balanced conditions could be present is during the day-period. When assuming this period from 8.00 to 18.00 hour as an average per day for the whole year, we obtain 365 days of 36.000 seconds, which equals 13.140.000 seconds. For this example the probability of islanding is calculated at 0,0000029 (about 3 E-6).

It must be stated that the 'relevant seconds in a year' is an arbitrary value and other values may also be used. The calculated probability must be interpreted as a ballpark figure.

For the balanced conditions given in chapter 8 the sum of the balanced conditions given in the table 9.1. The table shows the results for a fixed multiplier of 1x peak ratio and a variable margin for the active and reactive power balance. The data is taken from the figures 8.2, 8.3 and the figures given in annex 5. The values are in seconds.

	M = 2/2%	**M = 5/2%**	**M = 10/5%**	**M = 15/10%**
Bay 2	25	130	4077	25331
Bay 3	43	151	3081	17947
Bay 4	57	203	5358	30747
Bay 5	6	13	443	2531
Bay 6	37	104	1560	9060
Bay 7	0	9	147	1066

Table 9.1 Sum of the balanced conditions in seconds for a fixed multiplier of 1 and variable margin.

The probability of islanding is computed using formula 9.1 and the values in table 9.1. The results are presented in figure 9.1. The x-axis holds the individual Bays and the y-axis holds the probability of islanding. The y-axis has a logarithmic scale. The figure shows that for a given margin the probability of islanding is comparable for all the Bays, hence the probability of islanding does not depend on the number of houses connected to a Bay. The probability increases when using a larger margin during the analysis, which is also visible in the figures 8.2 and 8.3.

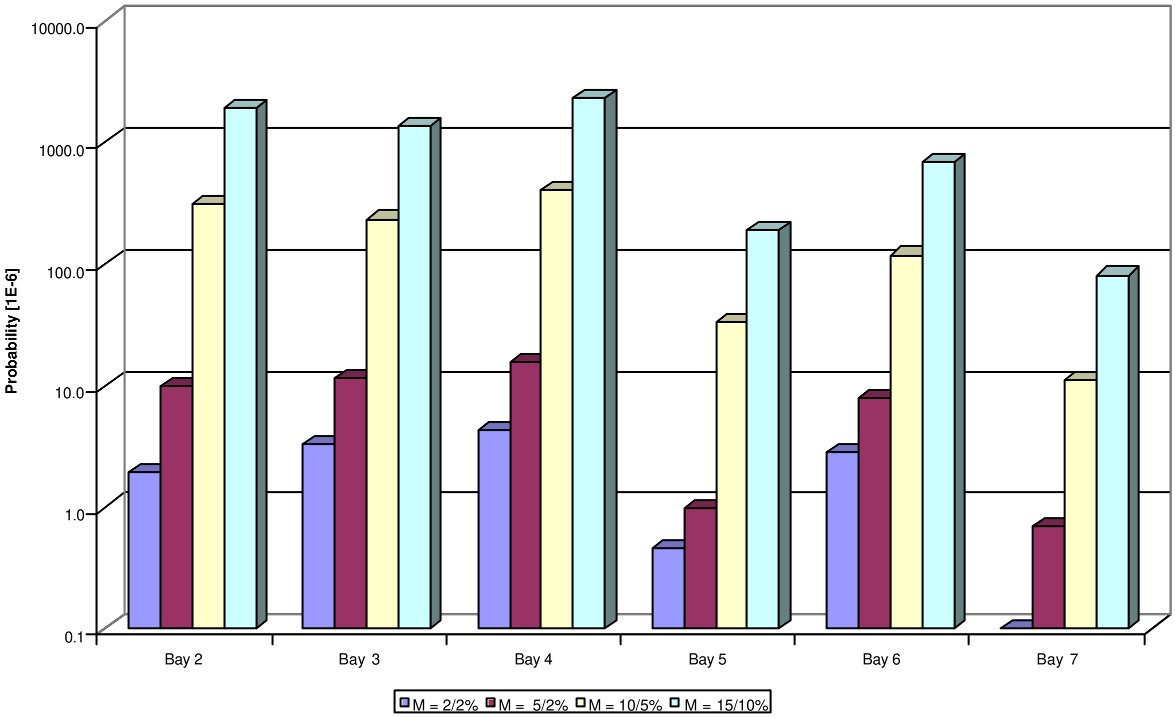


Figure 9.1 Probability of a balanced condition for a fixed multiplier 1 and a variable margin.

For the balanced conditions given in chapter 8 the sum of the balanced conditions given in the table 9.2. The table shows the results for a fixed margin of 5% for the active power and a 2% for the reactive power balance, the offset is made variable. The data is taken from the figures 8.4, 8.5 and the figures given in annex 6. The values are in seconds.

	0.75 x Peak Ratio	**0.9 x Peak Ratio**	**1 x Peak Ratio**	**2 x Peak Ratio**	**3 x Peak Ratio**
Bay 2	110	149	130	492	530
Bay 3	42	106	151	1401	2931
Bay 4	18	114	203	689	1169
Bay 5	0	4	13	412	1384
Bay 6	19	56	104	599	1664
Bay 7	0	0	9	535	1673

Table 9.2 Sum of the balanced conditions for a fixed multiplier of 1 and variable margin.

The probability of islanding is computed using formula 9.1 and the values in table 9.2. The results are presented in figure 9.2. The x-axis presents the individual Bays and the y-axis presents the probability of islanding. The y-axis has a logarithmic scale. An interesting observation is that for a low multiplier (0.75x and 0.9x) the probability of islanding reduces for the Bays 5 and 7. These Bays have a relatively large number of houses. For the higher multiplier (2x and 3x) the probability of islanding remains stable between the individual Bays (houses).

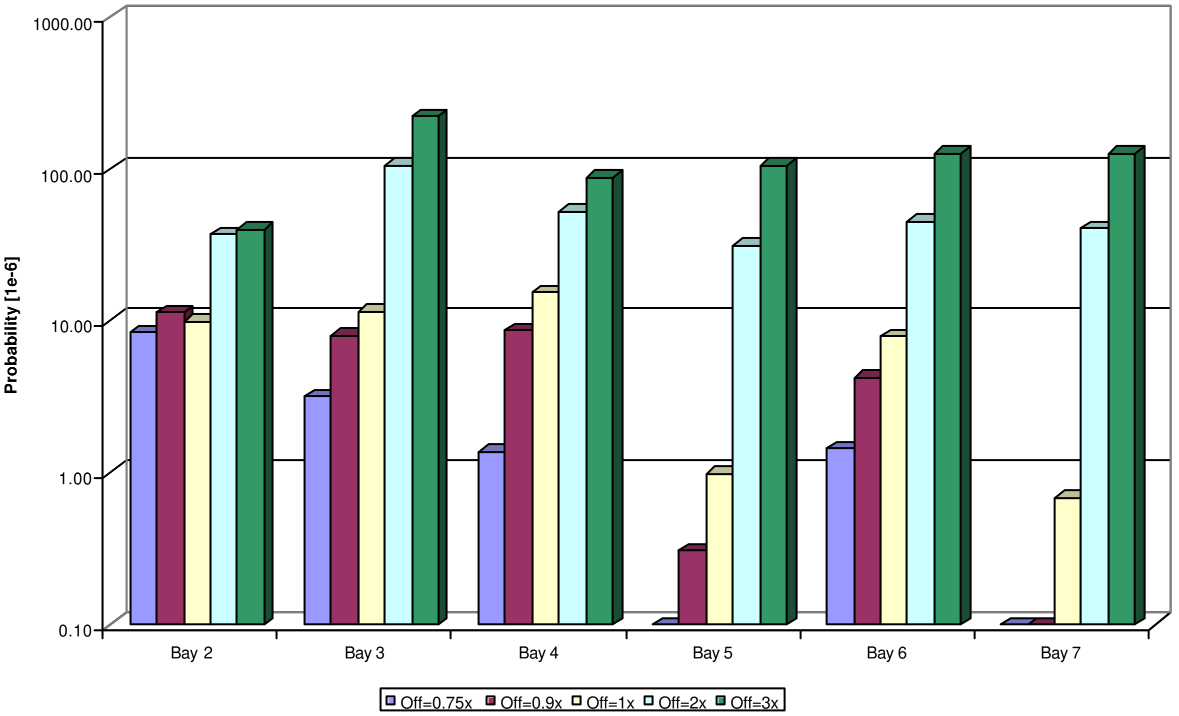


Figure 9.2 Probability of a balanced condition for a fixed margin 5/2 and variable multiplier.

When assuming islanding as a balanced condition for 5 or more seconds then the probability reduces significantly. This 5 seconds is an acceptable level as discussed in section 1.2. The results are shown in the figures 9.3 and 9.4 and are comparable with the figures 9.1 and 9.2.

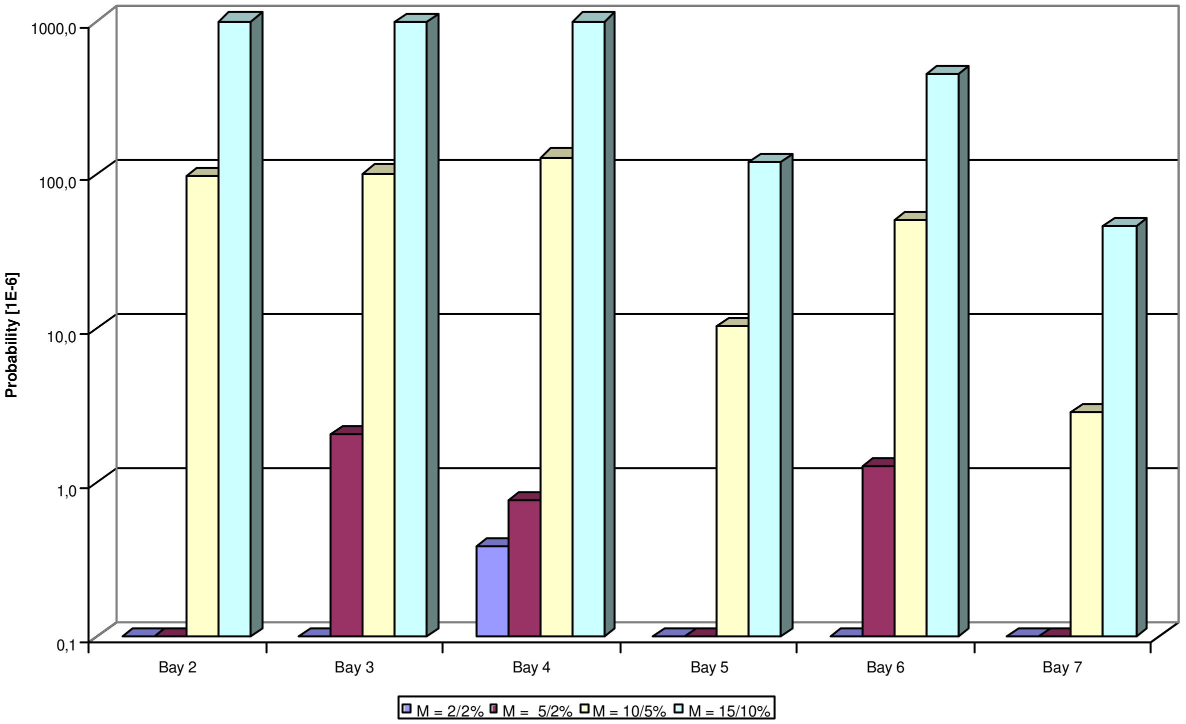


Figure 9.3 Probability of a balanced condition of 5 seconds or more for a fixed multiplier 1 and a variable margin.

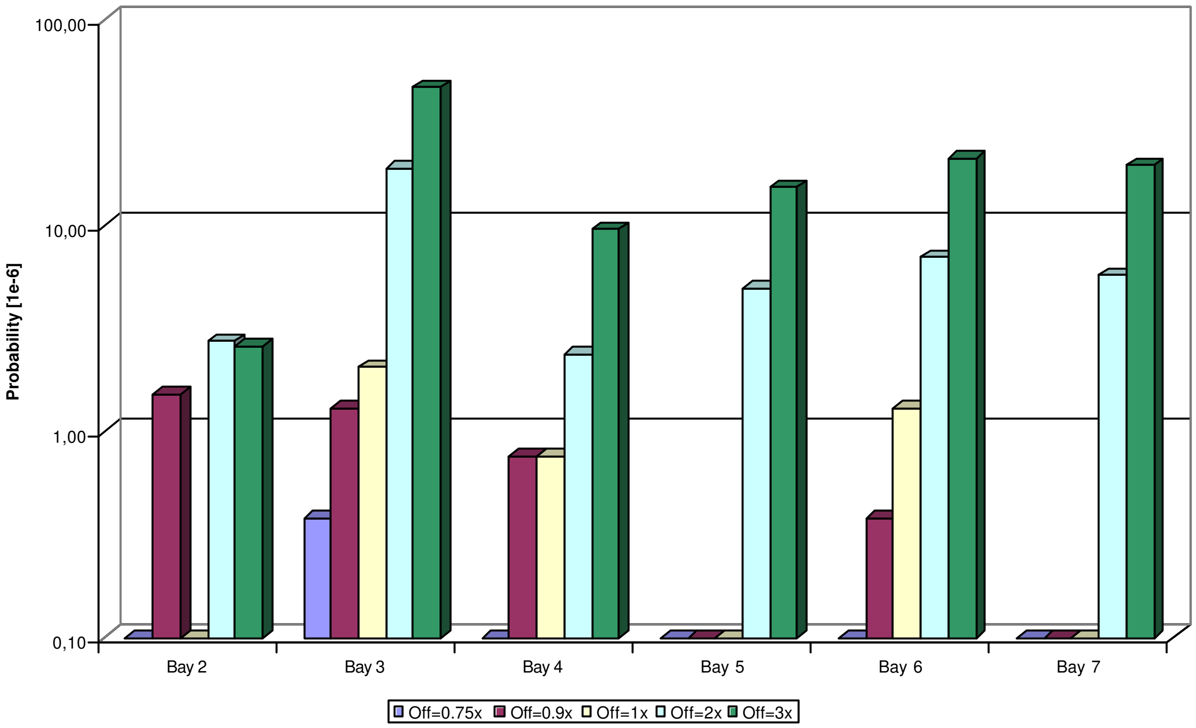


Figure 9.4 Probability of a balanced condition of 5 seconds or more for a variable multiplier and a fixed margin 5/2%.

From the figures the following conclusions can be made:

☞ The probability of a balanced condition does not depend on the number of houses connected to a feeder.

☞ The probability of occurrence of a balanced condition in a low voltage power network is well below 1E-6 to 1E-5.

9.2 Risk of encountering an island

Islanding happens only when the network is in a balanced condition and the network is disconnected at that very moment. The probability that islanding can occur is described in section 9.1. The probability that a part of a network is disconnected depends, in general, on how often maintenance is carried out on a low voltage power network. In a distribution network maintenance occurs is very seldom. In the Netherlands and in many other countries this is once every 5 to 10 years. Loss of mains is not directly a reason for balanced conditions as the loss of mains normally occurs at a ‘higher level’ in the power network or is a short circuit for which the inverters switch off automatically.

When multiplying the probability of a balanced condition with the probability of maintenance, the risk of encountering an island becomes virtually zero.

☞ The probability of encountering an island is virtually zero!

If in an unfortunate event a utility operative performs maintenance in a low voltage network and an islanding situation is present in the network he might be exposed to an unwanted presence of a voltage in the disconnected low voltage network. If he immediately touches the conductors he might experience an electrical shock. However, if he waits several seconds after the disconnecting the island becomes unstable and the voltage will disappear. Annex 5 and 6 show that an islanding condition never remains stable for more than 60 seconds.

☞ When waiting for 60 seconds after disconnecting of a low voltage power network an islanding condition, if present, will disappear due to the variation of the load.

The resulting risk and hazards involved with islanding are in detail described and discussed in [5].

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

In the report the following rules of thumb are made:

☞ Islanding is when a disconnected part of the power network is sustainable powered by the connected PV-systems or other embedded generators for a period of 5 or more seconds.

☞ A power network always requires reactive power.

☞ The maximum PV-power in a power network for which balanced conditions never occur is approximately two to three times the minimum night load of the relevant power network.

The minimum (night) load is fairly well know by utilities for varies parts of the network. Hence this rule of thumb can easily be used.

☞ Balanced conditions and subsequently probability of islanding can not occur if PV-systems are installed on every house with a power rating of about 400 W_{peak} or less.

From these rules of thumb it can be concluded that balanced conditions can only occur for a high penetration level of PV-systems connected to the low voltage power network. Balanced conditions do not occur when less than 400 W_{peak} is installed on every house. Although 400 W_{peak} is not an unrealistic size for a PV-system for an individual house it is the necessity that all houses in the residential area must equipped with at least a PV-system of 400 W_{peak}! In existing power networks where PV-systems are installed on the roofs it is not very likely that the 400 W_{peak} value is exceeded. In new to build residential areas where significant amounts of PV systems are planned, it is likely that the 400 W_{peak} value per house is exceeded.

☞ The margin (allowable mismatch) between load and generated PV power significantly determines the number and duration of balanced conditions.

The margins used in the evaluations can be categorised as from very strict to very wide. It is believed that the margin of 5% for active power and 2% is very likely to be realistic for electrical power networks. The wide margin of 15% for active power and 10% for reactive power are believed to be unrealistic. This must however be studied further.

☞ The penetration level of PV-systems does not significantly influence how often and for how long balanced conditions between the load and the PV-systems occurs.

☞ Balanced conditions between active and reactive load and the power generated by the PV-systems do occur very rarely for low, medium and even high penetration levels of PV-systems.

☞ Balanced conditions are randomly scattered over late spring, summer and early autumn

☞ The probability of a balanced condition does not depend on the number of houses connected to a feeder.

This conclusion is important as the number of houses connected to one feeder varies between countries. The study included feeders with only two houses connected up to 250 houses connected to one transformer. This shows the validity of the results for countries using pole-mounted transformers, normally feeding a few houses, and for countries using large distribution transformers feeding up to a few hundred houses.

☞ The probability of occurrence of a balanced condition in a low voltage power network is well below 1E-6 to 1E-5.

☞ The probability of encountering an island is virtually zero!

☞ When waiting for 60 seconds after disconnecting of a low voltage power network an islanding condition, if present, will disappear due to the variation of the load.

The overall conclusion of the work performed in this study is:

Balanced conditions occur very rarely for low, medium and high penetration levels of PV-systems. The probability that balanced conditions are present in the power network and that the power network is disconnected at that exact time is virtually zero.

Islanding is therefore not a technical barrier for the large-scale deployment of PV-system in residential areas.

10.2 Discussion in the validity of results for other types of power networks

For other countries two aspects may differ from the Dutch (North European) situation and may lead to the following interpretations of the results of this study:

1 Different solar irradiation pattern

Countries like California, Australia and the southern countries in Europe have a different solar irradiation pattern. For these countries the solar irradiation does not vary too much due to clouds, fog and other weather conditions. Also, the seasonal influence on the solar irradiation is limited.

Although not reported in this study the effect of this difference in solar irradiation pattern was investigated. By looking at many balanced conditions during the data analysis it was observed that during a balanced condition the solar irradiation is constant while the changes in the load causes an unbalance after a few seconds. From this it is concluded that the number of balanced conditions and duration does not significantly vary for a different solar irradiation pattern, hence other countries. The results and conclusions of this study will in general be relevant for these countries as well.

2 Different load profile

The houses in the residential area studied have a typical load in terms of electric appliances. Like in many other countries all Dutch houses have refrigerators and washing machines. The Dutch houses do not have air-conditioners when compared to more sunny countries. It is believed that the presence or air-conditioners have an effect on the results of this study as the (average) load of a house and power network is significantly higher.

This higher load means that the frequency distribution charts of the ratio (figure 5.2 and annex 3) shifts to the right. Also, the active power frequency distribution charts (figure 5.5 and annex 4) shifts to the right. This means that the PV-power for which balanced conditions cannot occur will increase. In this study we found 400 W_{peak} as the maximum PV-power on every house. For countries with a high air-conditioner load this value will be (much) higher.

It is expected that the presence of air-conditioners will not significantly change the number and duration of balanced conditions as air-conditioners do switch on and off.

10.3 Recommendations

It is strongly recommended that PV-inverters are operated at unity power factor. It is not advised to use PV-inverters with a variable power factor as this, at high penetration levels, may increase the number of balanced conditions and subsequently increase the probability of islanding.

Some discussions deal with the idea that in a power network with a surplus of PV-power islanding can occur. The idea is that due to the surplus of PV-power the voltage will rise and that some inverters will switch off, until a certain number of PV-inverters are keeping the voltage at the maximum voltage. In this study it is not possible to determine whether this could be true or not. However, when looking at the dynamic response of modern inverters and the electrical phenomena in power networks it is believed that this effect will not occur as unbalance in a power network immediately result in a significant change of voltage and/or frequency. A phenomena that is by far faster than the response time of any inverter.

Many islanding detection methods, sometimes very costly, are in use in the world and together with various test circuits to determine the effectiveness of the islanding detection method. All these test circuits have in common that a 100% balanced condition for active and reactive power balance is achieved before opening the test circuit. After the opening of the test circuit no alterations are made to active or reactive flow. This study showed that changes in the active and reactive load occur very frequently. It is recommended to include a small change, for example a few percent after a few seconds, in the matching load of the test circuit. This approach is realistic, as a 100% balanced match of active and reactive power does not occur in power networks. This may result in less complex islanding detection methods which are economically very cost effective.

Maintenance crews of utilities have to be informed that power sources may be connected to their low voltage power network. When maintenance is performed and islanding of the disconnected section is observed, it is recommended that the person wait for a few seconds. The islanding situation is expected to dissolve in a time frame of seconds or a minute. It is not recommended to actively disturb the islanding by grounding or reconnection for the power network because this may lead to dangerous situations.

11. REFERENCES

[1] IEA Task V: report IEA-PVPS T1-04: 'Information on electrical distribution systems in related IEA countries (revised version)', March 1998.

[2] IEA Task V: report IEA PVPS T5-02: 'Demonstration test results for grid interconnected photovoltaic power systems', March 1999

[3] Personal discussions with Christoph Panhauber from Fronius A.G. in Austria about sensitivity for balanced conditions for reactive and reactive power.

[4] Discussion with various national and international experts in the field of power system analysis and power system stability.

[5] IEA Task V: report IEA-PVPS T5-08: 'Risk Analysis of islanding of photovoltaic power systems within low voltage distribution networks', 2002.

12. ACKNOWLEDGEMENT

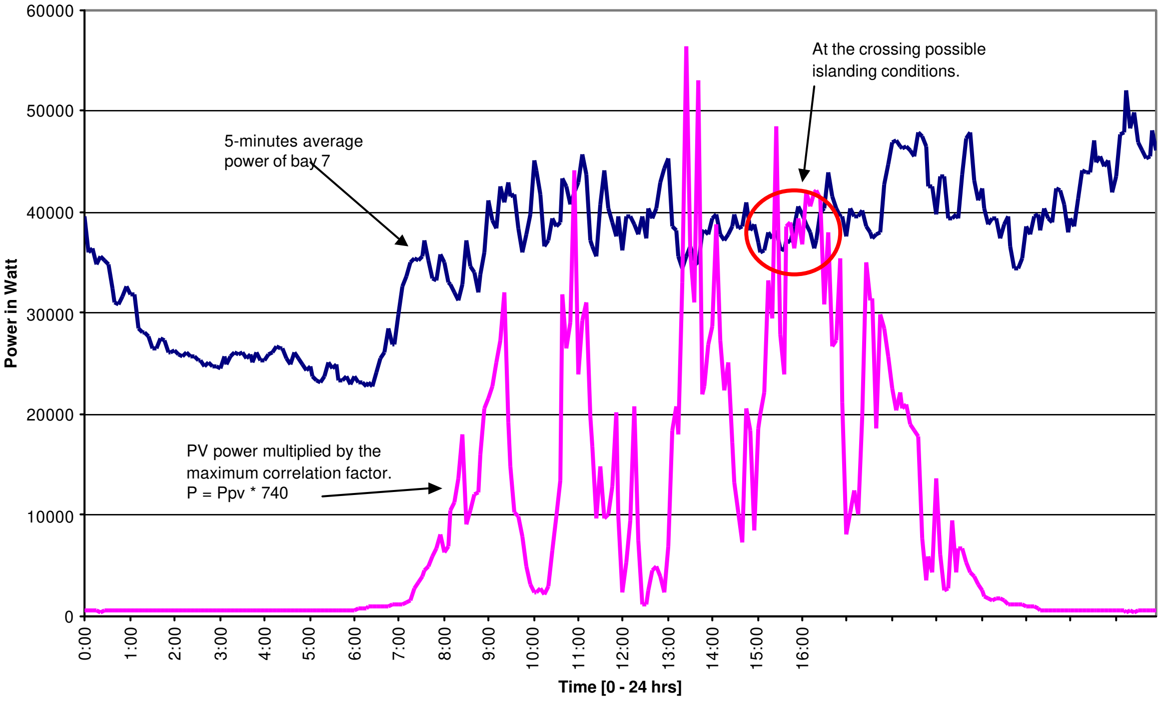
- The research work on the probability of islanding was funded by EnergieNed and NOVEM
- The KEMA organisation made a significant contribution in the data analysis and discussions with numerous discussions with experts in the field of distribution of electrical energy.
- The utility NUON is acknowledged for their kind permission to access the transformer cabinet for the measurements and their assistance during the collection of the data.
- The work has been discussed with the Task V working group. I kindly acknowlegde their support and fruitful discussions. Special thanks to Christoph Panhuber, Alan Collinson, Neil Cullen and Ronald van Zolingen for their critical and crucial discussions.
- Rob van Gerwen from KEMA is acknowledged for his kind assistance for the characterisation of the residential area as described in section 3.2.
- The sometimes-tedious data analysis, evaluations and reporting were made during many evenings. I thank my wife Bianca and daughters Rodé and Lynn for their support and patience.

ANNEXES

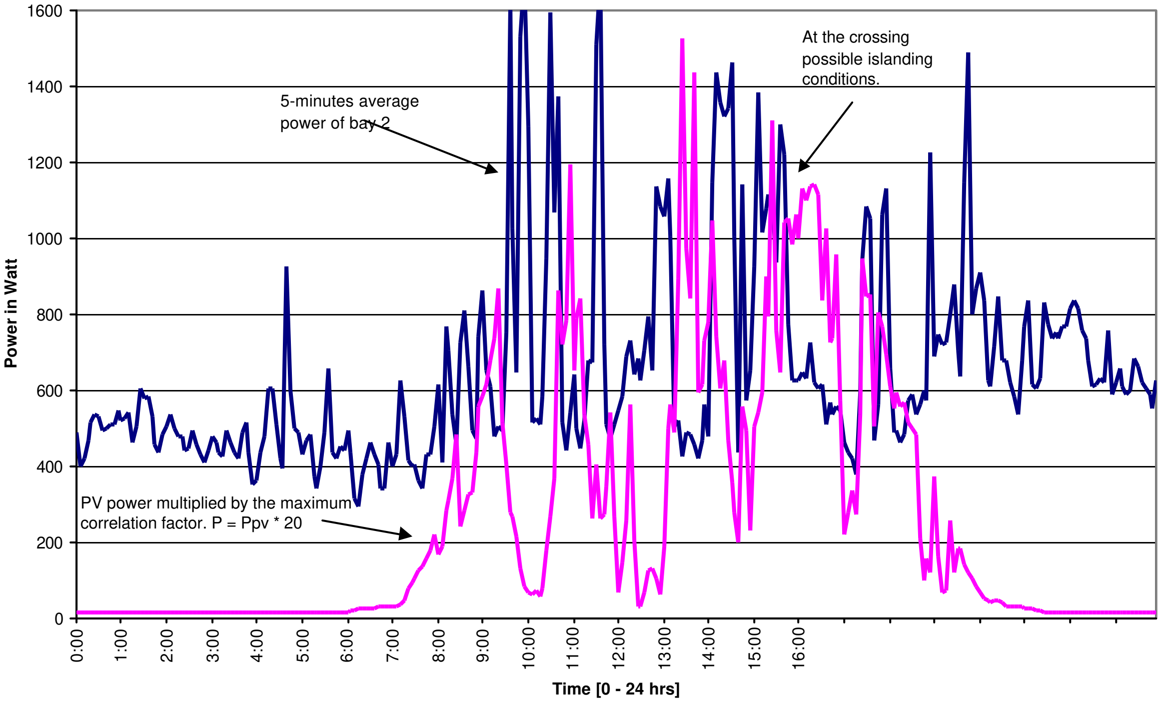
An overview of the annexes is given in the table below.

Annex	Title
1	Load profile at transformer for July 15 –1999
2	Load profile at transformer for December 15 – 1999
3	Ratio between load and PV of Bay 2 through 7
4	Active power frequency distribution chart for Bays 1 – 7
5	Balanced conditions - fixed multiplier and variable margin
6	Balanced conditions - fixed margin and variable multiplier

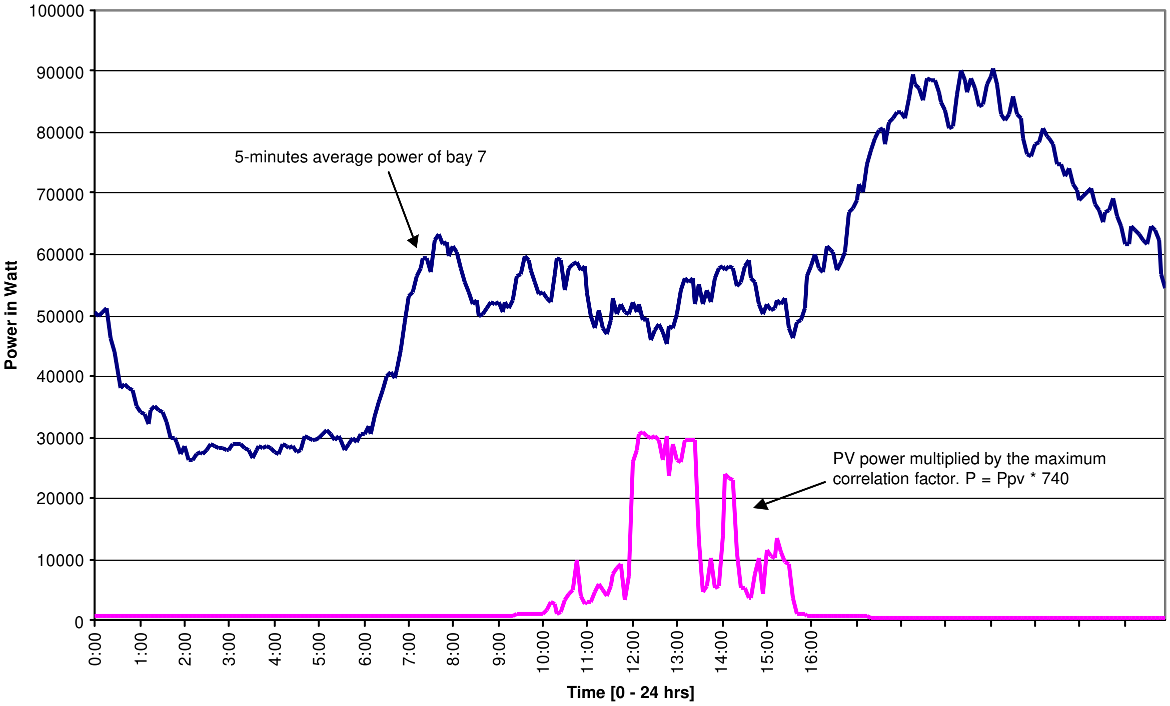
ANNEX 1 LOAD PROFILE AT TRANSFORMER FOR JULY 15 –1999



Average (5-minutes) load profile per phase of Bay 7 The power produced by the PV-system is multiplied the peak ratio (740 times). At the crossings of the load and PV-power balanced conditions may be stable for several seconds. The figure below shows the average load of the smallest Bay that includes only 2 houses per phase. The peak ratio for Bay 2 is 20.



ANNEX 2 LOAD PROFILE AT TRANSFORMER FOR DECEMBER 15 – 1999



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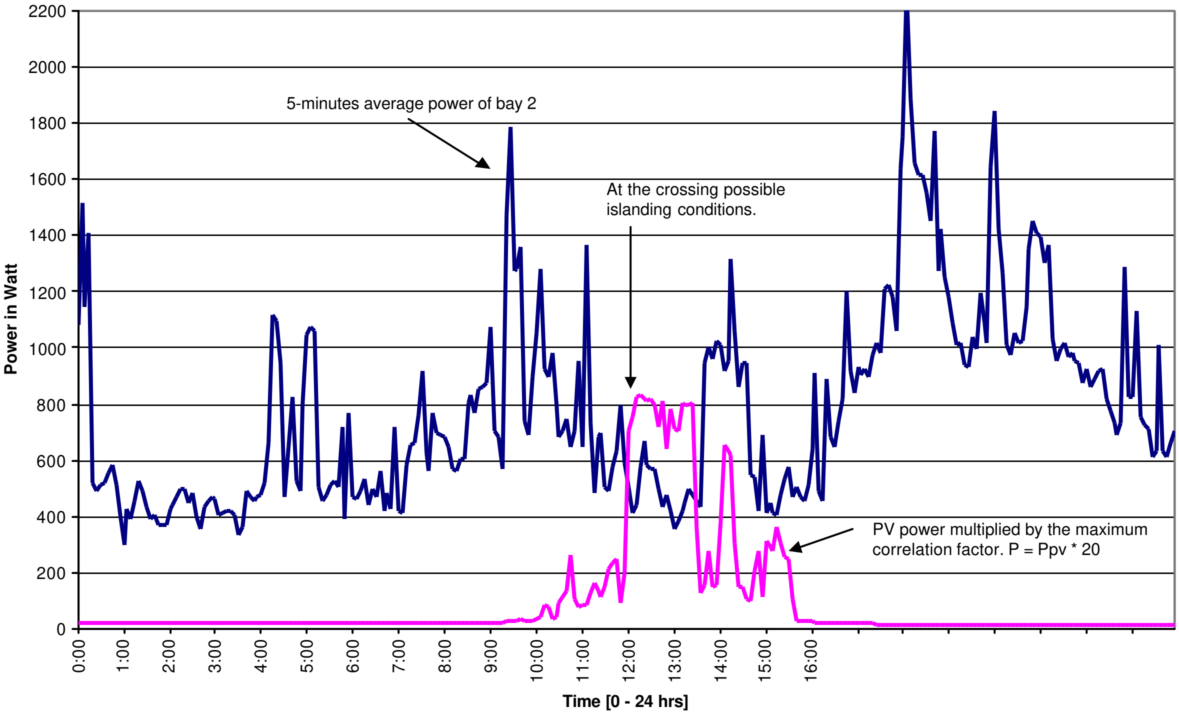
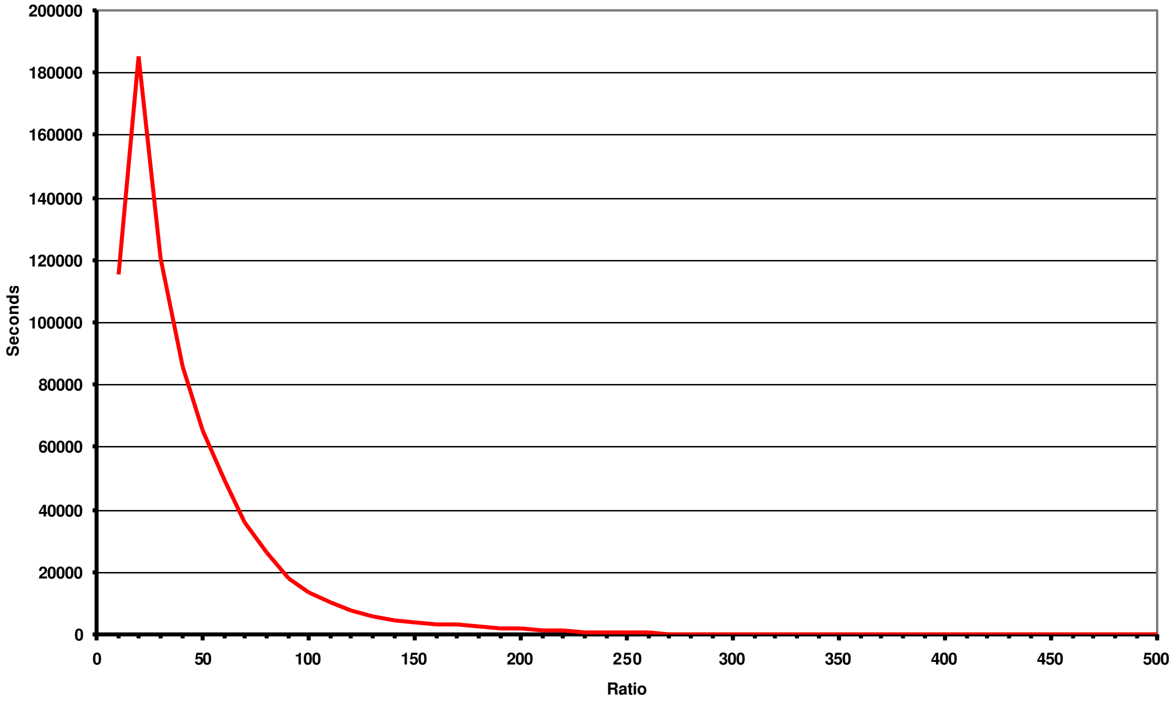


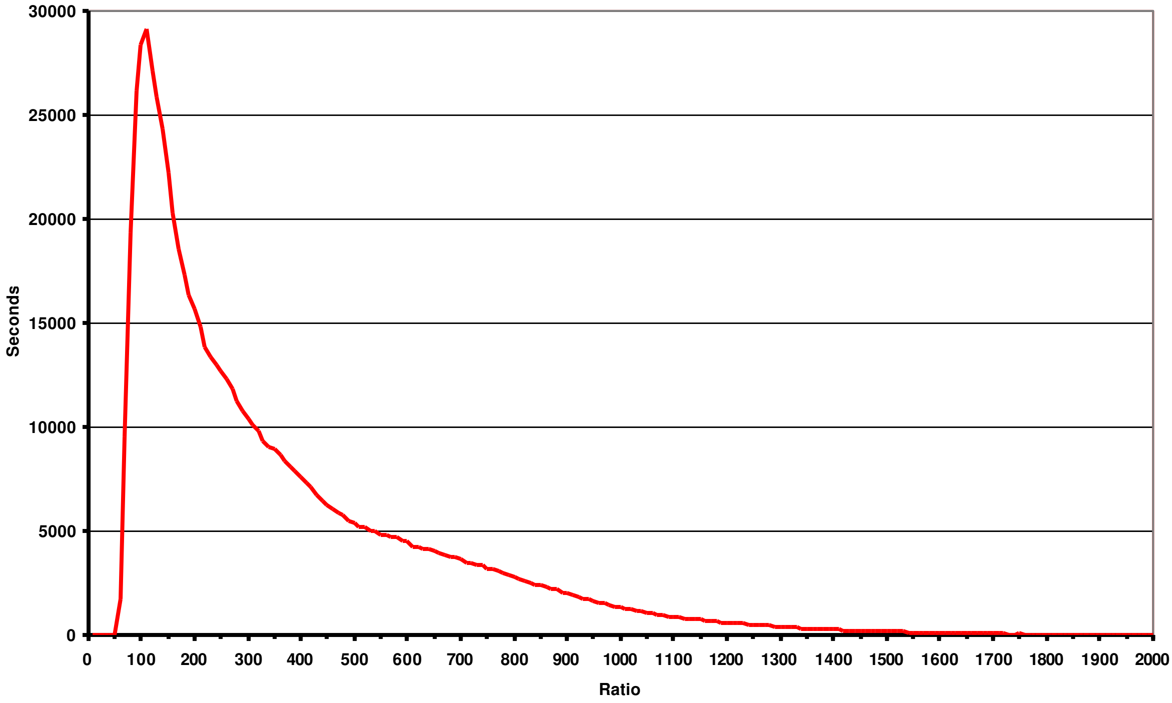
ANNEX 3 RATIO BETWEEN LOAD AND PV FOR BAY 2 THROUGH 7

Frequency distribution chart of the ratio between the loading of the power network and the power generated by the PV-system for the Bays 2 trough 7. The ratio is calculated over one full year per phase. The graph shows the average ratio for the three phases.

Bay 2

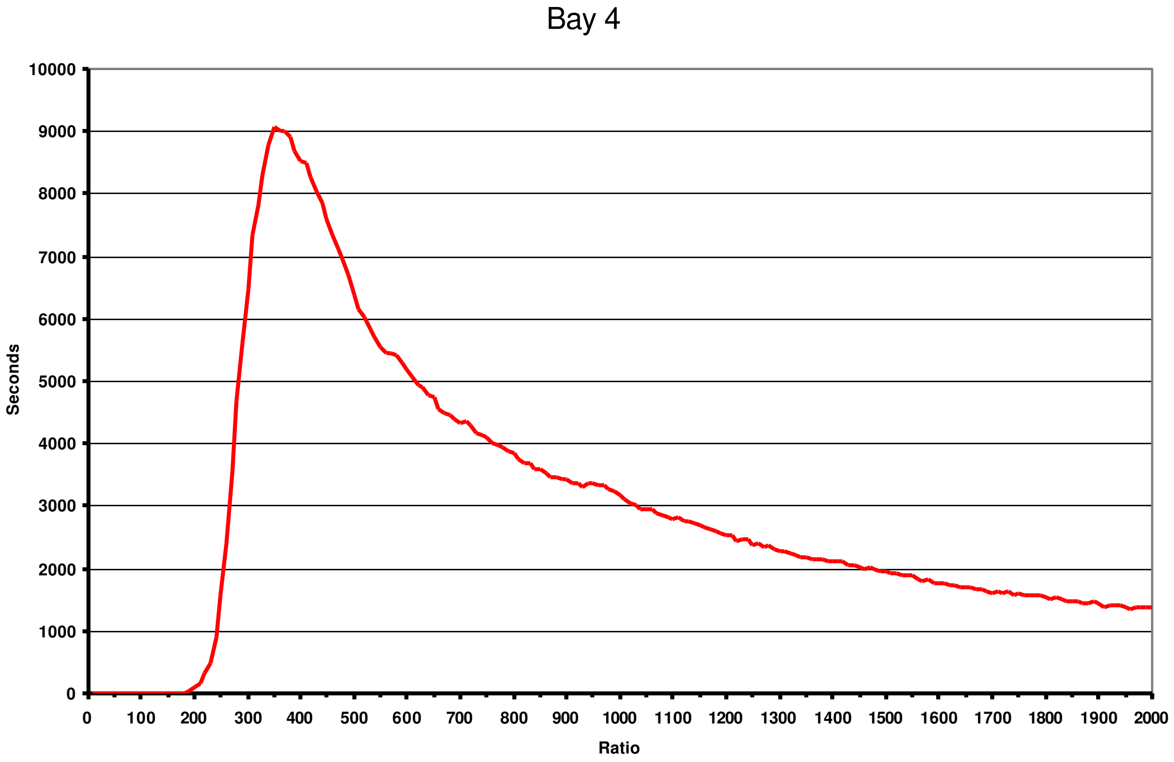


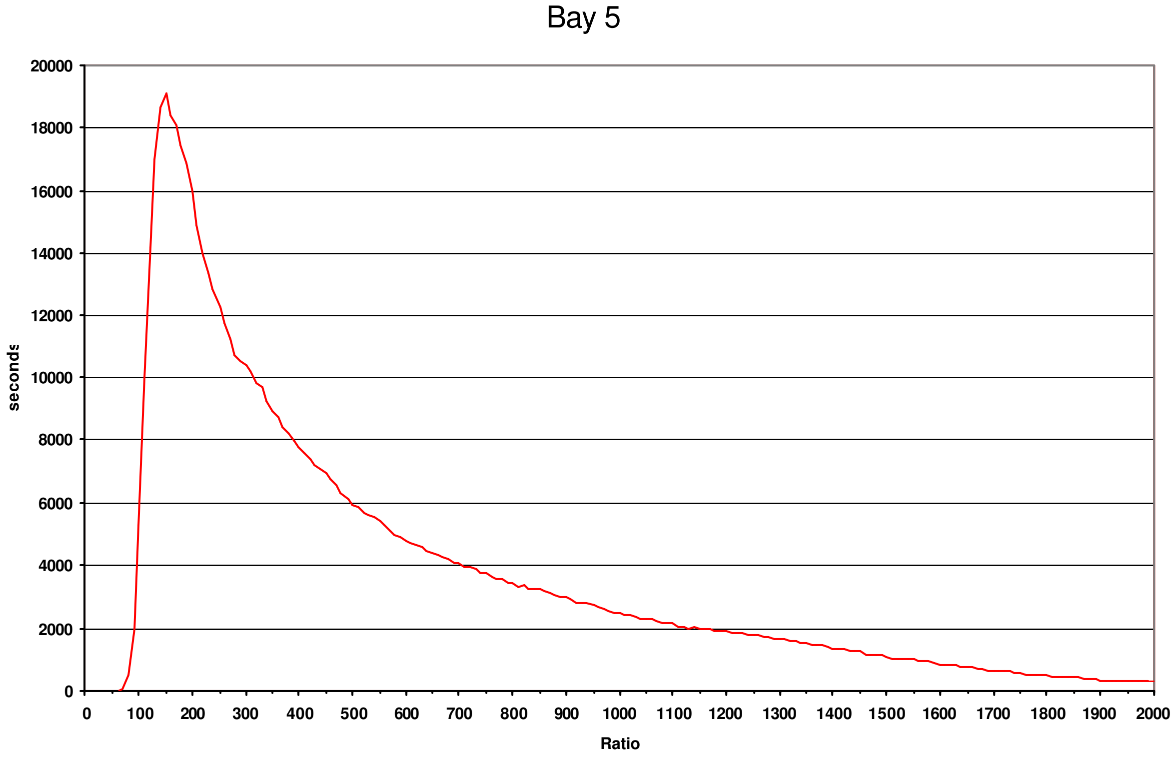
Bay 3



ANNEX 3 RATIO BETWEEN LOAD AND PV FOR BAY 2 THROUGH 7

Frequency distribution chart of the ratio between the loading of the power network and the power generated by the PV-system for the Bays 2 trough 7. The ratio is calculated over one full year per phase. The graph shows the average ratio for the three phases.

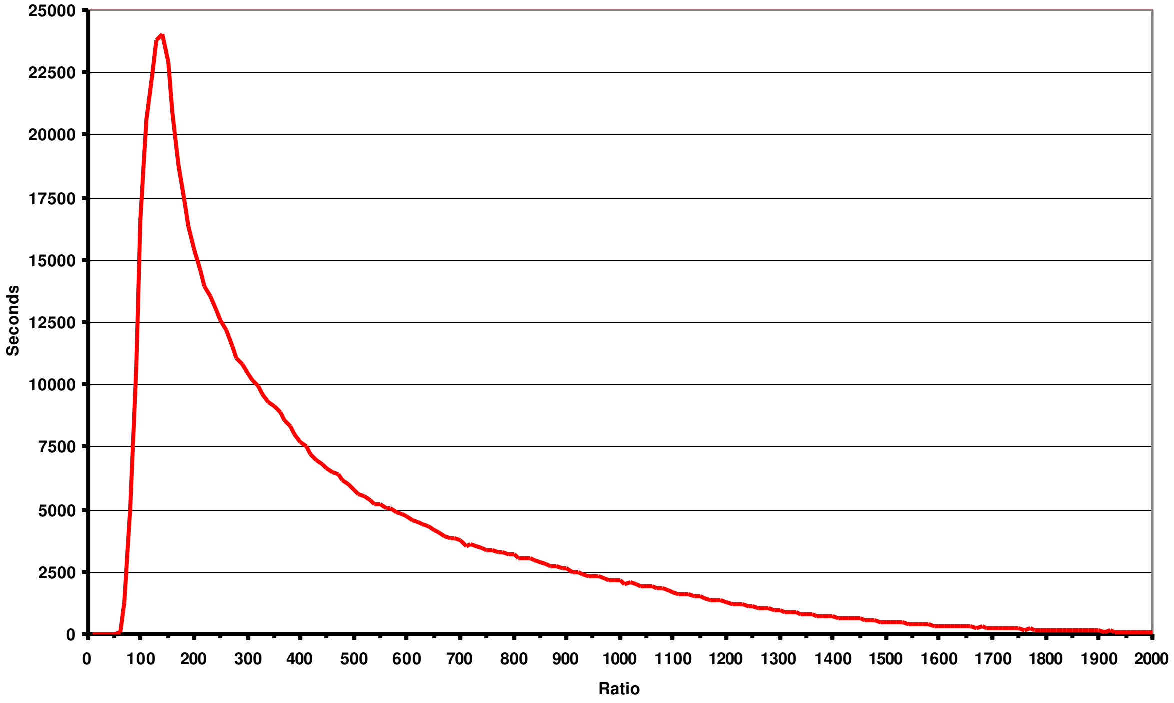




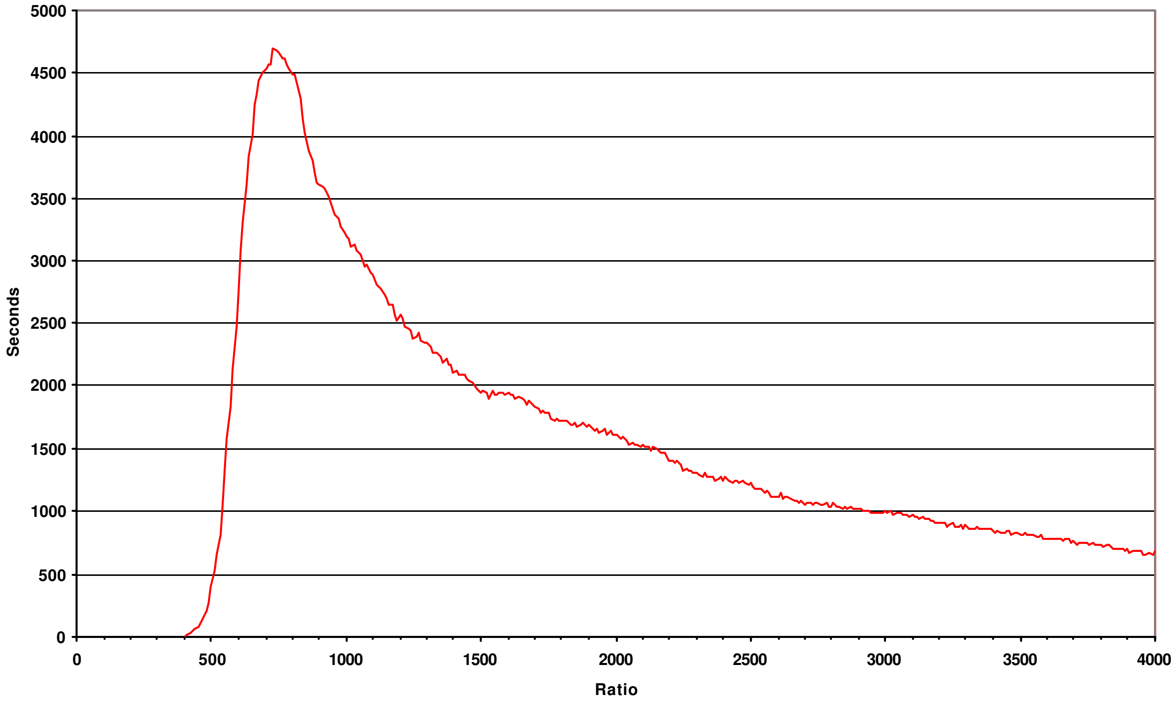
ANNEX 3 RATIO BETWEEN LOAD AND PV FOR BAY 2 THROUGH 7

Frequency distribution chart of the ratio between the loading of the power network and the power generated by the PV-system for the Bays 2 trough 7. The ratio is calculated over one full year per phase. The graph shows the average ratio for the three phases.

Bay 6



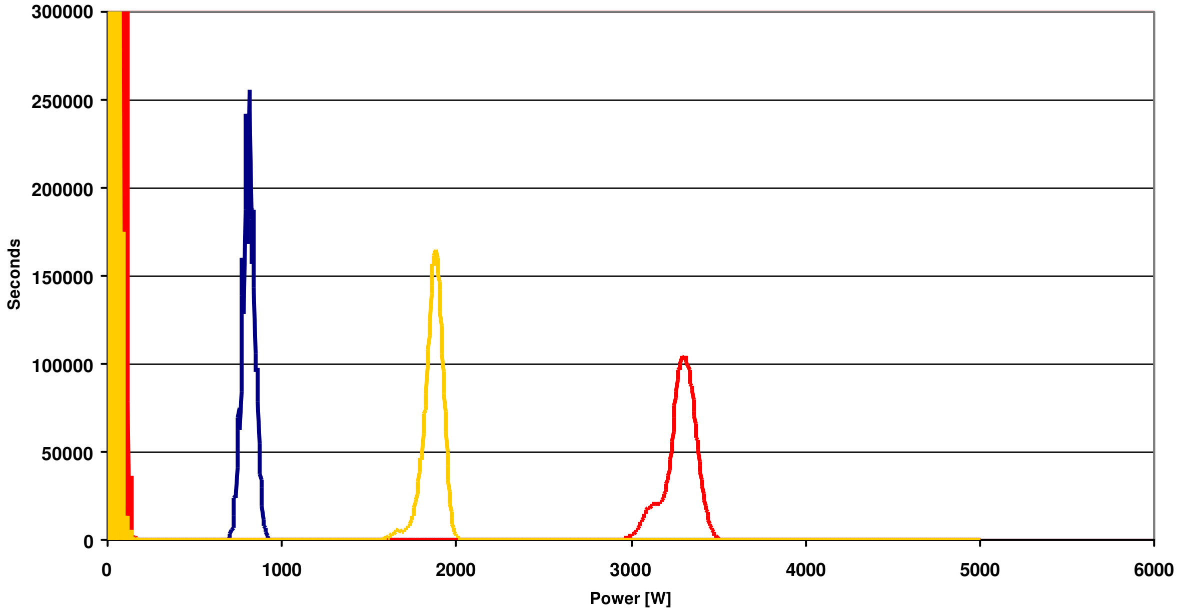
Bay 7



ANNEX 4 ACTIVE POWER FREQUENCY DISTRIBUTION CHART FOR BAYS 1 - 7

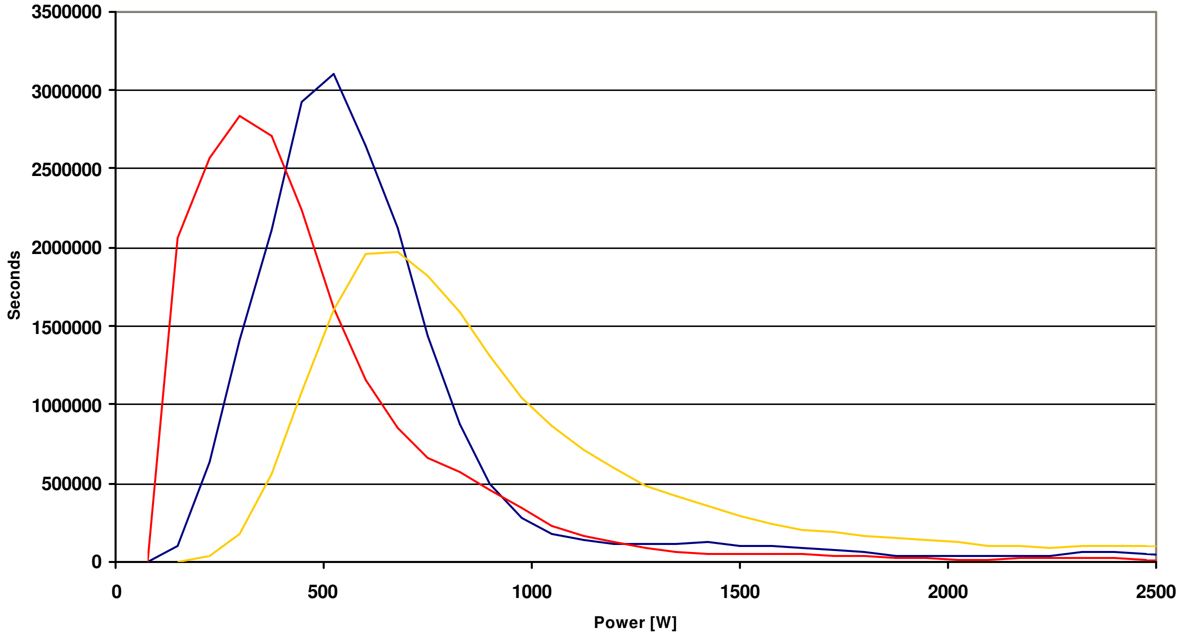
Active power frequency distribution charts for the Bays 1 through 7. The graphs present one full year and for day and night.

Active Power Distribution Bay 1 = Public Lighting



From the graph of Bay 1 we can conclude that the public lighting is not equally distributed over the three phases. The lines on the left-hand side of the graph close to the y-axis is noise

Active Power Distribution Bay 2



ANNEX 4 ACTIVE POWER FREQUENCY DISTRIBUTION CHART FOR BAYS 1 - 7

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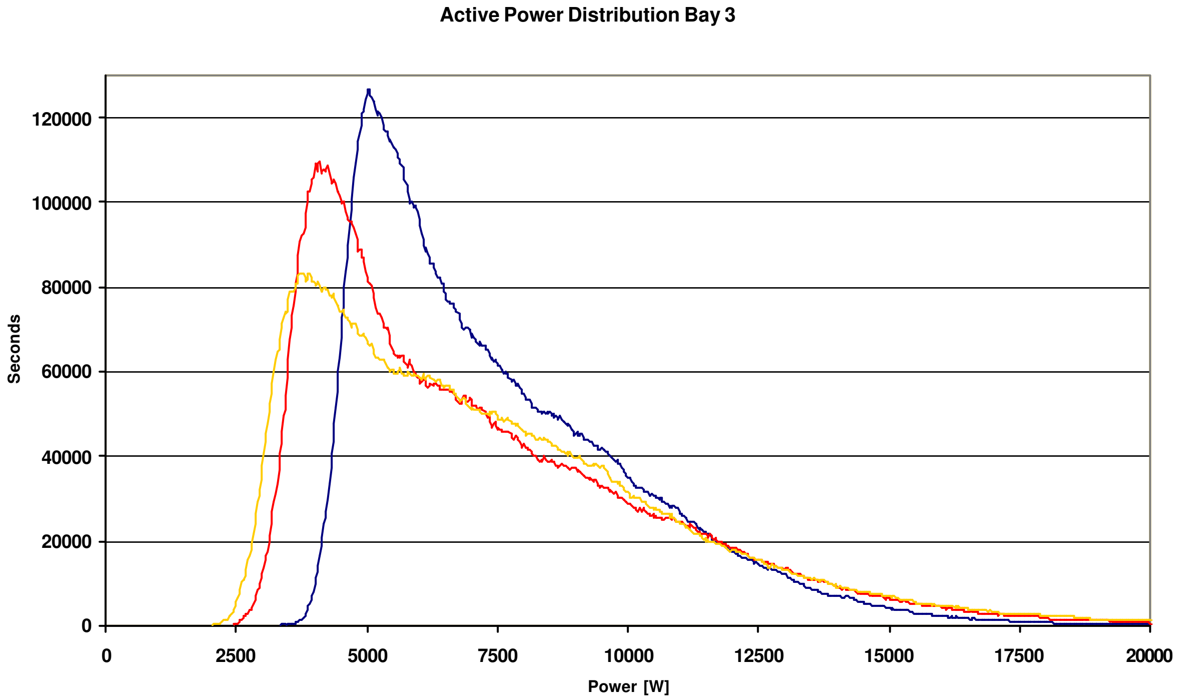
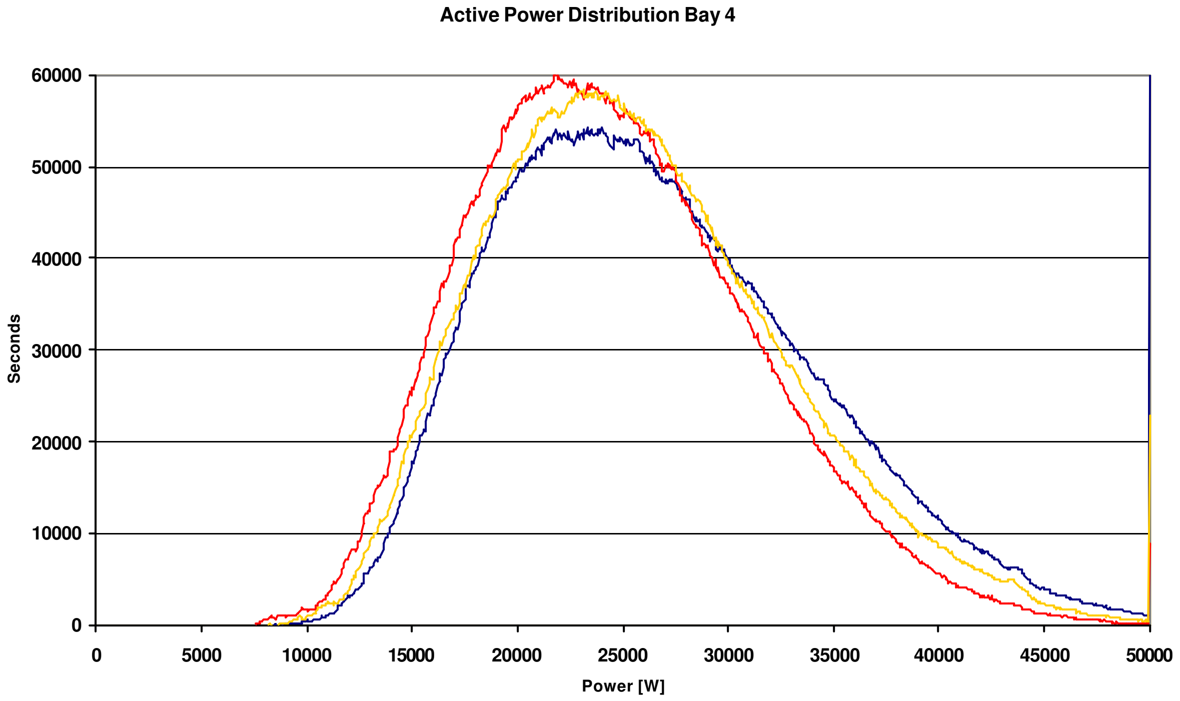
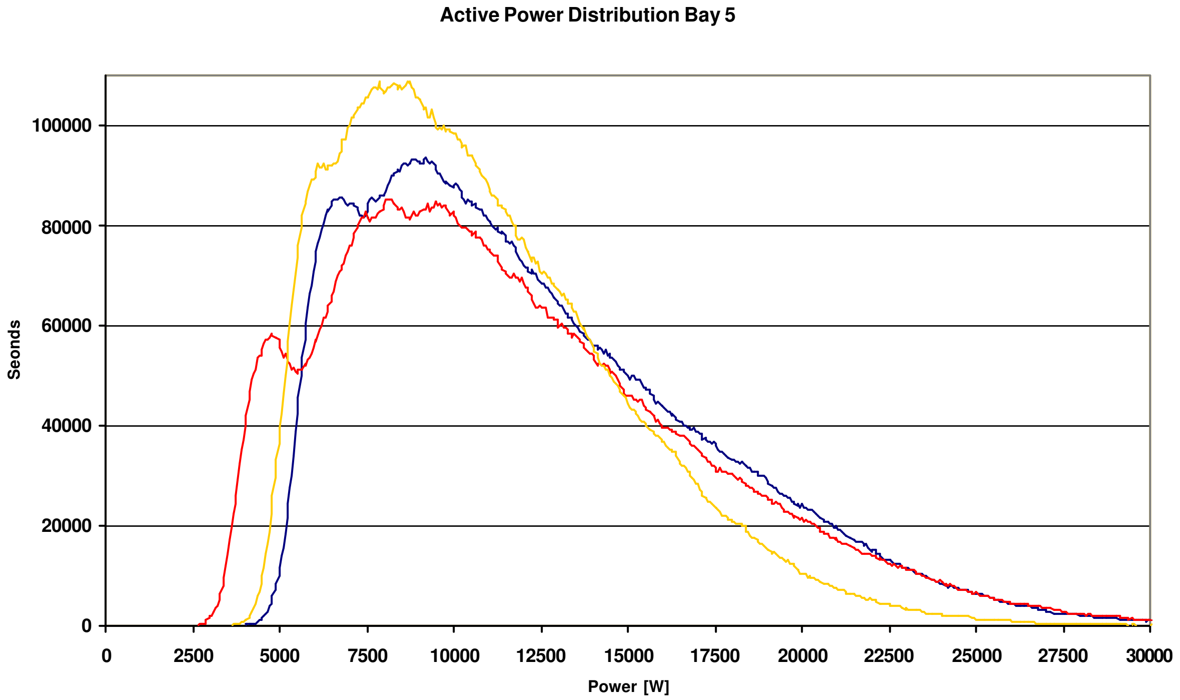
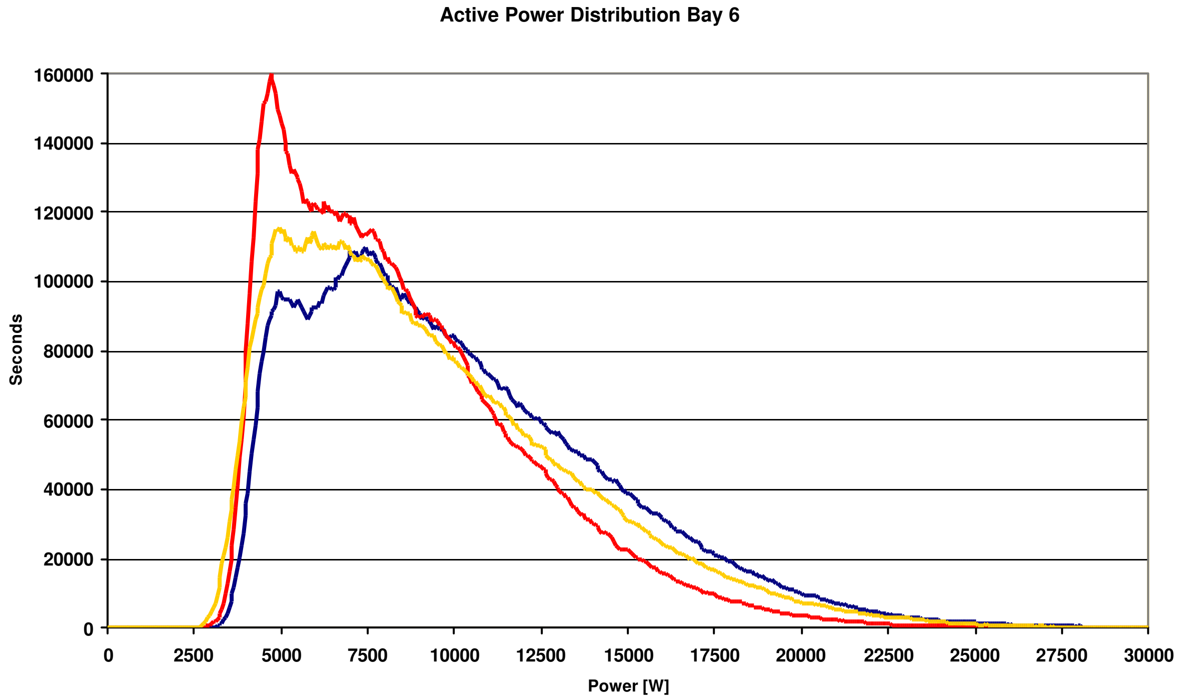




ANNEX 4 ACTIVE POWER FREQUENCY DISTRIBUTION CHART FOR BAYS 1 - 7

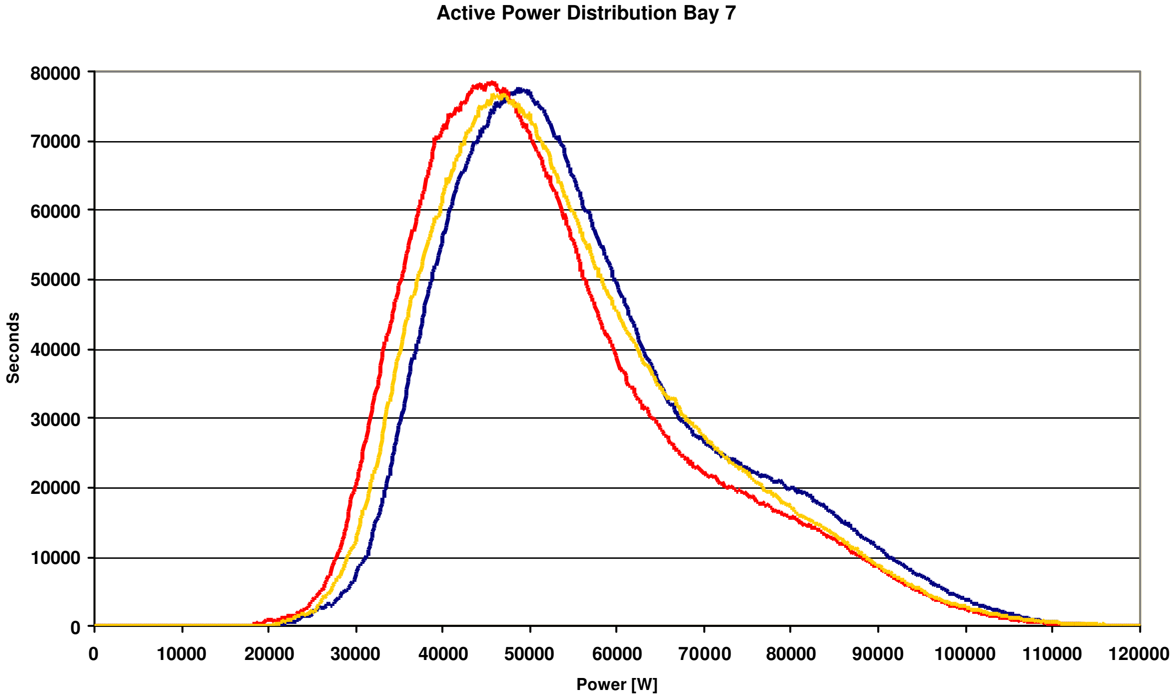
Active power frequency distribution charts for the Bays 1 through 7. The graphs present one full year and for day and night.





ANNEX 4 ACTIVE POWER FREQUENCY DISTRIBUTION CHART FOR BAYS 1 - 7

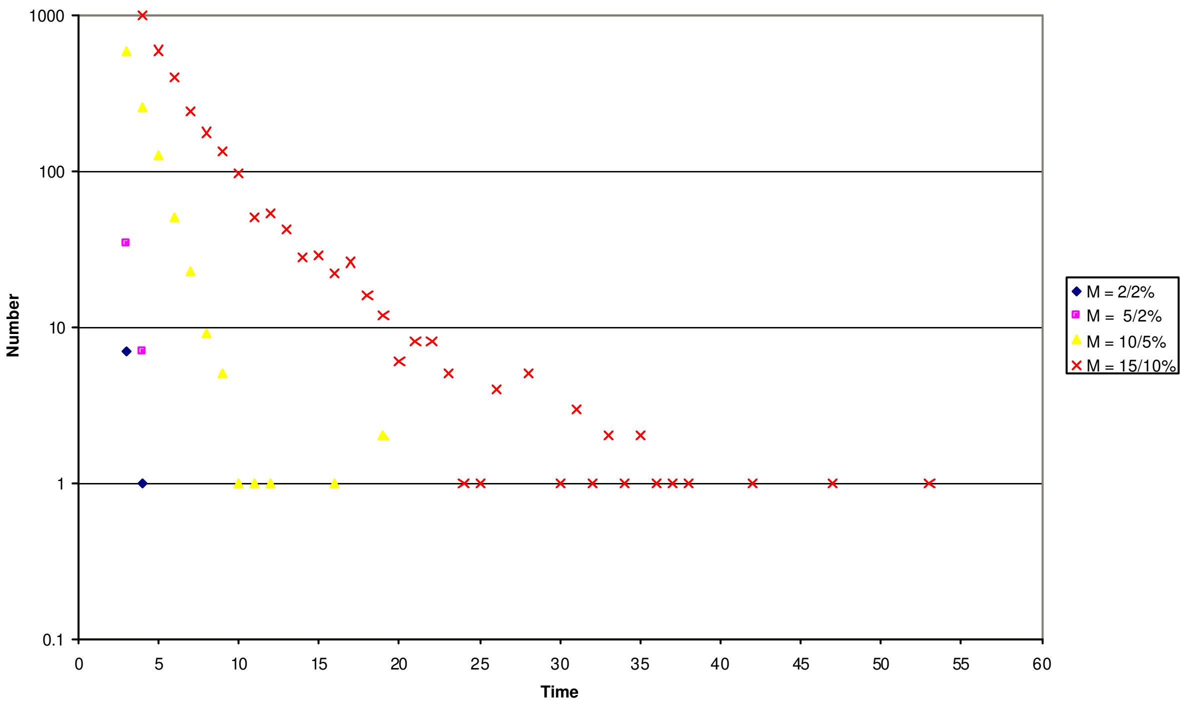
Active power frequency distribution charts for the Bays 1 through 7. The graphs present one full year and for day and night.



ANNEX 5 BALANCED CONDITIONS - FIXED MULTIPLIER AND VARIABLE MARGIN

Balanced conditions for active and reactive power for Bay 1 through 7 when using fixed multiplier and variable margin.

BAY 2



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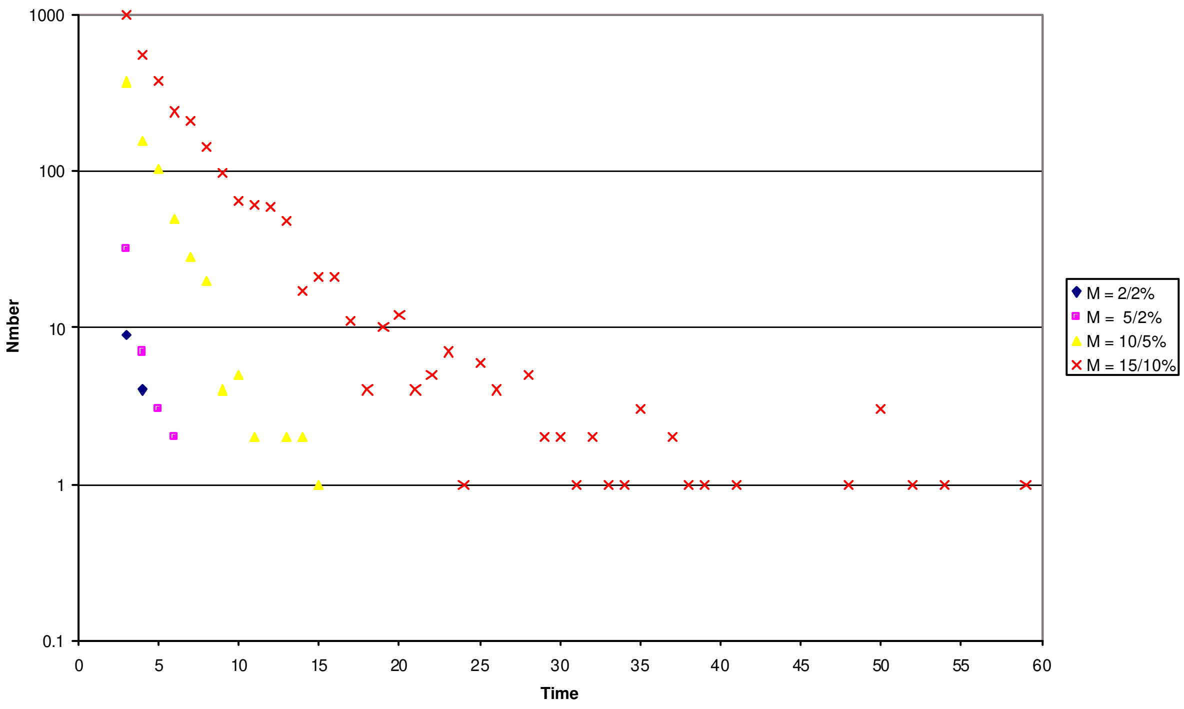
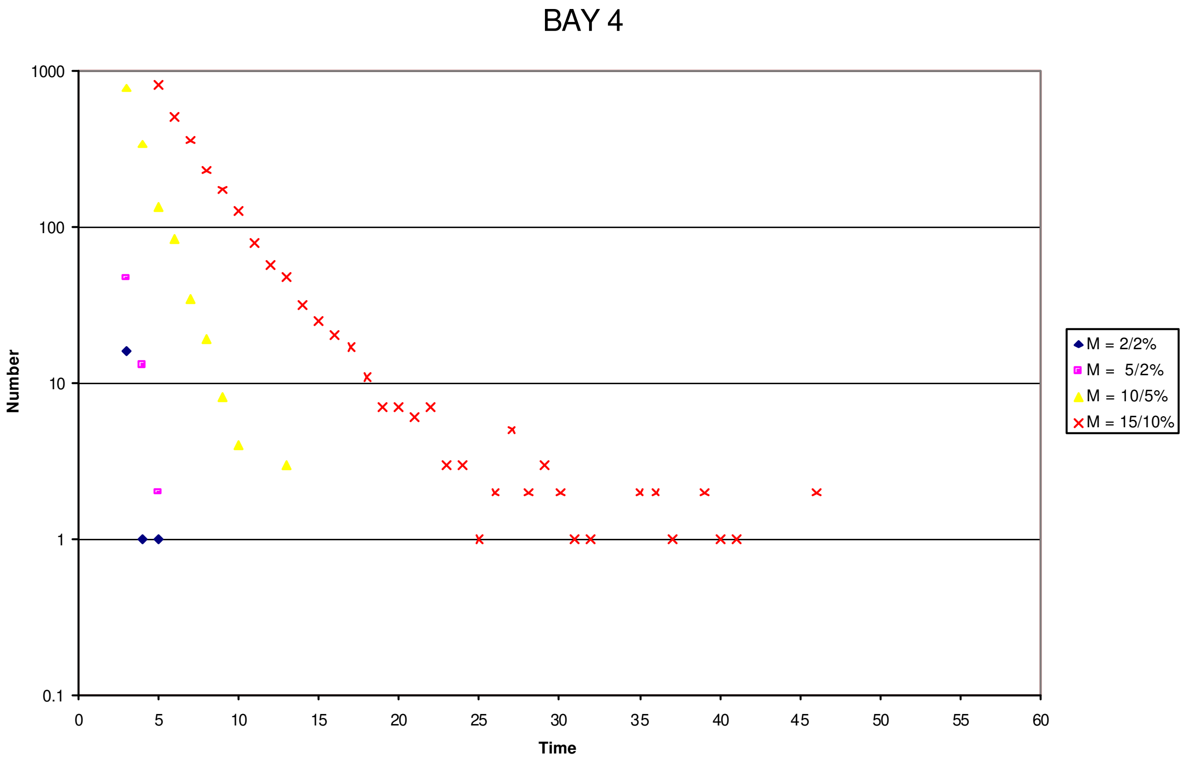
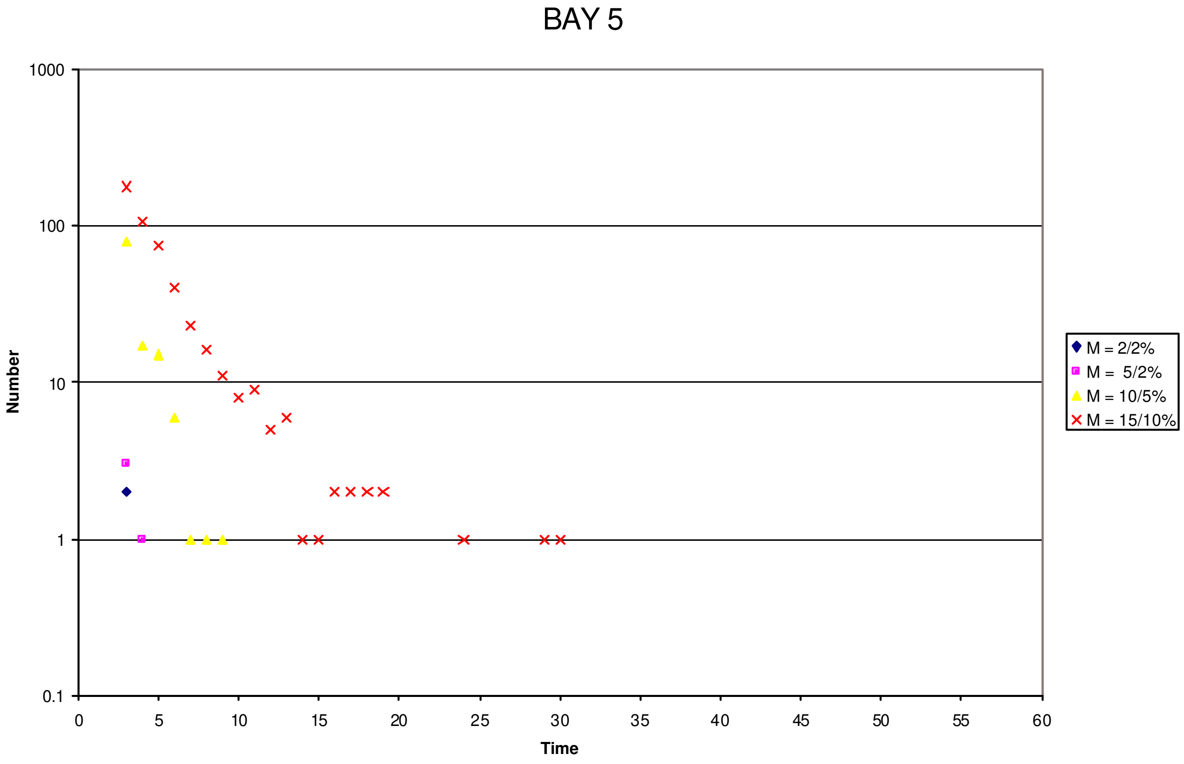


ANNEX 5 BALANCED CONDITIONS - FIXED MULTIPLIER AND VARIABLE MARGIN

Balanced conditions for active and reactive power for Bay 1 through 7 when using fixed multiplier variable margin.

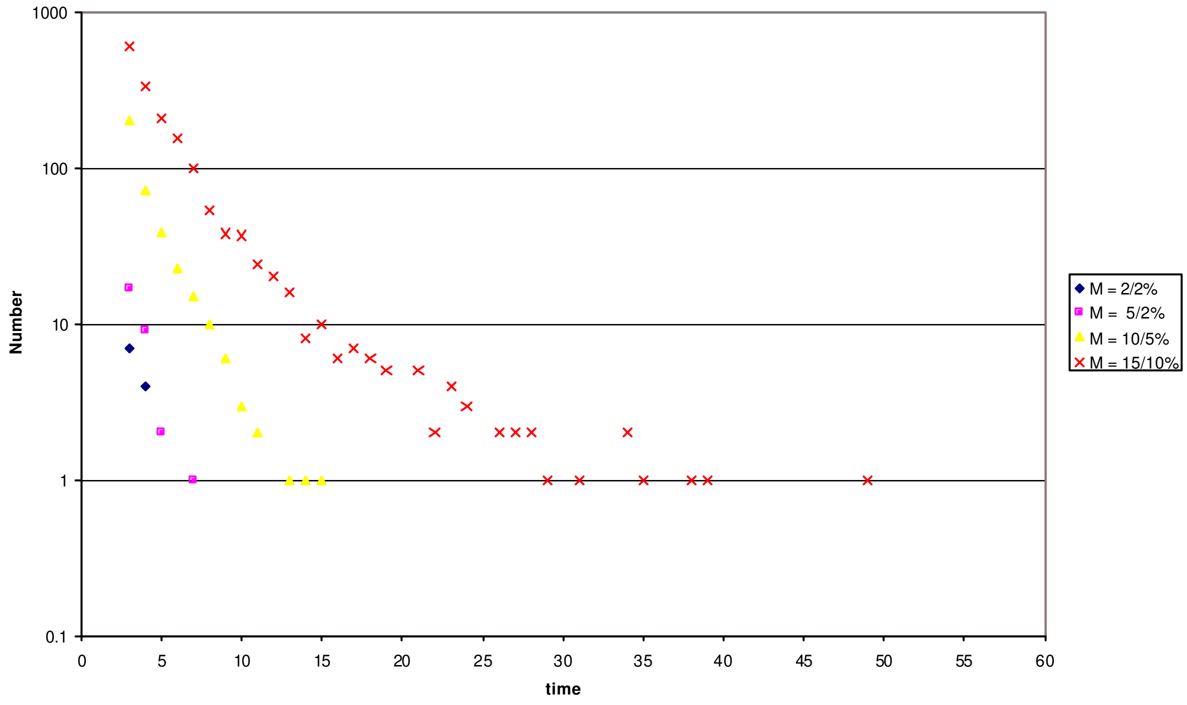




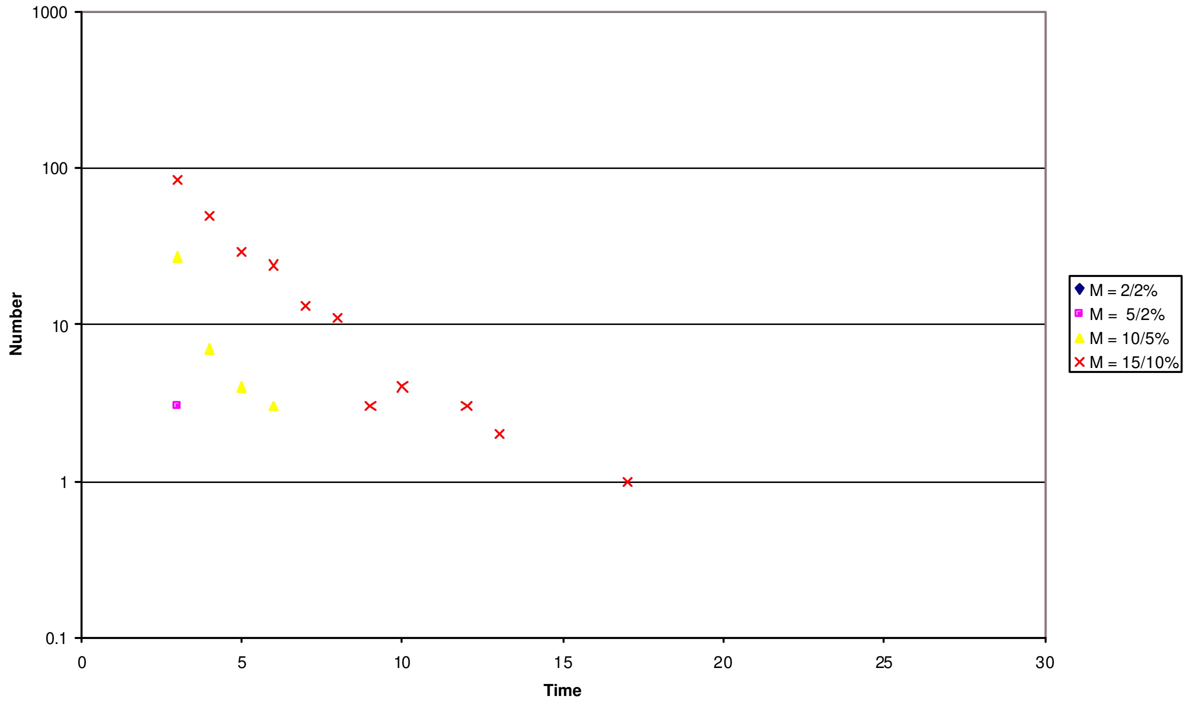
ANNEX 5 BALANCED CONDITIONS - FIXED MULTIPLIER AND VARIABLE MARGIN

Balanced conditions for active and reactive power for Bay 1 through 7 when using fixed multiplier and variable margin.

BAY 6

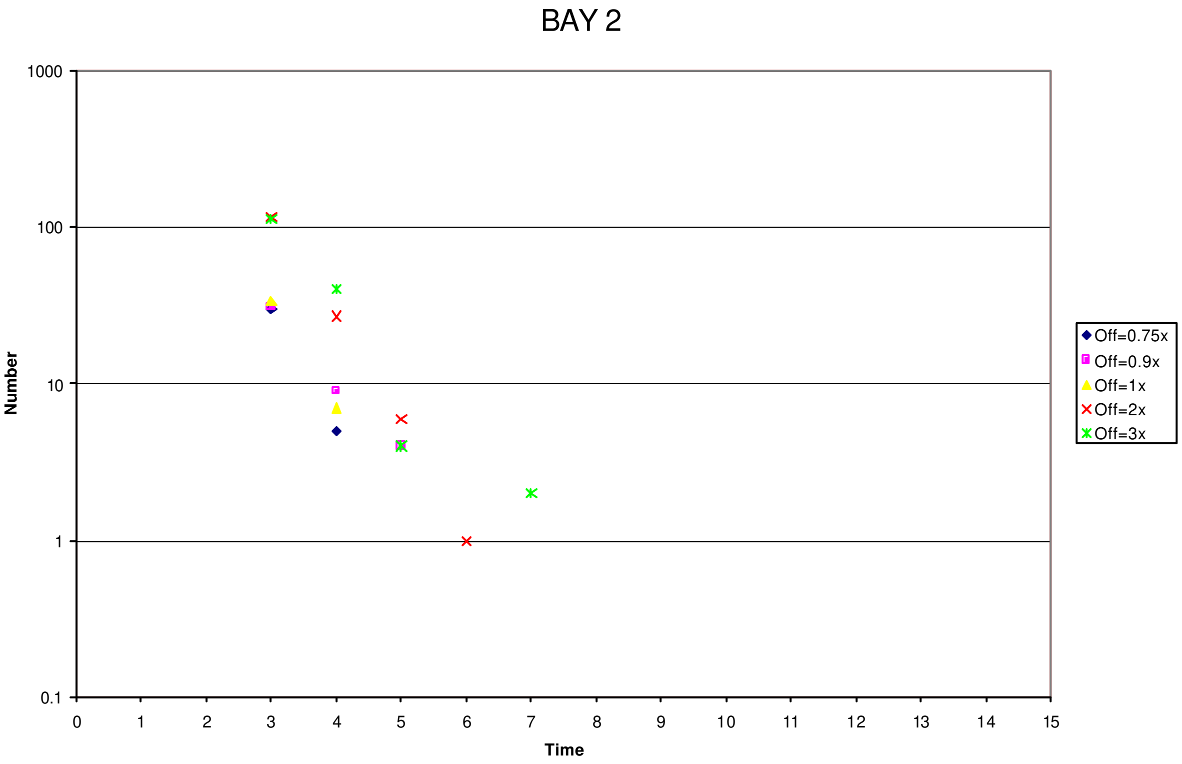


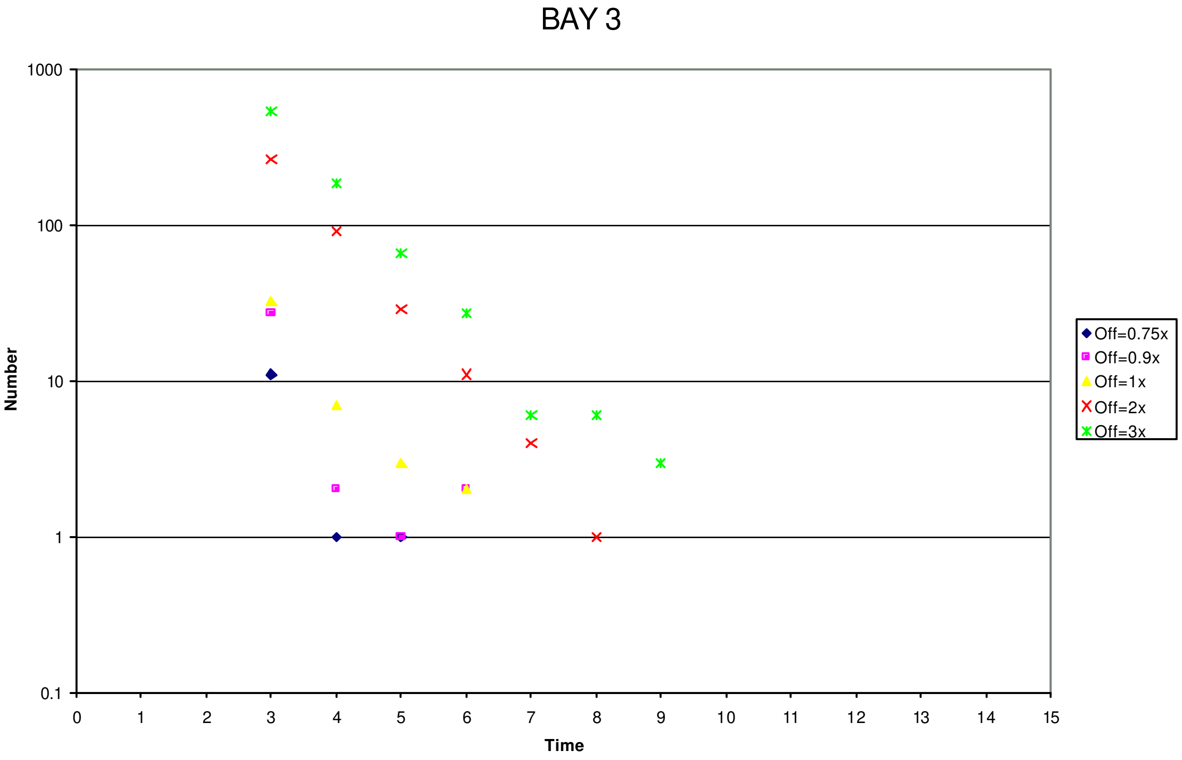
BAY 7



ANNEX 6 BALANCED CONDITIONS - FIXED MARING AND VARIABLE MULTIPLIER

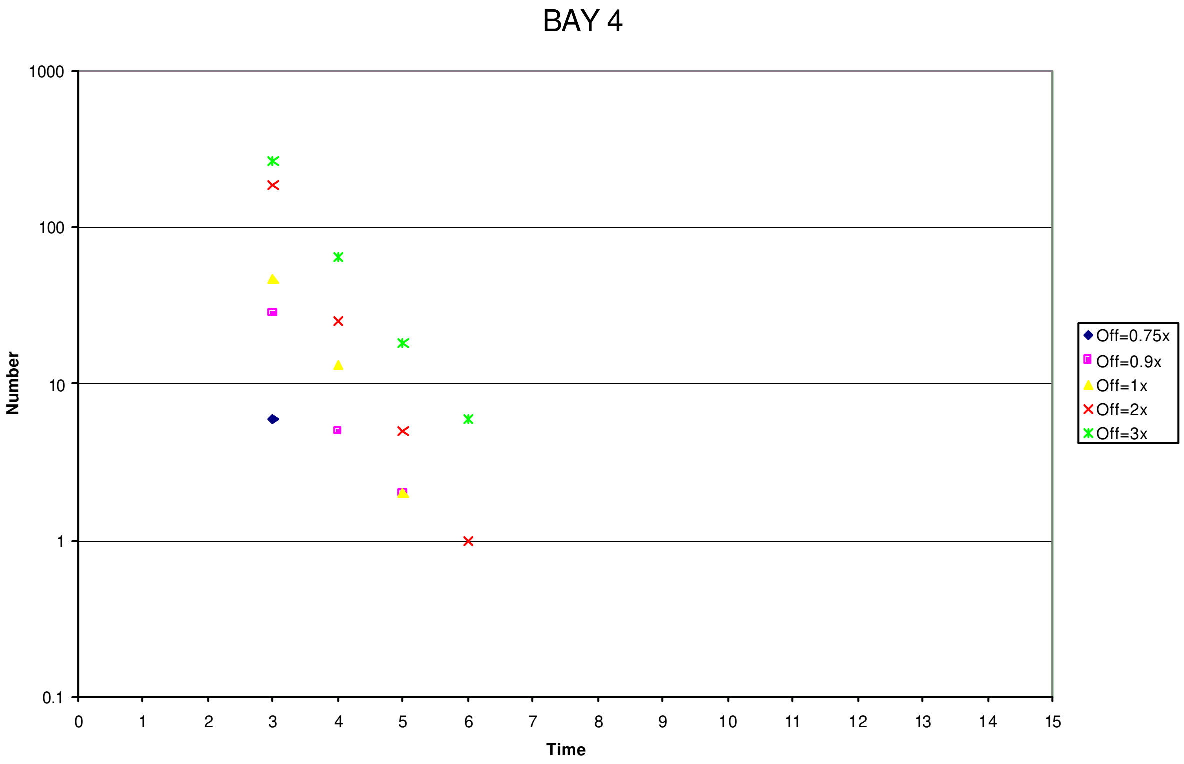
Balanced conditions for active and reactive power for Bay 1 through 7 when using fixed margin and variable multiplier.

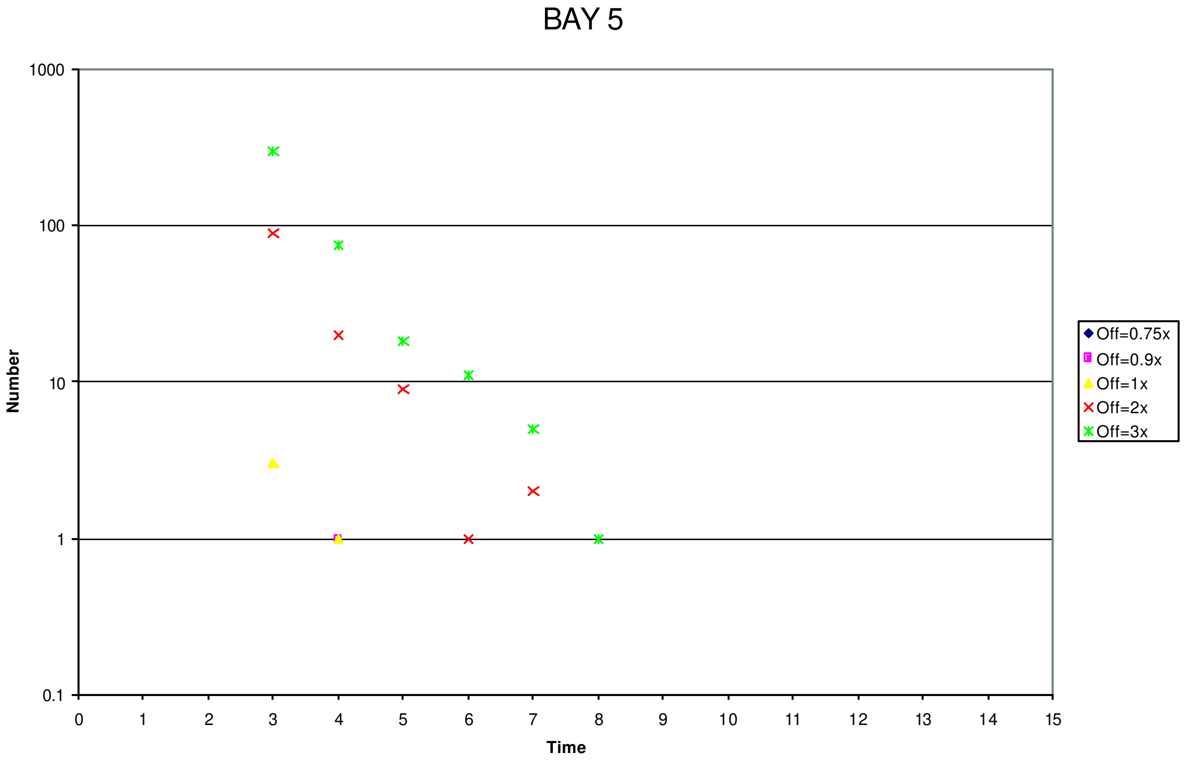




ANNEX 6 BALANCED CONDITIONS - FIXED MARING AND VARIABLE MULTIPLIER

Balanced conditions for active and reactive power for Bay 1 through 7 when using fixed margin and variable multiplier.





ANNEX 6 BALANCED CONDITIONS - FIXED MARING AND VARIABLE MULTIPLIER

Balanced conditions for active and reactive power for Bay 1 through 7 when using fixed margin and variable multiplier.