ADINE is a project co-funded by the European Commission

Project no: TREN/07/FP6EN/S07.73164/038533 /CONS

Project acronym: ADINE

Project title: Active Distribution Network

Deliverable 10:
Demonstration report on the use of existing voltage control methods

Due date of deliverable: 30.9.2008

Actual submission date: 30.9.2008

Start date of project: 1.10.2007 Duration: 36 months

Organisation name of lead contractor for this deliverable: Tampere University of Technology

Revision [1.0]

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
	Dissemination level	
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

TABLE OF CONTENTS:

1. INTRODUCTION 4

2. PRESENT-DAY DISTRIBUTION NETWORK VOLTAGE CONTROL 4

2.1. Constant voltage control 4

2.2. Line drop compensation 5

2.3. Other means of voltage control 5

3. VOLTAGE QUALITY REQUIREMENTS 6

4. DEMONSTRATION NETWORK 6

4.1. Network topology 6

4.2. Current voltage control methods 8

5. VOLTAGE QUALITY MEASUREMENTS 9

5.1. Substation Heinäaho 9

5.2. Feeder Äijäneva 14
5.2.1. Voltage drop 14
5.2.2. Maximum supply voltage 15

5.3. Feeder Ritari 16
5.3.1. Voltage drop 16
5.3.2. Maximum supply voltage 17

5.4. Substation Virrat 18

5.5. Feeder Killi 22
5.5.1. Voltage drop 22
5.5.2. Maximum supply voltage 23

5.6. Discussion on voltage quality measurements 24

6. POSSIBILITIES TO IMPROVE VOLTAGE QUALITY IN THE DEMONSTRATION NETWORK 25

7. SUMMARY 25

REFERENCES 26

1. INTRODUCTION

The aim of ADINE project is to develop and demonstrate a new active network management (ANM) method for distribution networks. Coordinated voltage control is one part of the new ANM method, and it will be demonstrated during the ADINE project. A part of a real distribution network from of our corporate cooperation partner Koillis-Satakunnan Sähkö Oy has been chosen for a coordinated voltage control demonstration network. The purpose of this report is to describe and demonstrate the use of existing voltage control methods in the demonstration network.

Before we can comprehend the functions and benefits of the new coordinated voltage control methods, we must first understand the basics of existing voltage control methods. This report describes the most common distribution network voltage control methods and then presents the demonstration network characteristics and the voltage control methods used in the demonstration network. Finally, voltage quality measurements are used to evaluate the performance of the existing voltage control methods. This report studies the voltage characteristics from the voltage control point of view. Quality indices not affected by the voltage control methods are left to lesser attention.

2. PRESENT-DAY DISTRIBUTION NETWORK VOLTAGE CONTROL

Both transmission and distribution networks experience voltage drops on each circuit proportional to the loading, which is constantly varying. Voltage regulation equipment is thus needed to offset the resulting voltage variations. The most common, and often the only, method of voltage control in distribution networks is to use automatic on-load tap changers in high voltage (HV) / medium voltage (MV) substation transformers. On-load tap changers allow the adjustment of the transformer voltage ratio without supply interruptions. One tapping step changes output voltage about 1.5 % and the whole control range of a tap changer is usually ±10–15 % of the nominal voltage [1]. Tap changers are controlled by automatic voltage control relays (AVRs). Relay operation is usually based on substation measurements and local logic. [2]

Current distribution networks have been designed to operate radially with unidirectional power flows. The voltage is usually highest at the substation and lowest at the end of the feeder. Therefore, the existing voltage control methods are quite straightforward. The voltage control is set to ensure that the supply voltage at the customer closest to the substation does not exceed maximum voltage during minimum load and the voltage at the farthermost customer does not go below the minimum voltage during maximum load. The existing methods are mainly based on the local control of substation transformer tap changers, but they also involve manually adjustable equipment such as tapped distribution transformers. The next chapters describe some of the most common voltage control methods.

2.1. CONSTANT VOLTAGE CONTROL

Automatic voltage control relays controlling the substation transformer tap changers can be set to operate either in a constant voltage mode or in a line drop compensation mode. In the constant voltage mode, the voltage control relay is set to maintain the secondary voltage constant at all times. Constant voltage control compensates the voltage variations in higher voltage levels and the voltage drop variations in the transformer. The secondary voltage remains constant within a certain tolerance. Generally 1–2 % tolerance is applied to ensure that a tap change does not immediately cause another tap change to the opposite direction. The only measurement needed is the voltage measurement from the substation secondary. If the difference between measured voltage and pre-selected voltage setting is larger than the tolerance, the voltage relay automatically initiates tap change after a time delay. The time delay prevents tap changes during short-time voltage variations, and also avoids excessive wear on the tap changer. Voltage relays usually apply inverse time characteristics to ensure faster operation during large voltage deviations. [2]

2.2. LINE DROP COMPENSATION

Line drop compensation, also known as voltage compounding, is used to offset the voltage drops in MV feeders and in low voltage (LV) networks. In line drop compensation, the substation transformer secondary voltage is varied depending on the load supplied from that transformer. During high loads, the secondary voltage is raised to compensate the increased voltage drops. On the other hand, at times of low load the voltage is reduced to ensure that the voltage near the substation does not exceed the maximum limit. The required amount of compensation is calculated from the measured transformer load current and line parameters. The line parameters are adjusted to model the average feeder impedance between the transformer and load. Line drop compensation changes the voltage setting on an automatic voltage control relay when necessary. Otherwise the relay operation is similar to the constant voltage control. Automatic voltage control is applied at most substations, but the use of line drop compensation is restricted to some substations in certain supply organizations. [2]

2.3. OTHER MEANS OF VOLTAGE CONTROL

Distribution network voltages are also controlled with reactive power compensators, in-line transformers and tapped distribution transformers. Some HV/MV substations have equipment for reactive power compensation, usually shunt capacitor banks or reactors. Shunt capacitors and reactors could be used to control the substation voltage, but in most cases they are used only to minimize the reactive power transfer through the substation transformer or the main grid connection point. Smaller capacitor banks and reactors are used along the MV feeders and in LV networks to control the distribution network voltage and suppress harmonics. Connecting shunt capacitors to the network causes voltage to rise at the connection points, thus reducing the voltage drops. Automatic relays can be used to switch the capacitors on and off depending on the load or the connection point voltage. Large customers may also have their own equipment for power factor correction, voltage support, harmonic suppression and flicker compensation. [2]

Distribution transformers often have tappings which can be selected off-load. The control range of tapping is typically ±5 % of the nominal voltage with one or two steps on both side of the nominal voltage. Since the tap changes must be done manually and off-load, the distribution transformer tappings are rarely changed. In-line transformers can be used to raise the voltage level in MV feeders. In-line transformers are sometimes installed on feeders with excessive voltage drops, usually lightly loaded and very long overhead feeders. [2]

3. VOLTAGE QUALITY REQUIREMENTS

The goal of voltage control is to maintain a good quality of supply. The quality of supply is good only if the supply voltage is within a specific range around the nominal voltage. The European standard EN 50160 defines maximum limits to the supply voltage variations. Under normal conditions during each period of one week 95 % of the 10 minute mean root-mean-square (RMS) values of the supply voltage must be within ±10 % of the nominal voltage (U_n). Furthermore, all 10 minute RMS values should be within the range of U_n +10/–15 %. [3]

The voltage tolerance of U_n +10/–15 % is quite large. Even smaller voltage variations can affect the lifetime and efficiency of electrical equipment. For example, 5 % increase in supply voltage halves the lifetime expectancy of incandescent light bulbs. Finnish Electricity Association SENER has given tighter recommendations for good and normal voltage quality [4]. SENER recommendations and EN 50160 limits for voltage variations are given in Table 1.

Table 1. Voltage variation limits for 10 minute RMS values during a period of one week [3][4].

	Good quality (SENER)	Normal quality (SENER)	Standard quality (EN 50160)
Voltage variation ($U_n = 230\,V$)	all $U_n \pm 4\,\%$ mean $U_n \pm 2{,}5\,\%$	all $U_n + 6/-10\,\%$	95 % of time $U_n \pm 10\,\%$ all $U_n + 10/-15\,\%$

Standard EN 50160 gives also limits for the voltage unbalance. Under normal operating conditions, during each period of one week, 95 % of the 10 minute mean RMS values of the negative phase sequence component of the supply voltage should be within the range 0 to 2 % of the positive phase sequence component (voltage unbalance factor (VUF) between 0–2 %).

4. DEMONSTRATION NETWORK

4.1. NETWORK TOPOLOGY

The demonstration network is part of an actual distribution network located in western Finland. The network is owned by Koillis-Satakunnan Sähkö Oy which is a medium-sized rural distribution company with about 15 000 customers. The demonstration network consists of four 20 kV medium voltage feeders supplied by three different substations. Substation *Heinäaho* supplies feeders *Äijäneva* and *Ritari*, substation *Virrat* supplies feeder *Killi* and substation *Killinkoski* supplies feeder *Virrat*. In this report, voltage levels in two substations and in three feeders are studied. Substation *Killinkoski* and feeder *Virrat* have been excluded from this study because of lack of measurement data. Information on the studied feeders and substations is shown in Tables 2 and 3 respectively. Figure 1 shows an illustration of the demonstration network topology.

Table 2. Feeder characteristics.

	Äijäneva	Ritari	Killi
Voltage	20 kV	20 kV	20 kV
Conductor type	overhead line	overhead line	overhead line
Length*	34.1 km	24.6 km	30.2 km
Peak power	751 kW	1297 kW	1294 kW
Distribution substations	44	39	46
Customers	275	288	479

* Length from the substation to the end of the feeder

Table 3. Substation characteristics.

	Heinäaho	Virrat
Transformer size	16 MVA	16 MVA + 10/7/7 MVA*
Transformer nominal voltage	110/21 kV	110/21 kV + 110/45/21 kV*
Capacitor bank	2.4 MVAr	-
Feeders	5	8 + 1 (20 kV + 45 kV)

*110/21 kV transformer supplies 20 kV network. 110/45/21 kV transformer supplies 45 kV network and provides backup supply to the 20 kV network.

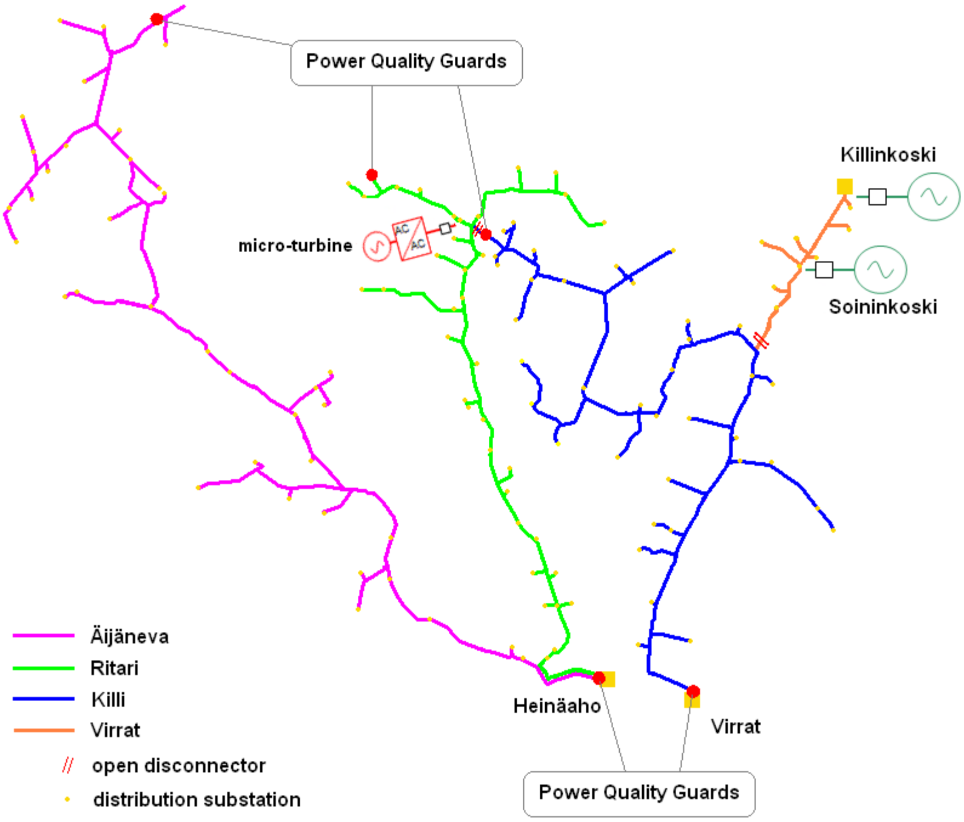


Figure 1. Demonstration network topology.

4.2. CURRENT VOLTAGE CONTROL METHODS

Currently only automatic on-load tap changers are used to control the voltage in the demonstration network. HV/MV transformers in substations *Heinäaho* and *Virrat* have on-load tap changers that can adjust the output voltage in steps of 1.67 % of the nominal voltage. The whole control range of the tap changers is ±15 % of the nominal voltage. The tap changers are controlled with digital ABB SPAU 341 C voltage regulator relays. The voltage relays are set to operate in a constant voltage mode, but line drop compensation mode is also possible. The voltage relay reference voltages are set to 1.03 p.u. (20.60 kV) and a 1.50 % tolerance is applied. [5]

Substation *Heinäaho* contains a large 2.4 MVAr capacitor bank. The main purpose of the capacitor bank is to control the reactive power flow between the main grid and the 110 kV regional networks. The capacitor bank is not used to control the distribution network voltage. The capacitor bank is in use only in winter weekdays roughly between 7 a.m. and 10 p.m. The operator switches the capacitors on in the morning and switches them off in the evening. There are two hydroelectric power plants in the demonstration area. Power plants are *Killinkoski* (4.5 MVA) and *Soininkoski* (1.5 MVA). Hydroelectric power plants are connected to the substation *Killinkoski* with a separate medium voltage feeder which does not belong to the demonstration network. It is possible to change the connection topology with disconnector so that the hydroelectric power plants are connected to the feeder *Virrat*, but currently they are not connected to the demonstration network. The operator can control the reactive power production in *Killinkoski* hydroelectric power plant. Currently the power plant is used to produce reactive power only in winter time.

Nowadays there is also a small 28 kW biogas powered micro-turbine at the end of feeder *Ritari*, but the voltage quality measurements in this report have been done before the installation of the micro-turbine. Therefore the effect of the micro-turbine does not show in the measurements. Currently the micro-turbine is operated in a unity power factor and it does not contribute actively to the voltage control. Many of the distribution transformers in the demonstration network have tappings, but they are all set to operate on a nominal transformation ratio. [5]

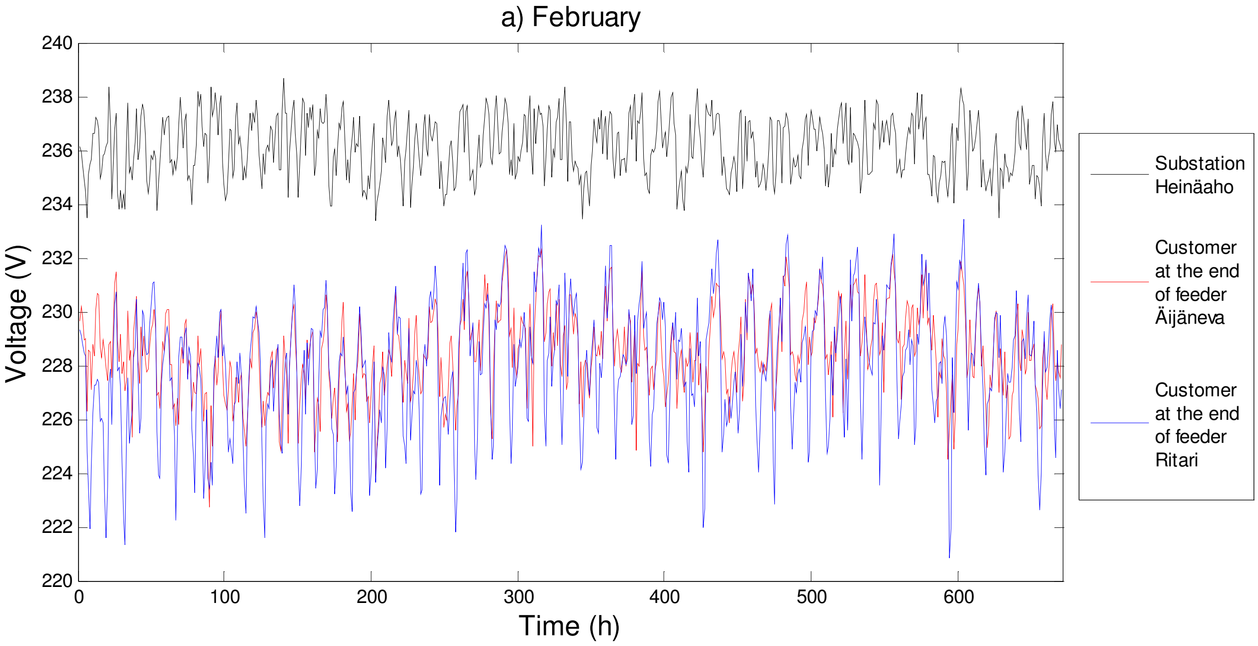
5. VOLTAGE QUALITY MEASUREMENTS

This report uses steady state voltage quality measurements to evaluate the performance of the existing voltage control methods. Steady state voltages were measured from substation MV busbars and from three low voltage customers. To keep the MV and LV measurements comparable, the substation MV busbar voltages were scaled down to the LV level. The measured LV customers were located at the tail ends of each feeder. The measurements were not located at the point of feeder minimum voltage, but they do represent the general voltage level at the end of each feeder. Figure 1 shows the measurement locations.

The voltage measurements were done with remotely readable EQL Power Quality Guards manufactured by MX Electrix. The Power Quality Guards recorded average phase voltages for each 10-minute recording period. The Power Quality Guards also collected several voltage quality values. Measured voltage unbalance factors are used to evaluate the voltage asymmetry in the demonstration network. Substation main transformer loadings were measured to evaluate the effect of load and reactive power compensation to the substation voltage. Real and reactive powers were measured with Enermet MT30E four quadrant meters.
This report concentrates to study the voltages during the maximum and minimum loadings. In Finland the maximum load usually appears in February and minimum load in July. Long-term power measurements from substations *Heinäaho* and *Virrat* also indicate that the average load is highest in February and lowest in July. Therefore these two months have been selected for analysis. All measurements were done during year 2006. Unfortunately there was an interruption in the measurement system between 12 and 21 July, so only 521 hours of data was collected in July. Next, the measurement results are given for each substation and feeder.

5.1. SUBSTATION HEINÄAHO

Measured average voltage in substation Heinäaho was 236.11 V (+2.66 %) in February and 235.96 V (+2.59 %) in July. The setting value for the substation AVR was 1.03 pu. Although the average substation voltages were quite close to the voltage setting value, the instantaneous voltage values differed from the setting value. The substation voltages were not constant, instead the voltages were continually changing. The average difference between consecutive voltage measurements was 0.45 V in February and 0.32 V in July. Standard deviations for the measured voltage data sets in February and July were 1.30 V and 1.25 V respectively. The black lines in Figures 2 a) and b) show how the substation hourly voltages vary in February and July. Figures 2 a) and b) also show how the supply voltages behave at the end of feeders Äijäneva and Ritari. The voltages at the end of the feeders are discussed further in section 5.2.



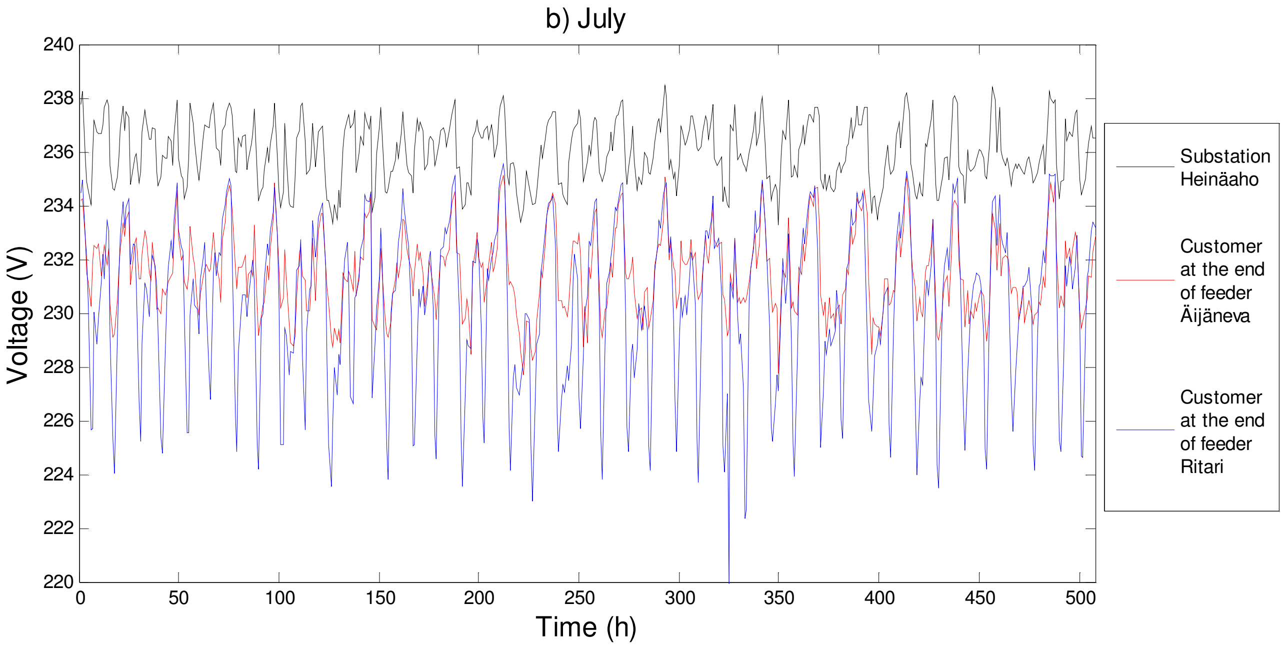
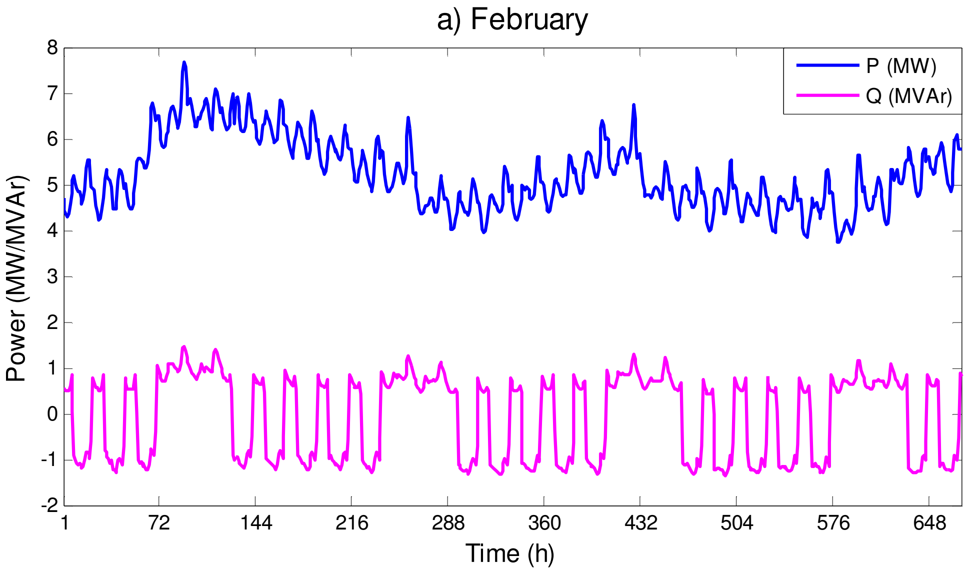


Figure 2. Measured average hourly voltages a) in February and b) in July.

The variations in the substation voltages can be caused by voltage variations in supplying HV network, transformer tap changes, load variations or changes in reactive power compensation. Figures 3 a) and b) show how the substation real and reactive power consumptions vary. There are clear daily cycles in real and reactive power consumptions. The consumption is larger in daytime and smaller at night-time. There are two consumption peaks in a day, one in the morning and one in the evening. Also, the real power consumption level varies because of outdoor temperature fluctuations. In February, the reactive power consumption varies considerably when the whole 2.4 MVAr capacitor bank is switched on and off. The substation even exports reactive power, when the capacitor bank is on. In July, the capacitor bank is switched off but the relative load changes are larger than in February.



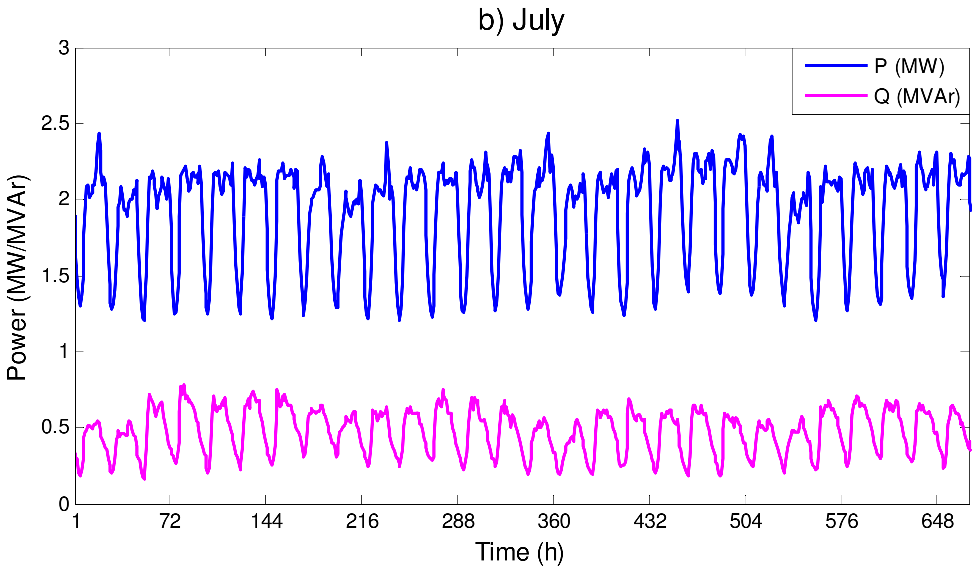


Figure 3. Real and reactive power consumptions a) in February and b) in July.

Figure 4 shows the substation voltage and reactive power measurements for a period of 48 hours. As can be seen from the Figure 4, the substation voltage changes every time the capacitor bank is switched on or off. When the capacitor bank is switched on the voltage level rises about 1 %, and when the capacitor bank is switched off the voltage drops about 1 %. The effect of load variations on the substation voltage level can be seen also from the Fourier analyses in Figures 5 and 6. The substation voltage, real power and reactive power have strong 24 hour cycles both in February and in July. Moreover, real power consumption and consequently also substation voltage has strong 12 hour cycles.

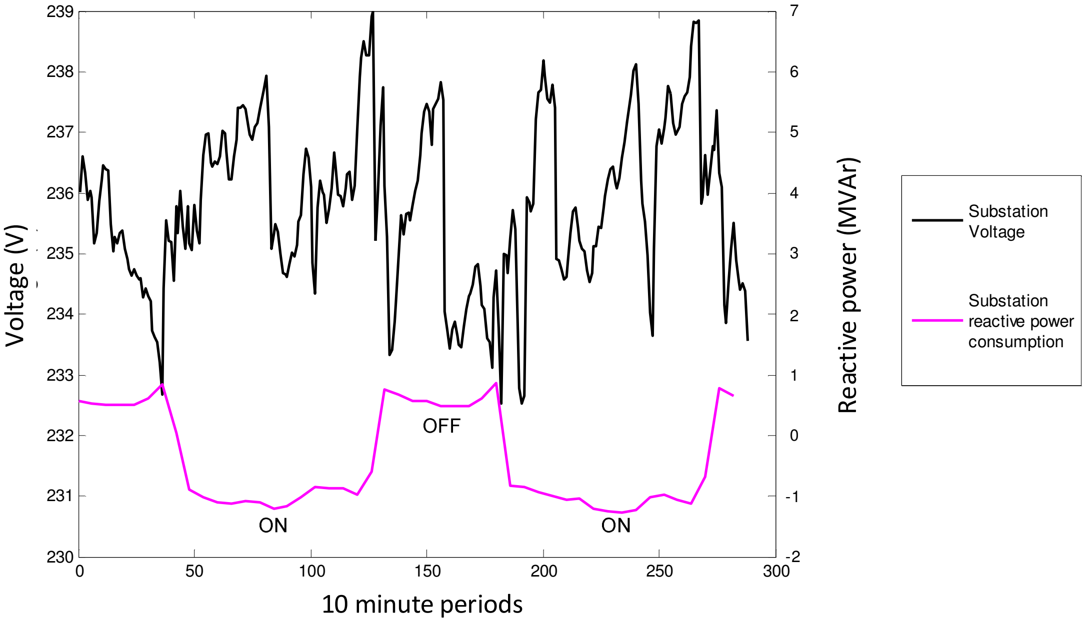


Figure 4. Substation voltage and reactive power.

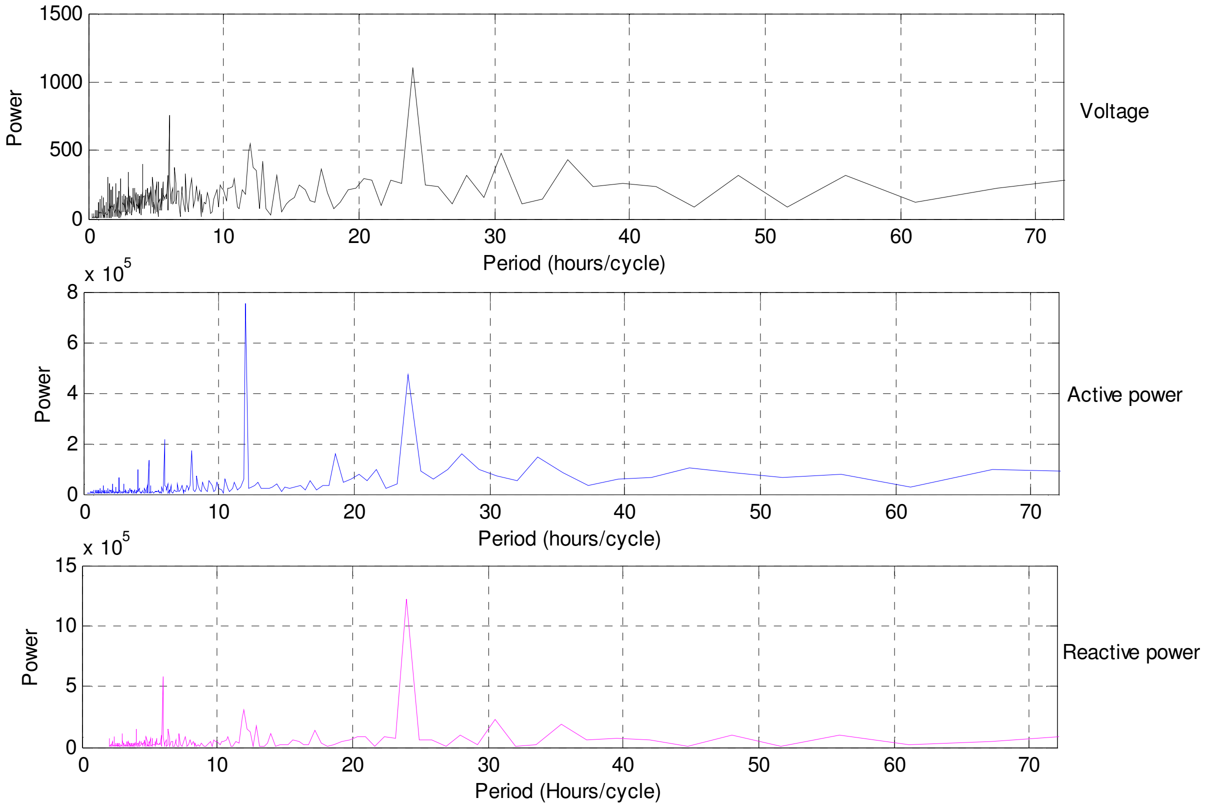


Figure 5. Power spectrum versus period of substation data in February.

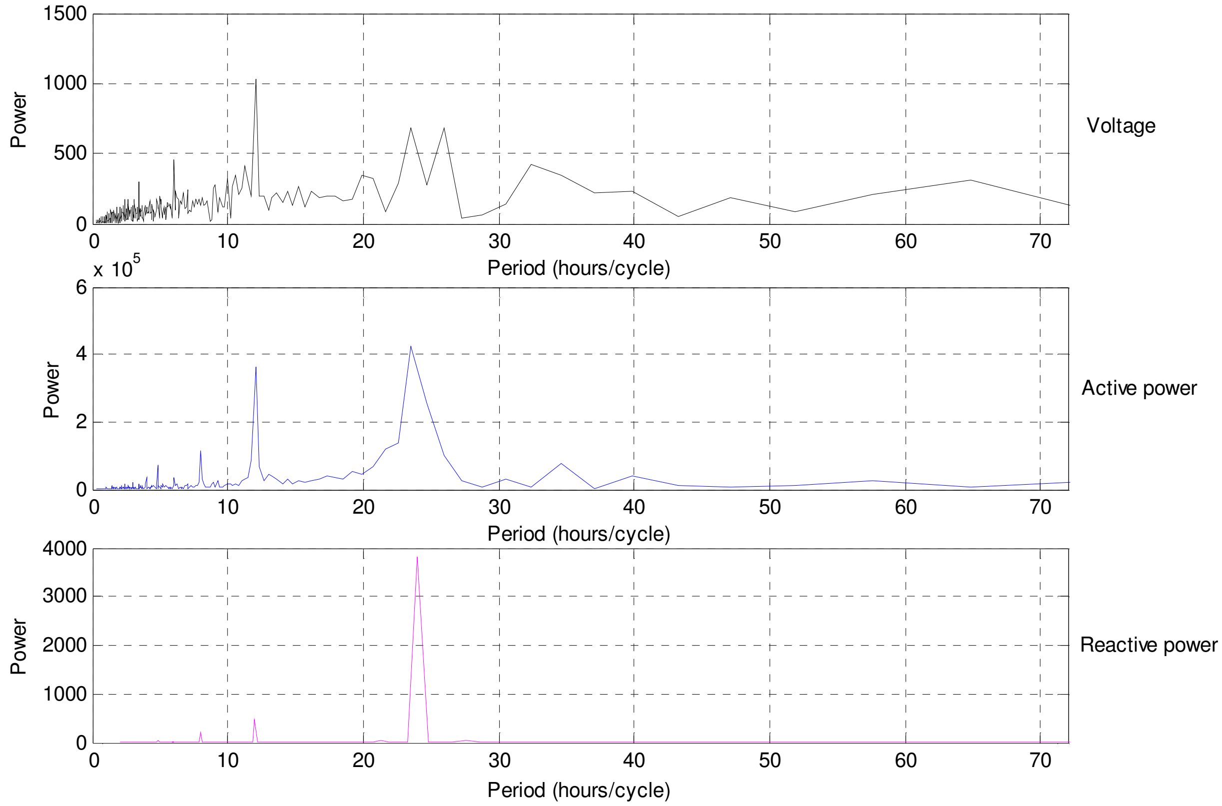


Figure 6. Power spectrum versus period of substation data in July.

The substation voltage unbalance was measured with the EQL Power Quality Guard. The average voltage unbalance factor in substation *Heinäaho* was 0.17 % in February and 0.06 % in July. The maximum values for 10 minute RMS voltage unbalance factors were 0.26 % in February and 0.15 % in July.

5.2. FEEDER ÄIJÄNEVA

5.2.1. Voltage drop

To find out the voltage level at the end of feeder Äijäneva, the steady state voltages were measured from a LV customer supply point at the tail end of the feeder. The distance between the distribution transformer and the substation is 33.0 kilometers, and the distance between the measured customer and the distribution transformer is 437 meters. The average voltage measured in February was 228.50 V (-0.65 %), the minimum voltage 216.91 V (-5.69 %) and the maximum voltage 234.29 V (+1.87 %). In February, the voltage level was maintained within EN 50160 limits at all times but the limit for minimum voltage (-4 %) in Sener recommendations for good voltage was violated 46 times (number of times when the 10 minute average phase voltages violated Sener limits). The blue bars in Figure 7 show the voltage distribution in February. The whole voltage range in the Figure 7 represents the voltage variation limits for 95 % of time in standard EN 50160, and the blue dash lines mark the Sener limits for good voltage.

In July, the average voltage was 231.53 V (+0.66 %), the minimum voltage 221.35 V (-3.76 %) and the maximum voltage 236.27 V (+2.73 %). All phase voltages were within Sener limits. The red bars in Figure 7 show the voltage distribution in July. During the whole year 2006 the average voltage was 230.01 V (±0.00 %), the minimum voltage 214.90 V (-6.56 %) and the maximum voltage 236.28 V (+2.73 %). The Sener limit for minimum voltage was violated 145 times.

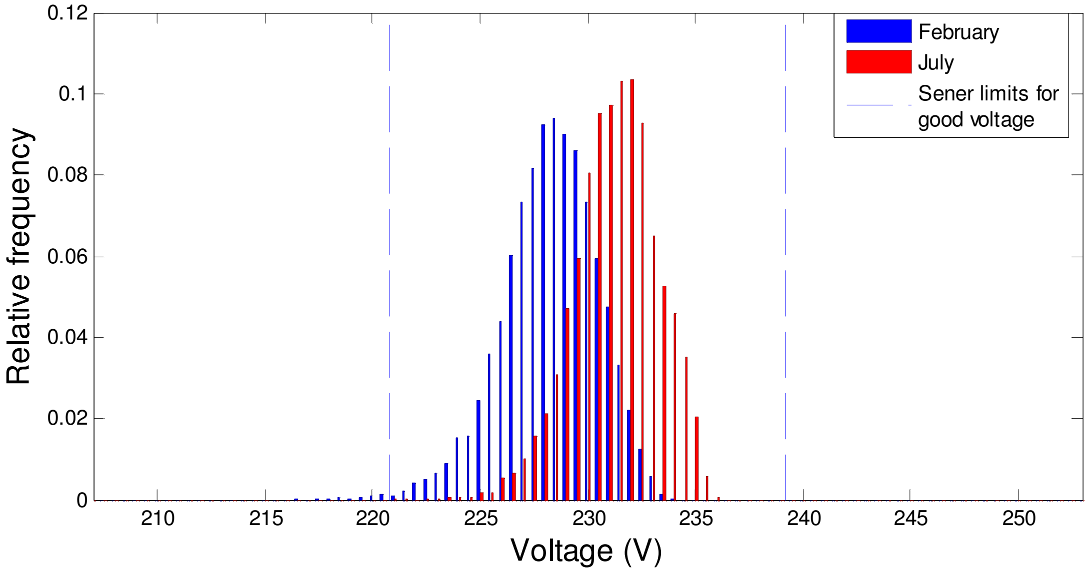


Figure 7. Voltage histogram for a customer at the end of feeder Äijäneva.

The measured average voltage unbalance factor at the end of the feeder *Äijäneva* was 0.32 % in February and 0.29 % in July. The maximum values for 10 minute RMS voltage unbalance factors were 1.28 % in February and 1.26 % in July. The voltage unbalance stayed within EN 50160 limits.

5.2.2. Maximum supply voltage

We had no measurements on a customer representing the maximum supply voltage. Instead the substation voltage measurements were used to estimate the voltage at the point of feeder maximum supply voltage. Network information system was used to calculate the voltage drop between the substation and the point of maximum supply voltage. Hourly voltage drops were calculated for one typical weekday both in February and July. The calculated voltage drops were then subtracted from the substation voltage measurements to generate maximum supply voltage estimates.

In February, the estimated maximum supply voltage was 232.08 V (+0.90 %) on average. The minimum voltage estimate was 226.79 V (-1.40 %) and the maximum voltage estimate 237.19 V (+3.12 %). All estimated 10-minute phase voltages stayed within Sener limits. In July, the average voltage estimate was 233.16 V (+1.37 %), the minimum voltage estimate 229.07 V (-0.40 %) and the maximum voltage estimate 237.59 V (+3.30 %). All estimated 10-minute phase voltages stayed within Sener limits. Figure 8 shows the estimated voltage distributions at the point of maximum supply voltage. The blue bars represent voltage distribution in February and the red stairs represent distribution in July.

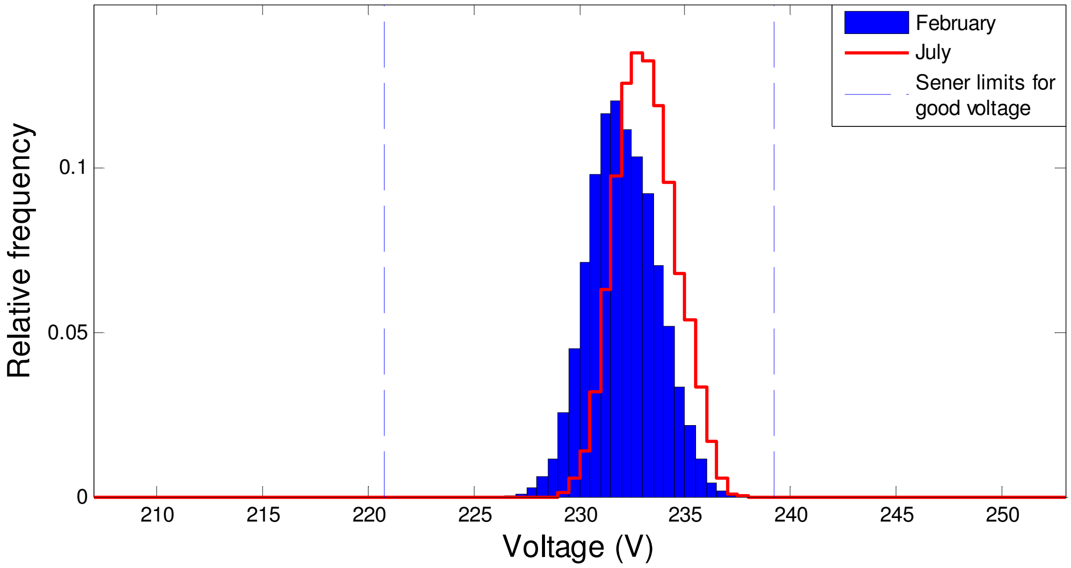


Figure 8. Estimated voltage histogram for the point of maximum supply voltage.

5.3. FEEDER RITARI

5.3.1. Voltage drop

As in feeder Äijäneva, also in feeder Ritari a customer supply point at the tail end of the feeder was metered. The distance between the distribution transformer and the substation was 21.8 kilometers, and the distance between the customer and the distribution transformer was 371 meters. The average voltage in February was 227.93 V (-0.90 %), the minimum voltage 211.64 V (-7.98 %) and the maximum voltage 237.85 V (+3.41 %). The voltage level was maintained within EN 50160 limits at all times but the limit for minimum voltage (-4 %) in Sener recommendations for good voltage was violated 627 times. The blue bars in Figure 9 show the voltage distribution in February.

In July, the average voltage was 230.35 V (+0.15 %), the minimum voltage 210.08 V (-8.66 %) and the maximum voltage 238.74 V (+3.80 %). The Sener limit for minimum voltage was violated 440 times. The red bars in Figure 9 show the voltage distribution in July. During the whole year 2006 the average voltage was 228.83 V (-0.51 %), the minimum voltage 206.02 V (-10.43 %) and the maximum voltage 239.36 V (+4.07 %). The Sener limit for minimum voltage was violated 8055 times and the limit for maximum voltage was violated once. The voltage fulfilled the steady state voltage quality requirements in Standard EN 50160. The -10 % voltage limit was violated once, but the -15 % limit was not exceeded.

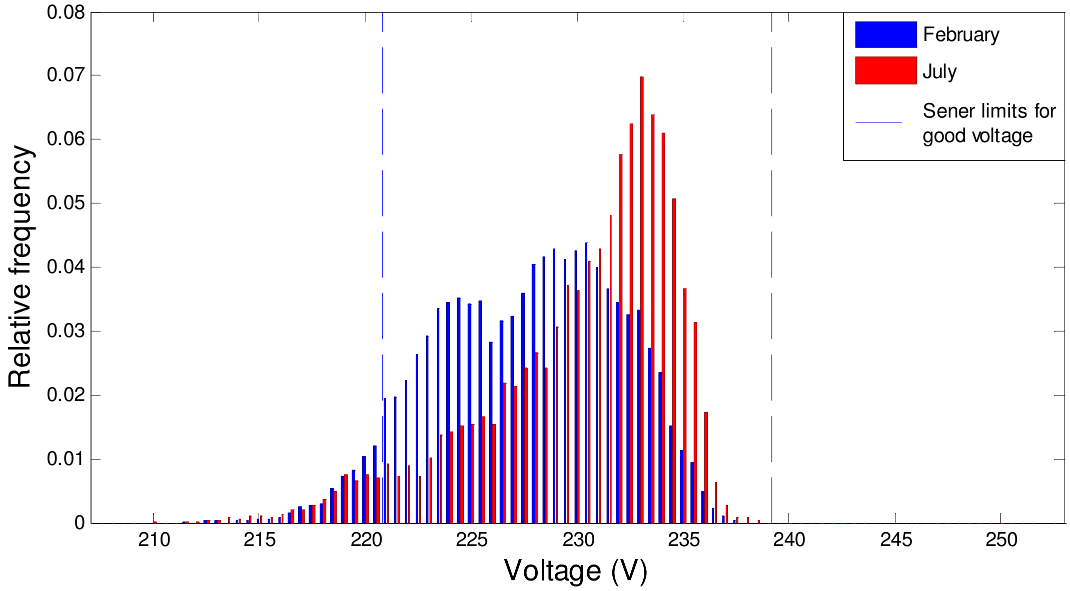


Figure 9. Voltage histogram for a customer at the end of feeder Ritari.

The measured average voltage unbalance factor at the end of the feeder *Ritari* was 0.20 % in February and 0.19 % in July. The maximum values for 10 minute RMS voltage unbalance factors were 1.27 % in February and 1.72 % in July. The voltage unbalance stayed within EN 50160 limits.

5.3.2. Maximum supply voltage

As in feeder Äijäneva, the maximum supply voltage estimates were generated from substation voltage measurements and voltage drop calculations.

In February, the estimated maximum supply voltage was 233.74 V (+1.63 %) on average. The minimum voltage estimate was 228.75 V (-0.54 %) and the maximum voltage estimate 238.00 V (+3.48 %). All estimated 10-minute phase voltages stayed within Sener limits. For July, the average voltage estimate was 235.00 V (+2.17 %), the minimum voltage estimate 230.21 V (+0.09 %) and the maximum voltage estimate 238.39 V (+3.65 %). All estimated 10-minute phase voltages stayed within Sener limits. Figure 10 shows the estimated voltage distributions at the point of maximum supply voltage. The blue bars represent voltage distribution in February and the red stairs represent distribution in July.

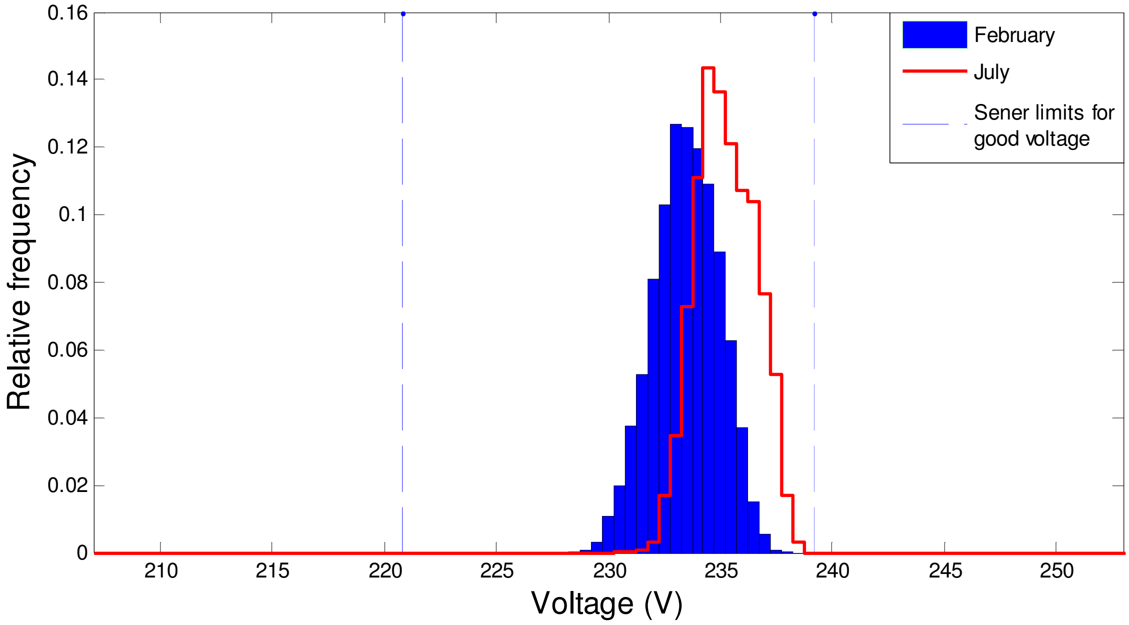
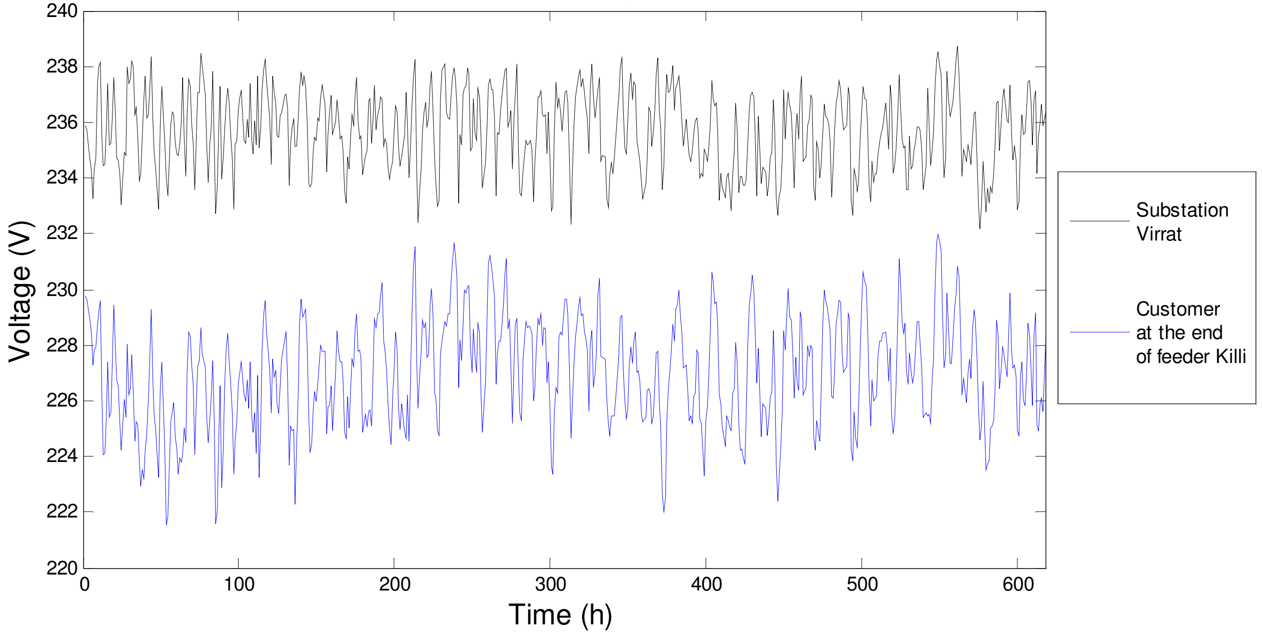


Figure 10. Estimated voltage histogram for the point on maximum supply voltage.

5.4. SUBSTATION VIRRAT

Measured average voltage in substation Virrat was 235.68 V (+2.47 %) in February and 235.13 V (+2.23 %) in July. The substation AVR voltage setting value was 1.03 pu. The differences between the measured average voltages and the AVR voltage setting value were a bit larger than in substation Heinäaho. The standard deviations were also larger 1.55 V in February and 1.65 V in July, but the average differences between consecutive voltage measurements were smaller 0.40 V in February and 0.29 V in July. The black lines in Figures 11 a) and b) show how the substation hourly voltages vary in February and July. The blue lines show how the supply voltages behave at the end of feeder Killi. The voltages at the end of feeder Killi are discussed further in section 5.5.

a) February



b) July

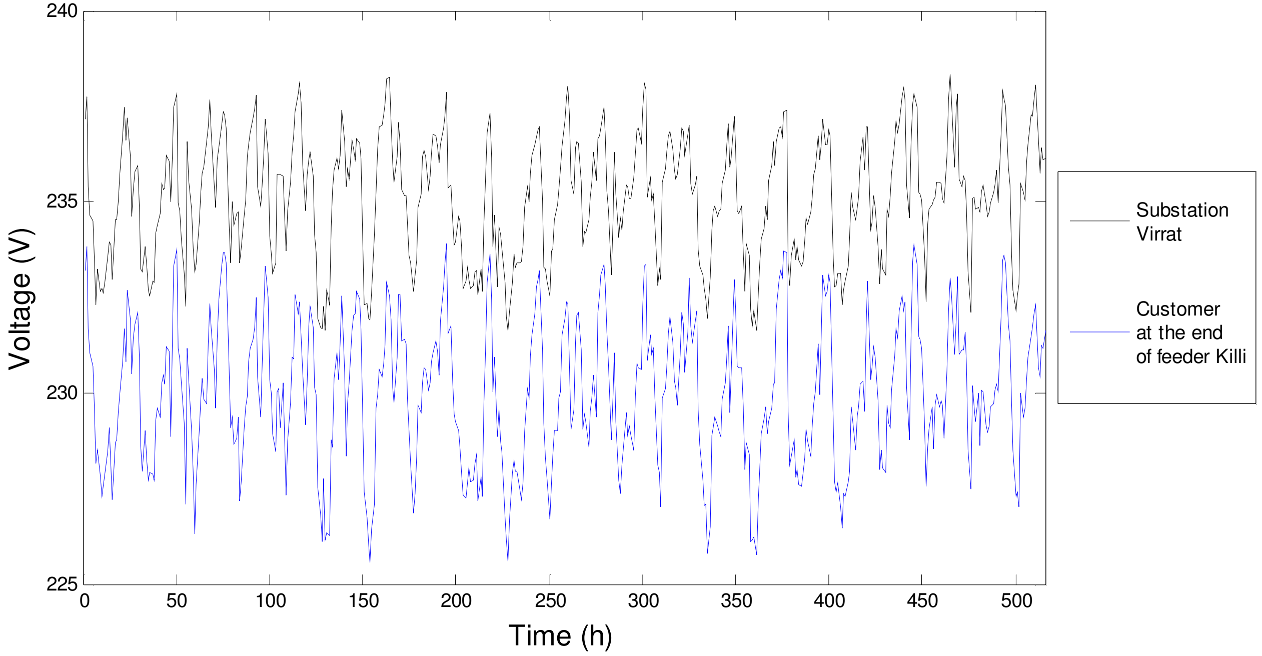


Figure 11. Measured average hourly voltages a) in February and b) in July.

There is no reactive power compensation in substation Virrat, but the variations in the substation voltages can be caused by voltage variations in supplying HV network, transformer tap changes or load variations. Figures 12 a) and b) show how the substation real and reactive power consumptions vary. The consumption is larger in daytime and smaller at night-time. There are two consumption peaks in a day, one in the morning and one in the evening. Also, the weekends have lower power consumptions than weekdays. Especially in February, the real power consumption varies because of outdoor temperature fluctuations. The cyclic behavior of power consumption can be seen also from the Fourier analyses in Figures 13 and 14. The substation voltage, real power and reactive power have strong 24 hour cycles both in February and in July. Moreover, real power consumption and consequently also substation voltage has strong 12 hour cycles.

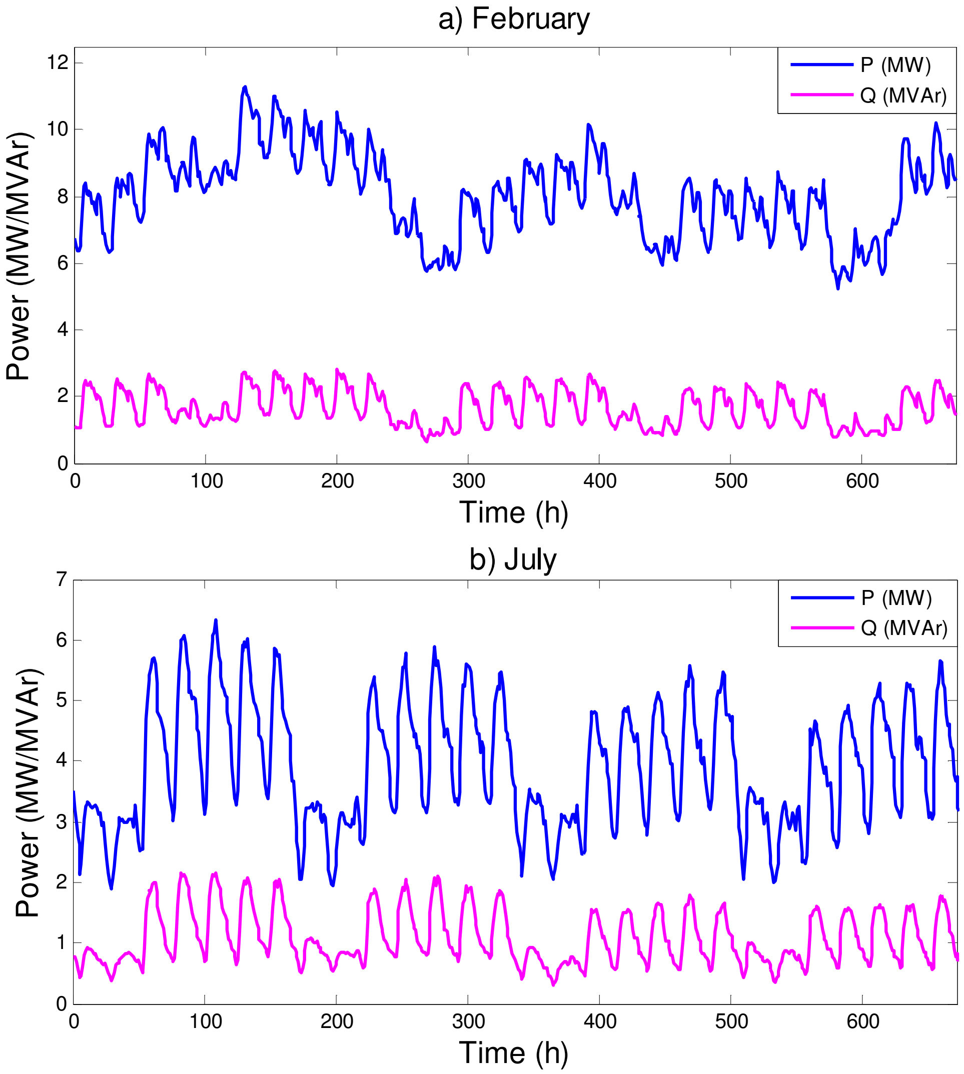


Figure 12. Real and reactive power consumptions a) in February and b) in July.

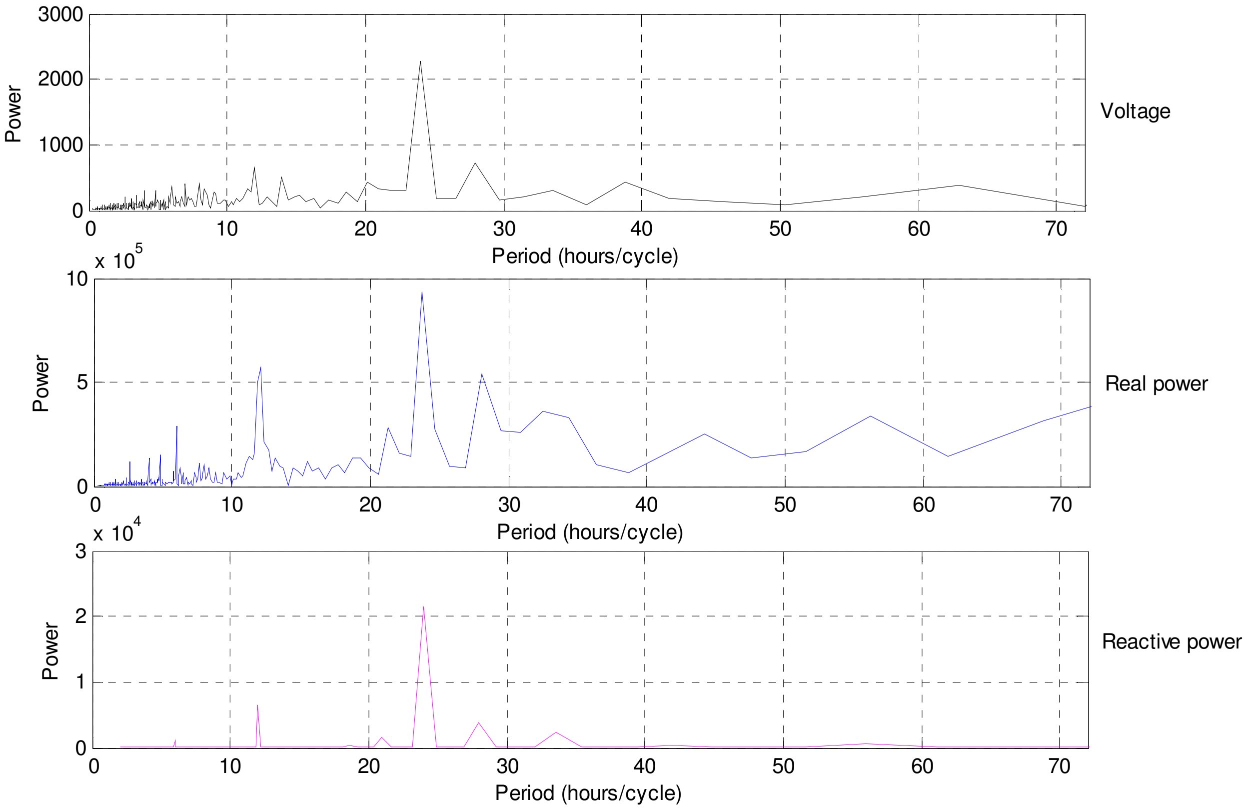


Figure 13. Power spectrum versus period of substation data in February.

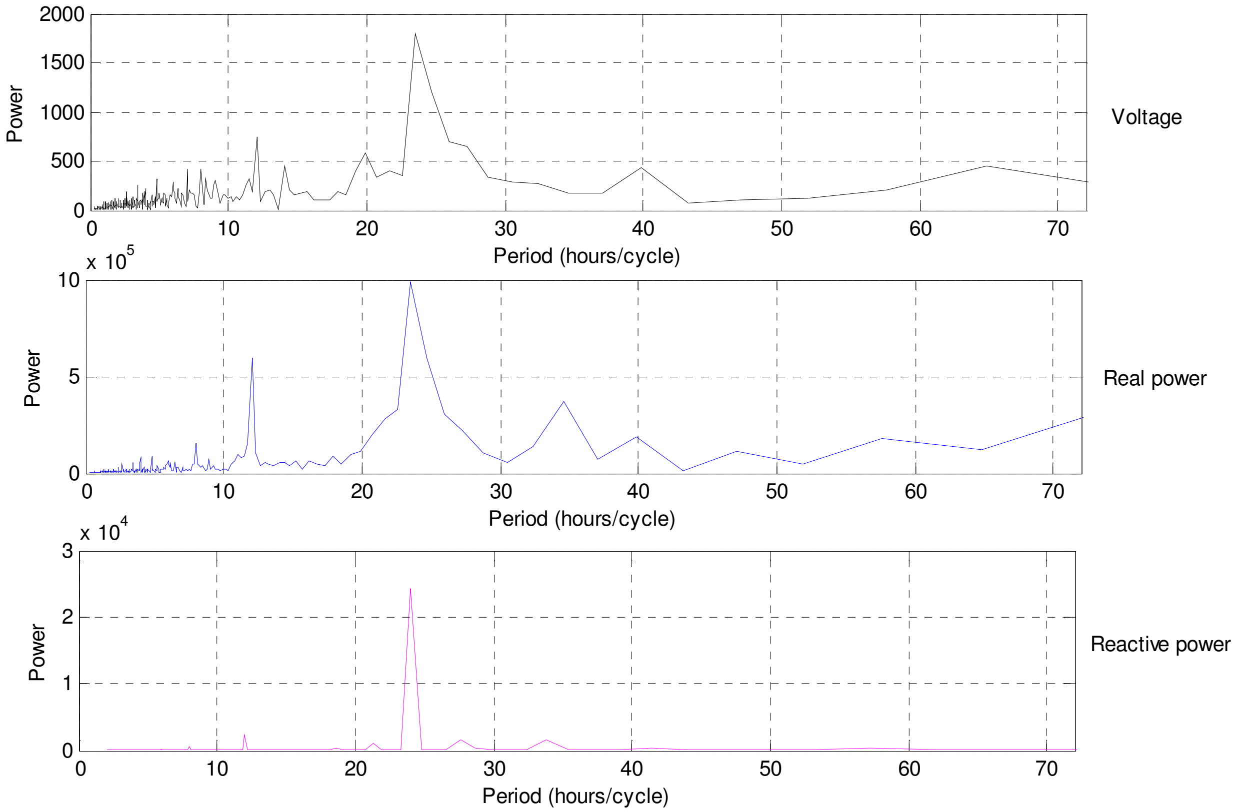


Figure 14. Power spectrum versus period of substation data in July.The measured average voltage unbalance factor in substation Virrat was 0.13 % both in February and in July. The maximum values for 10 minute RMS voltage unbalance factors were 0.29 % in February and 0.26 % in July.

5.5. FEEDER KILLI

5.5.1. Voltage drop

A customer supply point at the tail end of the feeder *Killi* was metered. The distance between the distribution transformer and the substation was 29.3 kilometers, and the distance between the customer and the distribution transformer was 185 meters. The average voltage in February was 227.01 V (-1.30 %), the minimum voltage 218.48 V (-5.01 %) and the maximum voltage 233.05 V (+1.33 %). The voltage level was maintained within EN 50160 limits at all times but the limit for minimum voltage (-4 %) in Sener recommendations for good voltage was violated 41 times. The blue bars in Figure 15 show the voltage distribution in February.

In July, the average voltage was 230.00 V (±0.00 %), the minimum voltage 222.81 V (-3.13 %) and the maximum voltage 235.20 V (+2.26 %). All phase voltages were within Sener limits. The red bars in Figure 15 show the voltage distribution in July. During the whole year 2006 the average voltage was 228.83 V (-0.51 %), the minimum voltage 218.47 V (-5.01 %) and the maximum voltage 235.55 V (+2.41 %). The Sener limit for minimum voltage was violated 93 times.

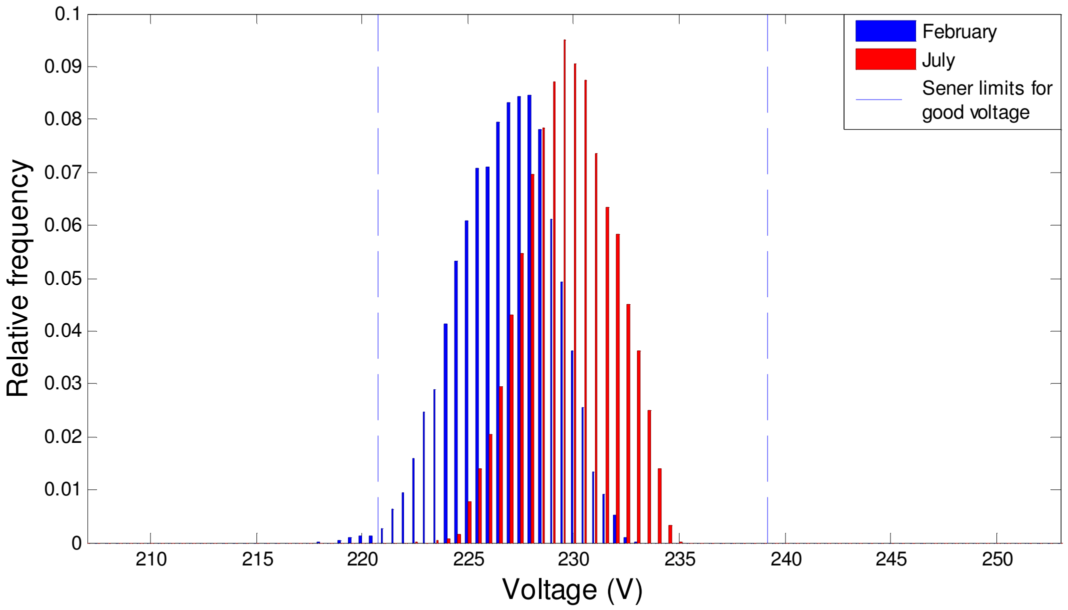


Figure 15. Voltage histogram for a customer at the end of feeder Killi.

The measured average voltage unbalance factor at the end of the feeder *Killi* was 0.08 % in February and 0.13 % in July. The maximum values for 10 minute RMS voltage unbalance factors were 0.66 % in February and 0.84 % in July. The voltage unbalance stayed within EN 50160 limits.

5.5.2. Maximum supply voltage

Maximum supply voltage estimates once again were generated from substation voltage measurements and voltage drop estimates calculated with network information system.

In February, the estimated maximum supply voltage was 234.86 V (+2.11 %) on average. The minimum voltage estimate was 228.90 V (-0.48 %) and the maximum voltage estimate 240.36 V (+4.50 %). The voltage level was maintained within EN 50160 limits but the limit for maximum voltage (+4 %) in Sener recommendations for good voltage was violated 137 times. In July, the average voltage estimate was 235.13 V (+2.23 %), the minimum voltage estimate 229.32 V (-0.30 %) and the maximum voltage estimate 240.56 V (+4.59 %). The Sener limit for maximum voltage (+4 %) was exceeded 230 times. Figure 16 shows the estimated voltage distributions at the point of maximum supply voltage. The blue bars represent voltage distribution in February and the red stairs represent distribution in July.

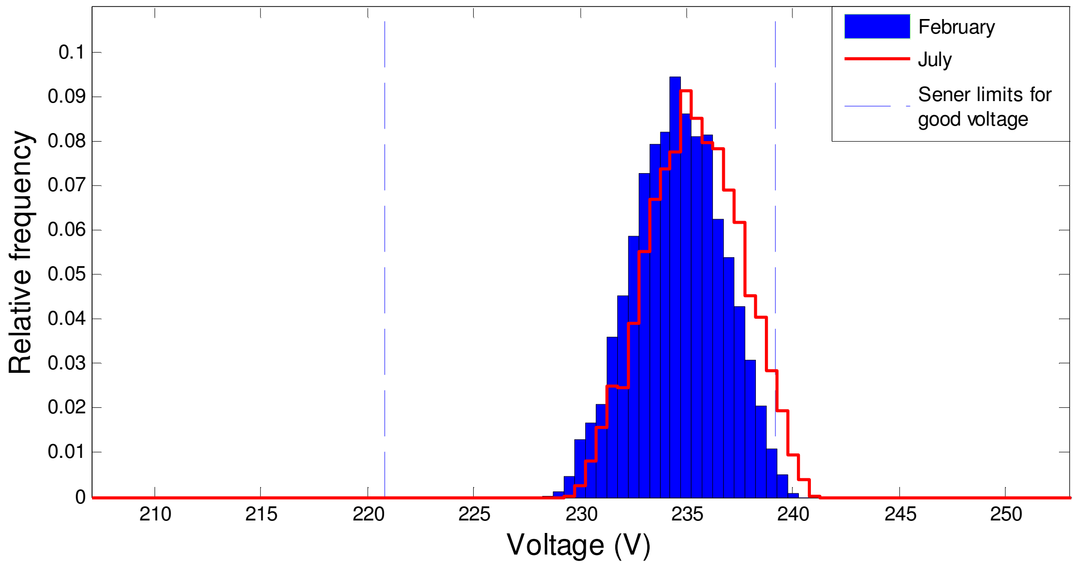


Figure 16. *Estimated voltage histogram for the point on maximum supply voltage in feeder Killi.*

5.6. DISCUSSION ON VOLTAGE QUALITY MEASUREMENTS

The measurements showed that the present voltage quality in the measurement points fulfils the requirements in standard EN 50160. Furthermore, the voltage quality is good most of the time according to the Sener recommendation for good voltage quality.

It is impossible to make a comprehensive voltage quality analysis with the measurements available, but the measurements do give a reasonably good indication of the voltage control performance. The measurements at the end of the feeders did not coincide with the points of minimum supply voltage. Nevertheless, the measurements represent the general voltage level at the end of each feeder fairly well. In the demonstration network, where the medium voltage network voltage drops are 2.4–3.6 % at maximum, the design of low voltage networks has a bigger effect on the final minimum supply voltage than the voltage control system. The calculated maximum supply voltage estimates can be expected to be sufficiently accurate. The voltage drops between the substations and the points of maximum supply voltage are small and thus also the possible estimation errors are small.

Currently, the substation on-load tap changers are solely responsible for the demonstration network voltage control. According to the voltage quality measurements, the AVR reference voltages seem to be well chosen. The problem is that the substations *Heinäaho* and *Virrat* do not supply only the demonstration network feeders. Many other feeders are also connected to these substations. Some of these feeders are longer and have larger voltage drops than the demonstration feeders and some of them are short underground cable feeders. Therefore, it is impossible to give comprehensive recommendations for the best possible reference voltages.

When considering only the demonstration feeders, the measured minimum voltages at the end of feeder *Ritari* indicate a need to increase the reference voltage in substation *Heinäaho*, but then the maximum supply voltage would exceed the Sener limit for good voltage. Situation is similar in substation *Virrat*. If we try to decrease the reference voltage so that the maximum supply voltage would satisfy the Sener recommendation for good voltage, the voltage level at the end of the feeder would decline below the Sener limit for good voltage. The Sener recommendation for good voltage quality can not be fully satisfied in the demonstration network with existing voltage control methods.

6. POSSIBILITIES TO IMPROVE VOLTAGE QUALITY IN THE DEMONSTRATION NETWORK

The demonstration network voltage quality could be improved using the line drop compensation feature available in the existing AVRs. Based on the voltage quality measurements presented in chapter 5, increasing the reference voltage in substation *Heinäaho* during high loads and decreasing the reference voltage in substation *Virrat* during light loads would provide some improvements to the voltage quality.

Especially at the end of feeder *Ritari*, the voltage range of variation is so wide (from -8.66 % to+3.80 %) that it is uncertain that the line drop compensation alone could keep the voltages within the Sener recommendations for good voltage quality. Feeder *Ritari* would benefit from coordination of distributed generation and substation voltage control. Controlling the reactive power output of the micro-turbine could provide a little improvement to the voltage profile in feeder *Ritari*.

Even it would not be possible to satisfy the limits for good voltage quality at all times, advanced coordinated voltage control methods could be used to minimize the amount of voltage limit violations. In coordinated voltage control the AVR operation is coordinated with distribution network state estimation. In the simplest coordination methods, the substation transformer on-load tap changers are controlled based on the estimated maximum and minimum supply voltages. In more complex systems, optimization algorithms are used to minimize the amount and severity of voltage limit violations.

7. SUMMARY

This report described the most common present-day distribution network voltage control methods. The demonstration network used in the ADINE project was introduced and the performance of existing voltage control methods was demonstrated. The voltage quality measurements revealed that adequate voltage quality, which satisfies the requirements in standard EN 50160, is easily obtained with existing voltage control methods. If voltage quality requirements are raised from standard quality to good quality, the existing voltage control methods can not keep the supply voltages within the new limits. Maintaining good voltage quality at all times requires new voltage control methods.

REFERENCES

1. Aura, L. & Tonteri, A. Sähkökoneet ja tehoelektroniikan perusteet (in Finnish). Porvoo 1996, WSOY. 544 p.
2. Lakervi, E. & Holmes, E.J. Electricity distribution network design. 2nd Edition. London 1995, Peter Peregrinus Ltd. 325 p.
3. EN 50160:1999 E. Voltage characteristics of electricity supplied by public distribution systems. Brussels 1999, CENELEC. 14 p.
4. Jakeluverkon sähkön laadun arviointi (in Finnish). Helsinki 2001. Finnish Electricity Association SENER. 29 p.
5. Raiskinmäki, E. & Rinta-Opas, A. Koillis-Satakunnan Sähkö Oy. Discussions 3.6.–28.8.2008.