Industrial Electrical Engineering and Automation

Voltage regulation in distribution systems - Tap changer and Wind Power

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Abstract

Power quality is an important issue for the distribution network companies. They must guarantee the electricity supply fulfilling the requirements for the consumers. In this thesis we investigate specifically voltage requirements. We use transformers and tap changers to see how the voltage works in an electric system and we analyze the relationships with other aspects of the system's performance, like power losses or tap changer operation.

Lunds Energi wants to investigate any change that could improve the voltage quality. For that purpose, they provide us with real data of their systems, consisting of a city system and a countryside system with the characteristics of the lines, the transformers, the generation and the loads. Also, they supply the load profiles over one day which are made up of 24 values, one per hour. Using PowerWorld Simulator, first we build a generic system to run some simulations and extract conclusions that could be useful for the voltage problems in the real systems. Then, we build the city and countryside system and we run different cases, firstly focusing on identifying the problems experienced by Lunds Energi, and subsequently modifying the settings to look for potential improvements.

Analyzing the simulation results we do not find a significant voltage problem in the city system, however, there is a low voltage problem at some costumers of the countryside system. Changing the settings of the transformer would improve the voltage quality and also the addition of a line drop compensation system would be positive. Globally, based on the results of the simulations, we confirm that there is a direct relation between the voltage set point and the losses and, also, between the deadband amplitude and the tap changer operation.

In the case of the countryside system, Lunds Energi considers connecting wind turbines to the net. We simulate this case as well, in order to analyze the problem of too high voltage in some buses and we calculate the power we are allowed to generate without going out of the voltage limits. The conclusion is that this is a very interesting solution because we can inject enough power to feed all the loads and since the generation is close to the consumer we are reducing the power losses too. We propose some turbines those are currently in the market and are suitable for the system.

For the future work, we suggest some modifications to study these systems. It could be more realistic to use load profiles with higher resolution to have a more realistic idea of the performance of the tap changer in the transformers. Also, it is more realistic to add the measurements of the voltage in the beginning of the system instead of assuming a constant value. The last suggestion is to work with other types of load models, than constant power since the relation between the voltage and the losses is then different.

Contents

1. Introduction

1.1. Voltage settings

Power quality is an important issue for distribution network companies. They must guarantee the electricity supply for the customers, while fulfilling certain quality requirements. Public institutions are involved in this topic as well. There are European standards and, usually, every country has specific regulations for power quality too. One of these requirements is the voltage level. It has to be kept between the established limits. In order to do that, the distribution network companies should decide the best strategy using the technology within reach. In that case, thinking of the voltage, the transformers are the main tool, especially transformers with tap changer.

Lunds Energi wants to investigate if changes in their systems could improve the power quality. They provide us with real data consisting of a city system and a countryside system, with the characteristics of the lines, the transformers, the generation and the loads. Also, they supply the loads profiles of one day which are made up of 24 values, one per hour.

With PowerWorld, first we build a generic system that could help to find useful information related to the real system. Based on the real data, we build the models and we run several simulations of them. Once we have the results of the simulations, we analyze them in order to discover potential problems. Then, we modify the settings of the model, especially in the transformer side, to investigate any change in the system that could improve the voltage quality. Another aim of this thesis is to confirm theoretical aspects of the voltage, related to the set point and the deadband. So, with help of the simulation results, we look for relations between the voltage and others parts of the system like the losses or the tap changer operation.

1.2. Wind power generation

Due to the current environmental problems and the increasing demand of electricity, we have to find new solutions to generate clean energy. One of these options is to install wind turbines, which is often done at distribution level close to the consumers.

Our aim in this field is to see the impact on the voltage level caused by the addition of the wind turbines in the system. Specifically, we do it in a countryside system where there is the possibility to install wind turbines in a small scale. This changes of course the operation of the system in terms of voltage; therefore, we need to find out the new settings for the transformers that are suitable for the consumers. So, we have to analyze the system, calculate the power that we can connect and then, suggest different wind turbines that are currently in the market and that are suitable for our system.

2. Theory

2.1. Voltage drop

To control the voltage level for the consumers, we have to consider the voltage drop (V_d) in each line of the system. All the electrical lines have certain impedance that causes a difference between the sending and receiving end voltage. [1]

In a 3-phase line with a positive sequence voltage, we have impedance in the line Z:

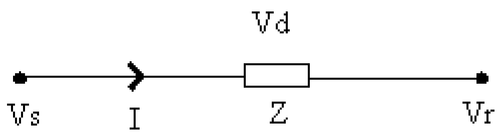


Figure 2.1: Simplified line.

$V_d = V_s - V_r = Z*I$

We assume a 3-phase positive sequence voltage, so the impedance of the line is

$Z = R + jX$.

And the line to line voltage drop is:

$V_d \approx \sqrt{3}\,(I_P*R + I_Q*X)$

Where I_p represents the resistive component of the current and I_q the reactive one. [2]

Different solutions have been implemented throughout the years to minimize the losses in a line. One of them is to use a 3-phase system instead of a single-phase system. If we compare these systems assuming that the same real power P is delivered, all the conductors have equal resistance R, the same phase-earth voltage V is applied and the power factor is unity:

- In a single-phase line, the current is I=P/V and the neutral line is also loaded, so the voltage drop is Vd=2*R*I.
- In a 3-phase line, the power is divided between the three phases so each phase carries I/3. In a symmetrical positive sequence case, the neutral is unloaded. Therefore, the voltage drop is Vd=(I/3)*R.

Using a 3-phase line, we are reducing the losses by six times when compared to a single-phase line. [2]

Another method to reduce the losses is raising the voltage level because with the same power delivered, as we know P=V*I, if we increase the voltage we are decreasing the current and, therefore, the losses in the line. But we have to bear in mind that the higher the voltage level is, the tougher the insulation requirements become.

2.2. Voltage control

There are several methods to control the voltage in order to keep high quality electricity supply. Some of them are introduced below:

- Tap-changing transformers.

A tap changer can vary the number of turns in one side of the transformer and thereby, change the transformer ratio. Normally, this can vary between 10-15% in steps of 0.6-2.1%. There are several options to design the control of the voltage. One of them is to set a nominal value of the voltage with a deadband in a point of the line, and to control it with an integral controller. [3]

- LDC system (Line Drop Compensation).

It is based on calculating the voltage drop knowing the reactance and resistance of the line and then, applying the set voltage based on these values with the tap changers of the transformers. Figure 2.2 shows the main operation of the LDC system. [4]

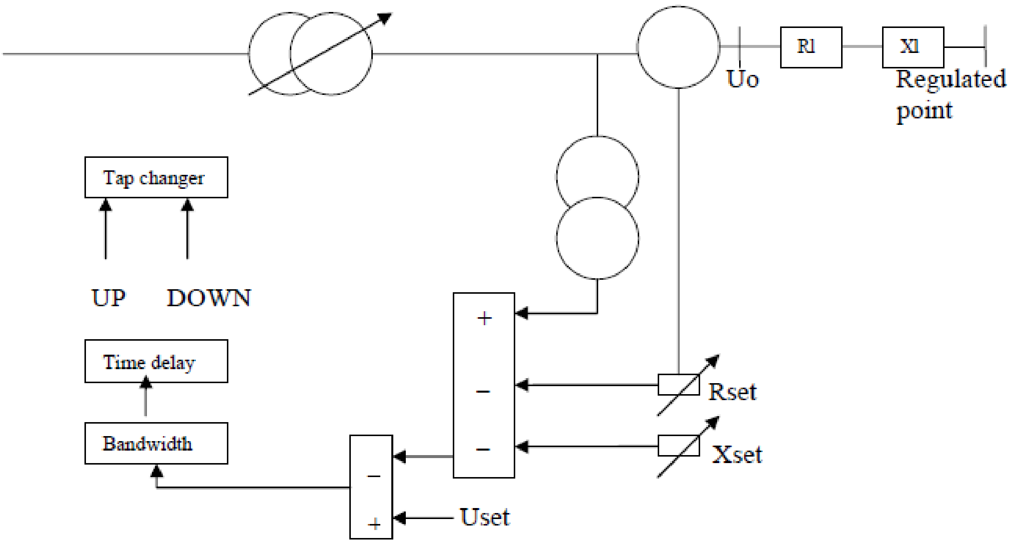


Figure 2.2: Basic operation of LDC system. [5]

- Compensation with reactive elements.

For mainly reactive networks voltage is correlated with the reactive power so, one way to control it is to connect compensators and reactors in the nodes. In distribution lines, there are several methods to control the power from the reactive elements like switched fixed capacitors/inductors, Static Var Compensator (SVC) or the static synchronous compensator (STATCOM). They are based on measuring the line voltage and comparing it with a given reference. So, we connect capacitive compensators if we have to increase the voltage or we connect reactive compensation if we have to decrease it.

This method depends totally on the R/X ratio of the line. The compensation with reactive elements is more useful with a low resistance cable, i.e. a cable with a low R/X ratio, because the reactive power has a larger impact on voltage. In a transmission network, that uses overhead lines and transformers, this R/X ratio is usually low, around 0.1, so this would be a good tool to control the voltage. However, in distribution lines frequently underground cables are used, with a higher resistance and R/X ratio around 0.5-1. That means that reactive compensation is not as much efficient as in transmission lines but these compensation methods are also used in distribution systems. [5]

2.3. Quality requirements

In order to unify values for the different electrical parameters, there are some documents and laws that propose requirements in a European or international level to preserve acceptable voltage quality for customers. We are going to present one of them, EN 50160. It gives the main voltage parameters and their permissible deviation in public low voltage (LV) and medium voltage (MV) electricity distribution systems. While EN 50160 suggests limits for public supply networks, several European countries have additional rules for electricity supply conditions. Many of these national regulations cover areas which are not included in this document. [6]

The next table shows the main supply voltage requirements in EN 50160:

Power frequency	LV, MV: mean value of fundamental measured over 10s ±1% (49.5 - 50.5 Hz) for 99.5% of year -6%/+4% (47- 52 Hz) for 100%
Voltage magnitude variation	LV, MV: ±10% for 95% of week, mean 10 minutes rms values
Rapid voltage changes	LV: 5% normal

	10% infrequently P*lt* ≤ 1 for 95% of week MV: 4% normal 6% infrequently P*lt* ≤ 1 for 95% of week
Supply voltage dips	Majority: duration <1s, depth <60%. Locally limited dips caused by load switching on: LV: 10 - 50%, MV: 10 - 15% (Figure 1)
Short interruptions of supply voltage	LV, MV: (up to 3 minutes) few tens - few hundreds/year Duration 70% of them < 1 s
Long interruption of supply voltage	LV, MV: (longer than 3 minutes) <10 - 50/year
Temporary, power frequency overvoltages	LV: <1.5 kV rms MV: 1.7 *Uc* (solid or impedance earth) 2.0 *Uc* (unearthed or resonant earth)
Transient overvoltages	LV: generally < 6kV, occasionally higher; rise time: ms - μs. MV: not defined
Supply voltage unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values, up to 3% in some locations

Table 2.1: Supply voltage requirements in EN 50160 [6]

2.4. Voltage variation with the load

In electric distribution systems, there are variations in the voltage caused by the changes in the power consumed by the load. So, it is necessary to analyze these changes in the load to prevent the variations of the voltage, and keep it within the correct values.

To make the calculations of the voltage dependent of the load in a distribution system, we are going to use a Thévenin equivalent circuit with the impedance of a transformer, the impedance of the line. Figure 2.3 shows the scheme of a load connected to the circuit.

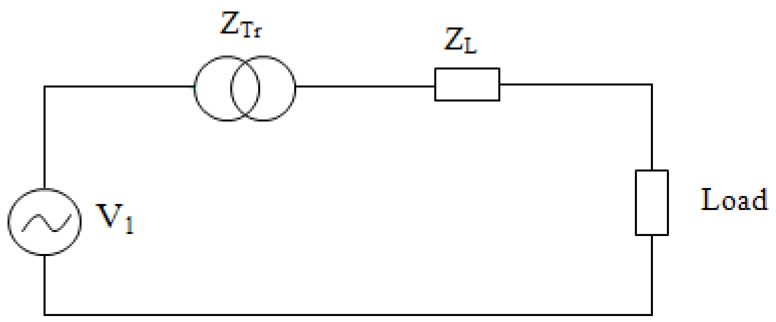


Figure 2.3: Thévenin equivalent circuit with load.

In the next list we can see the information of the circuit parameters.

- V_1= 10 kV
- Line:
  Length = 8 km

  Impedance per kilometer = 0.3360 + j0.3537 Ω

  Z_l= 2.69 + j2.83 Ω

- Transformer:
  Nominal power = 40 MVA

  Reactance = 0.1 p.u.

  Impedance = j0.1 x 10^2/ 40 = j0.25 Ω

- Load:
  Power factor = 0.9

We will make the calculations in per unit values. The base we are going to use is S_{base} = 1.5 MVA and V_{base} = 10 kV.

In the figure 2.4 we can see a simplification of the Thévenin equivalent circuit.

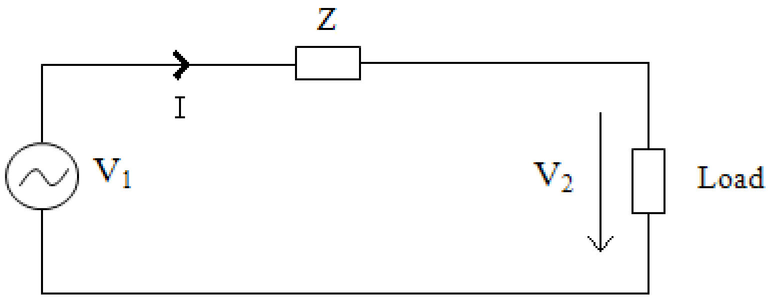


Figure 2.4: Simplified Thévenin equivalent circuit with load.

S_{base} = 1.5 MVA

V_{base} = 10 kV

- V_1 = 1 p.u.
- $Z = Z_{tr} + Z_l$ = 0.0404 + j0.0462 p.u.
- Cos(φ) = 0.9

Once we have defined the circuit we need to know which load profile we will use. In Figure 2.5 the load profile is depicted. We represent the active power and the power factor is 0.9 constant. The data has been taken from Southern California Company. It represents a residential customer class without electric heating in 2009. [7]

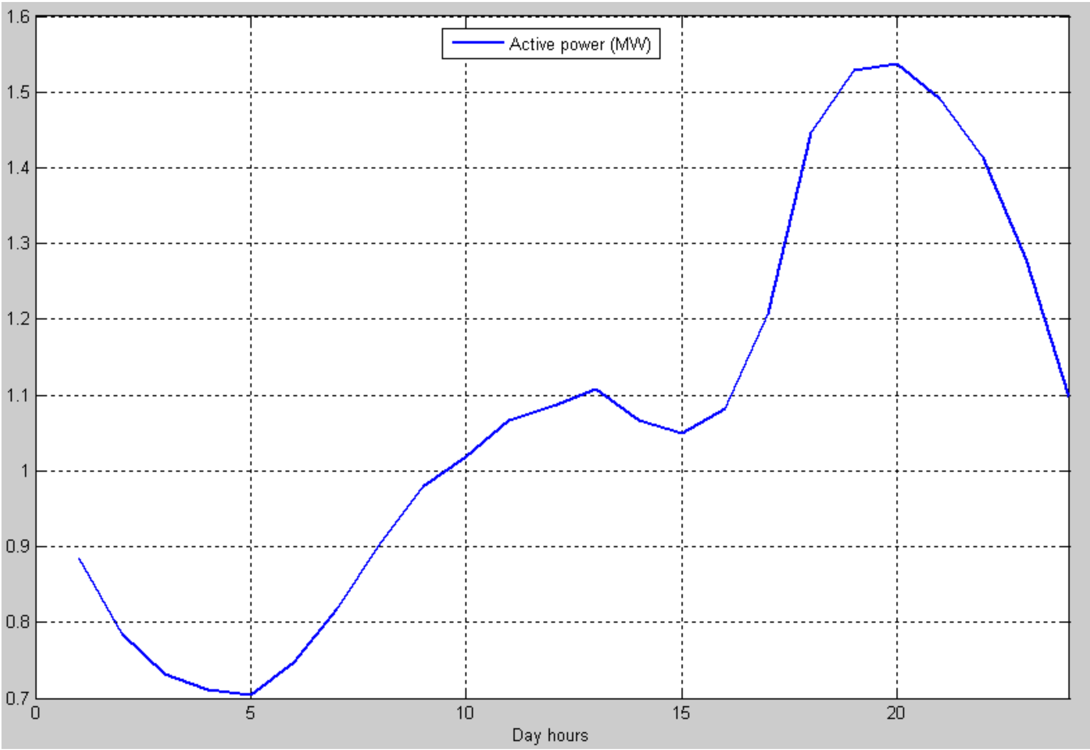


Figure 2.5: Data of the load profile 2/01/2009. [7]

Using the simplified Thévenin equivalent circuit and the load profile we can calculate the voltage variation in the load side. First, we need to calculate the expressions and then, use the numerical values. Italic letters are used for complex quantities.

$S = V_2 \cdot I^* = V_2 \cdot [(V_1 - V_2)/Z]^* \rightarrow (S/V_2)^* = (V_1 - V_2)/Z \rightarrow$

$V_1 - V_2 = (S^* \cdot Z)/V_2^* = (P - jQ) \cdot (R + jX)/V_2^*$

If we assume that the voltage angle is 0º degrees, we can simplify the formula without using complex numbers, resulting in easier calculations:

$V_1 - V_2 = (P - jQ) \cdot (R + jX)/V_2$

This expression is a second order equation and the solution for the voltage V_2 is:

$$\mathbf{V_2 = [V_1 + \sqrt{(V_1^2 - 4 \cdot (P - jQ) \cdot (R + jX))}]/2}$$

We can simplify even more the formula for the calculation deleting the complex terms.

$V_1 - V_2 = (P \cdot R + Q \cdot X)/V_2$

And the second order equation solution is:

$$\mathbf{V_2 = [V_1 + \sqrt{(V_1^2 - 4 \cdot (P \cdot R + Q \cdot X))}]/2}$$

Figure 2.6 shows the results of the voltage in the load side (V_2) using the last two expressions. The blue line represents the first expression and the red one the approximation. This calculation has been made with Matlab. The function used is shown in detail in Appendix A.

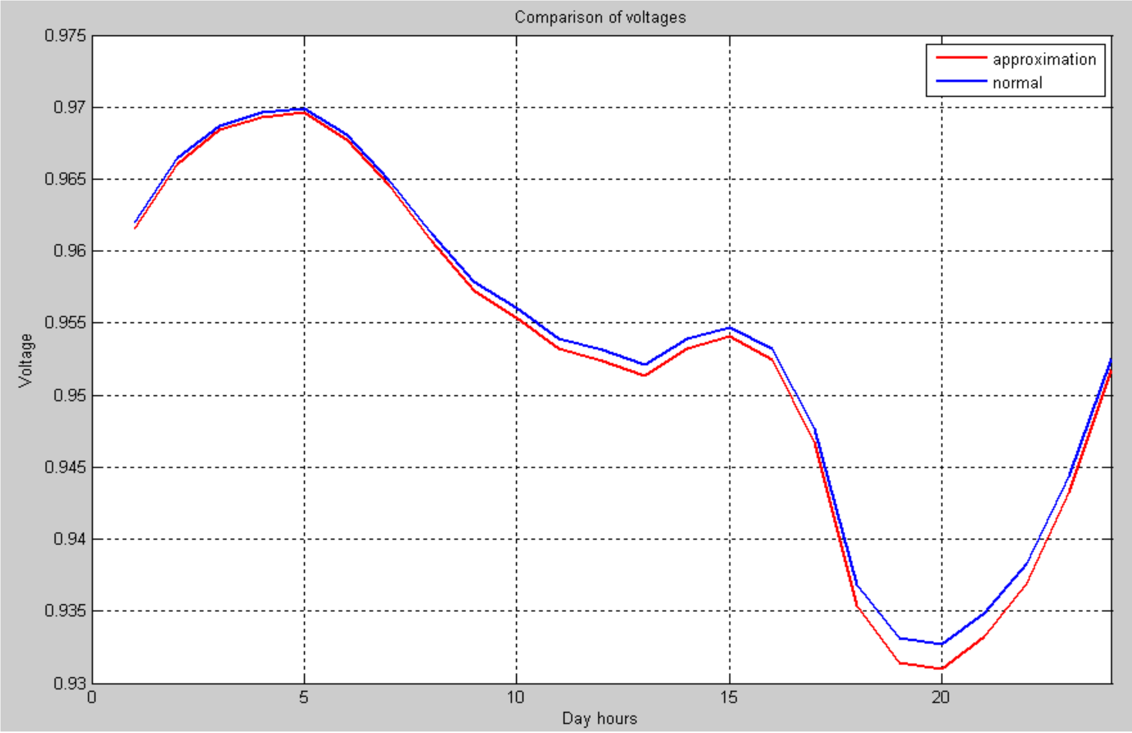


Figure 2.6: Voltage in the load side.

We can compare both results to see how big the difference is and how large the error made is with the last simplification. As we can see, with the simplification the voltage calculated is smaller and the difference increases when the level of the voltage decreases.

So, we conclude that the voltage decreases when the power increases. The reason is related to the losses in the line. Once the power increases, the current in the line increases and, therefore, the losses are higher. That means, the voltage at the load end of the line is lower.

3. Test systems

3.1. Generic system

The goal of this work with PowerWorld is to become familiar with the program, and to create a simple model in order to draw conclusions valid for the real systems.

PowerWorld Simulator is a useful power system analysis tool. It has many options allowing the engineer to build different kinds of systems and simulate them. The simulation results can be visualized in different ways, from graphical plots to animated flows with interactive tools. [8]

3.1.1. Description

The system that we will use for the simulation is made up of three buses with the generator, the transformer, the line and the load. In Figure 3.1 the diagram of PowerWorld is represented.

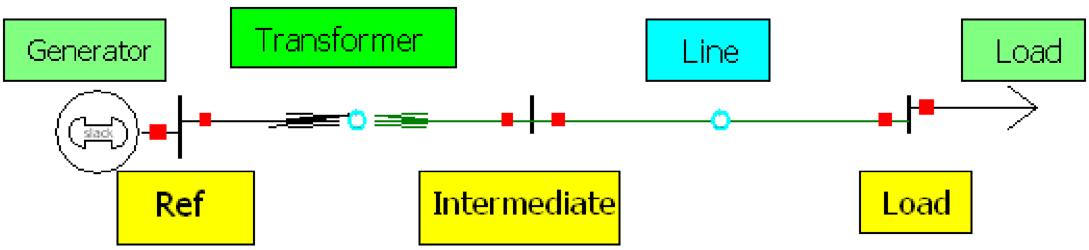


Figure 3.1: Diagram of the system in PowerWorld.

The model represents a Medium Voltage distribution power line. The parameters of the components are defined below.

- **Buses**

  Reference bus: 130 kV
  Intermediate bus: 10 kV
  Load bus 10 kV

- **Generator**

  Voltage: 130 kV

- **Transformer**

  130 kV/10 kV
  Nominal power: 40 MVA
  Impedance: j0.25 Ω
  Tap changer:
  - Minimum voltage: 0.99 p.u.
  - Maximum voltage: 1.01 p.u.
  - Tap steps: 33
  - Minimum tap ratio: 0.9
  - Maximum tap ratio: 1.1

- **Line**

  Length: 8 km
  Impedance: 2.69 + j2.83 Ω

- **Load**

  The load profile is the same as we used in the section 2.4. It is showed in Figure 2.5.

3.2. City system

3.2.1. Description

The system consists of two loads, an industry that is connected to the transformer through three parallel cables, and a public grid connected through a long cable and three equal transformers. Figure 3.2 shows the PowerWorld diagram.

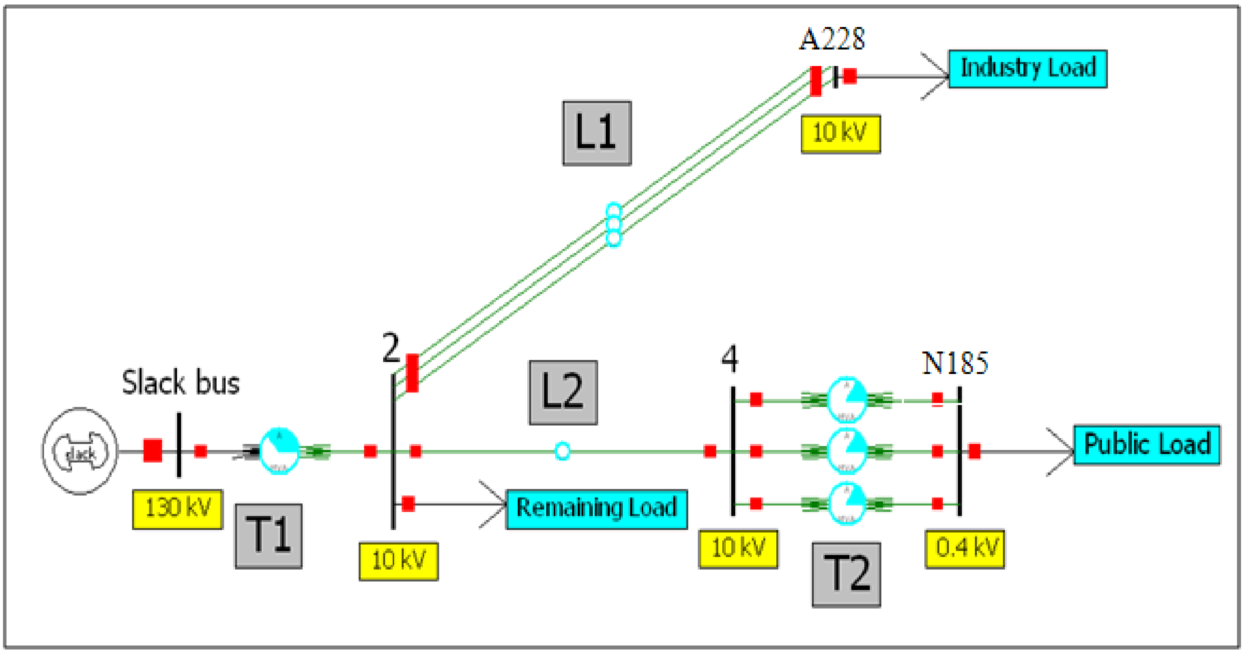


Figure 3.2: City system diagram in PowerWorld

Next, we define a list with the parameters of the system.

- **Transformer T1**
  130 kV/10 kV
  Nominal power: 40 MVA
  Impedance: 17.45%
  Tap changer:
    - Tap steps: 19
    - Minimum tap ratio: 0.8497
    - Maximum tap ratio: 1.1503

  P_0 = 13.8 kW
  $P_{s.c.}$ = 125.9 kW
  I_N = 159.3 A

- **Transformer T2**
  10 kV/0.4 kV
  Nominal power: 800 kVA
  Impedance: 4.5%

- **Line L1**
  Three parallel cables of the type AXCEL 3x240mm^2, each 2 km long.
  AXCEL 3x240mm^2
    - Series resistance: 0.125 Ω/km
    - Series reactance: 0.0848 Ω/km
    - Shunt charging: $132 \cdot 10^{-6}$ Mhos/km

- **Line L2**
  8 km AXCEL 3x240mm^2

3.2.2. Load profiles

We will use load profiles that represents a day. They consist of 24 values, one per hour, and they have active and reactive power values. We have three profiles: industry load, public load and remaining load.

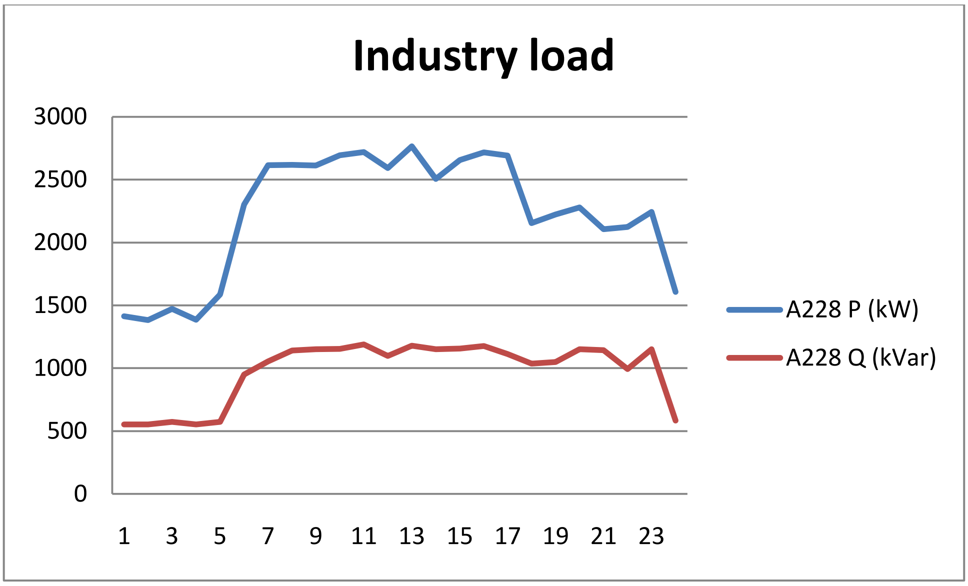


Figure 3.3: Industry load profile.

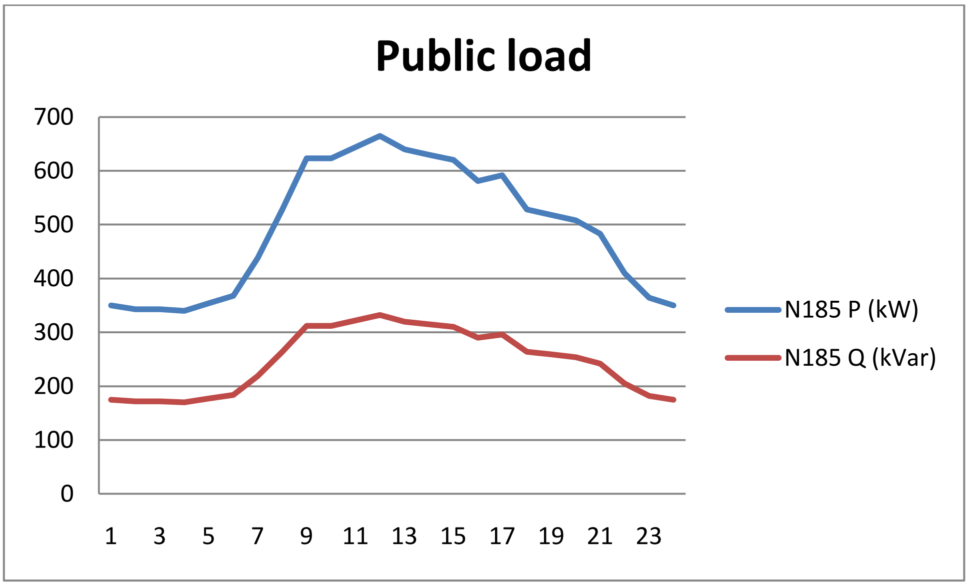


Figure 3.4: Public load profile

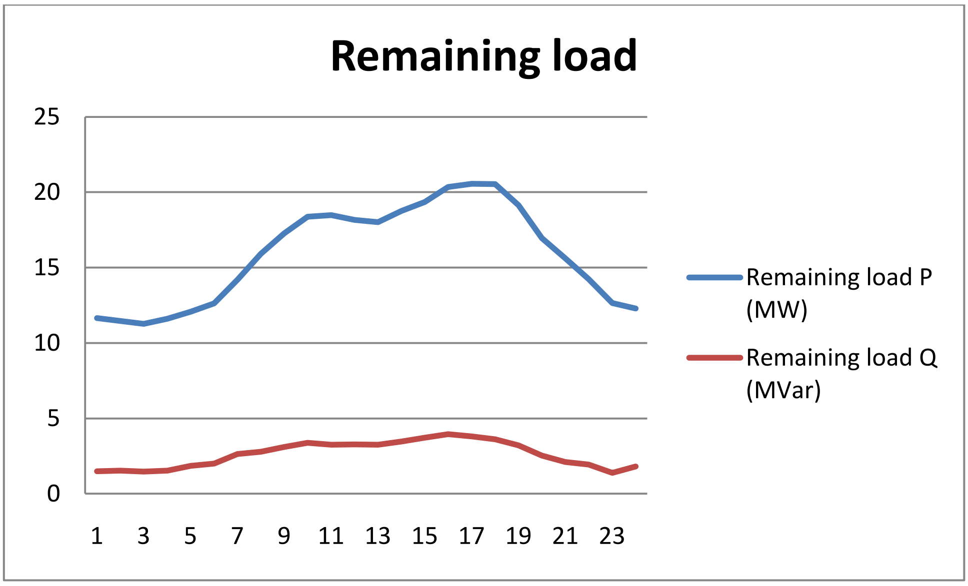


Figure 3.5: Remaining load profile

3.2.3. Alternative

Looking at the results of the simulations (see 4.2) there are not so many possibilities for the tap changer operation. It could work either without changes or with two changes. Therefore, in order to make the case interesting and experience more tap changer operation with the different deadband, we will increase the difference in the load profile between the low and the high consumption levels during the day in both the industry and the public buses. Also, we will double the impedances of all the lines and the transformers.

We have modified only the profiles of the industry and public load. The next figures represent them.

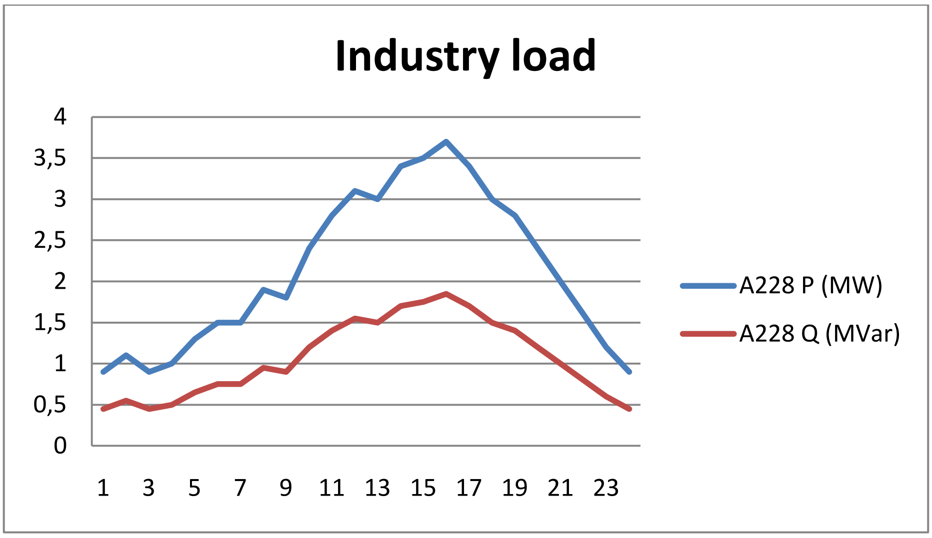


Figure 3.6: Industry load profile.

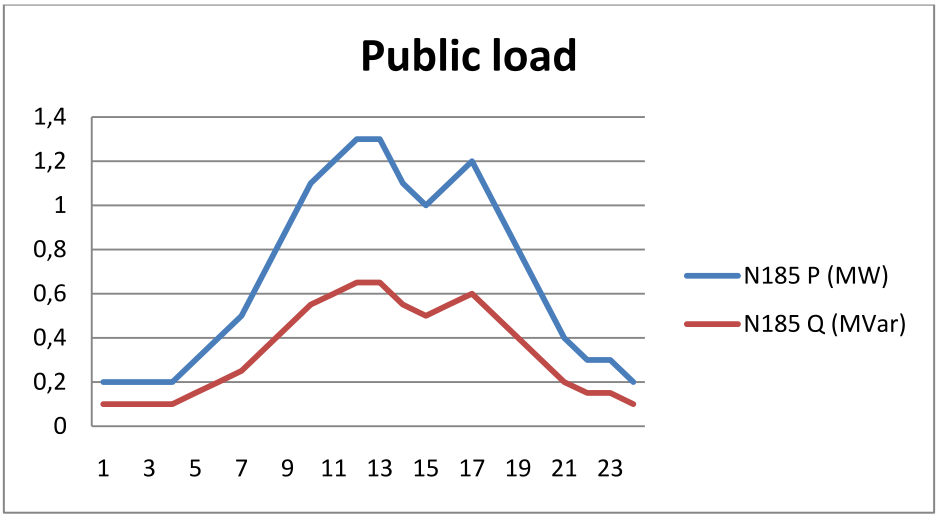


Figure 3.7: Public load profile

3.3. Countryside system

3.3.1. Description

The system consists of several loads. Three of them are placed in a 10 kV line, called net load, and the others after a transformer, in a 400 V line. Half of the transformer load comes from the net load and it is assumed to be split 1/3 in each station. The next figure shows the PowerWorld diagram.

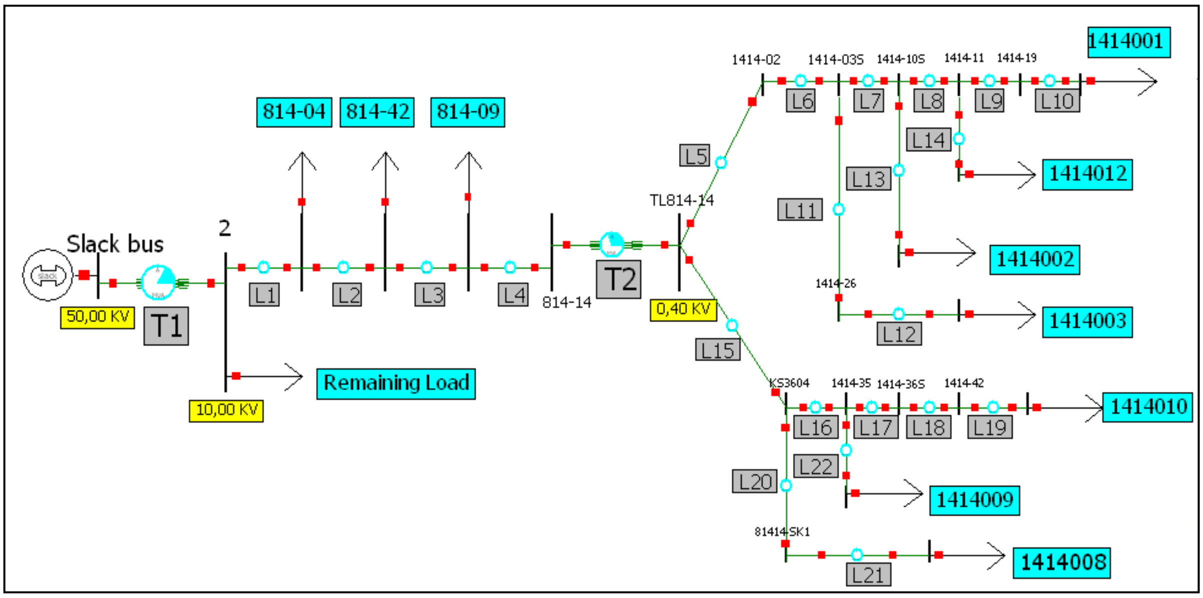


Figure 3.8: Countryside system in PowerWorld.

Next, we define a list with the parameters of the system.

1. **Transformer T1**

   50 kV/10 kV
   Nominal power: 6.9 MVA
   Impedance: 6.2%
   Tap changer:
   - Tap steps: 19
   - Minimum tap ratio: 0.8497
   - Maximum tap ratio: 1.1503

2. **Transformer T2**

   10 kV/0.4 kV
   Nominal power: 50 kVA
   Impedance: 4.5%
   Tap changer:
   - Tap steps: 5
   - Minimum tap ratio: 0.95
   - Maximum tap ratio: 1.05

3. **Lines**

In this model we are using different types of cables and overhead lines. The main characteristics of them, used in PowerWorld, are defined in the appendix C. In Table 3.1 the length and the type of all the lines in the model are shown. AXCEL is a medium voltage cable. N1XV, EKKJ and ALUS are low voltage cables. FeAl is an overhead line.

Line	Type	Length	Line	Type	Length
L1	FeAl 62	6 km	**L12**	EKKJ 10	18 m
L2	FeAl 62	5 km	**L13**	EKKJ 10	23 m
L3	AXCEL 3x25mm2	3 km	**L14**	EKKJ 10	47 m
L4	AXCEL 3x25mm2	3 km	**L15**	N1XV 95	191 m
L5	N1XV 95	310 m	**L16**	N1XV 50	162 m
L6	FeAl 31	68m	**L17**	N1XV-AS 50	67 m
L7	FeAl 31	442 m	**L18**	ALUS 50	388 m
L8	FeAl 31	70 m	**L19**	EKKJ 10	25 m
L9	FeAl 31	486 m	**L20**	N1XV 10	13 m
L10	EKKJ 10	30 m	**L21**	EKKJ 10	13 m
L11	FeAl 19	370m	**L22**	EKKJ 10	24 m

Table 3.1: Lines description in countryside sytem.

3.3.2. Load profiles

In this system, there are three types of loads: net load, public load and remaining load. We represent them in three different graphics with the profile of all the buses included in each load. We will use load profiles that represent a day consisting of 24 values, one per hour, and they have active power values.

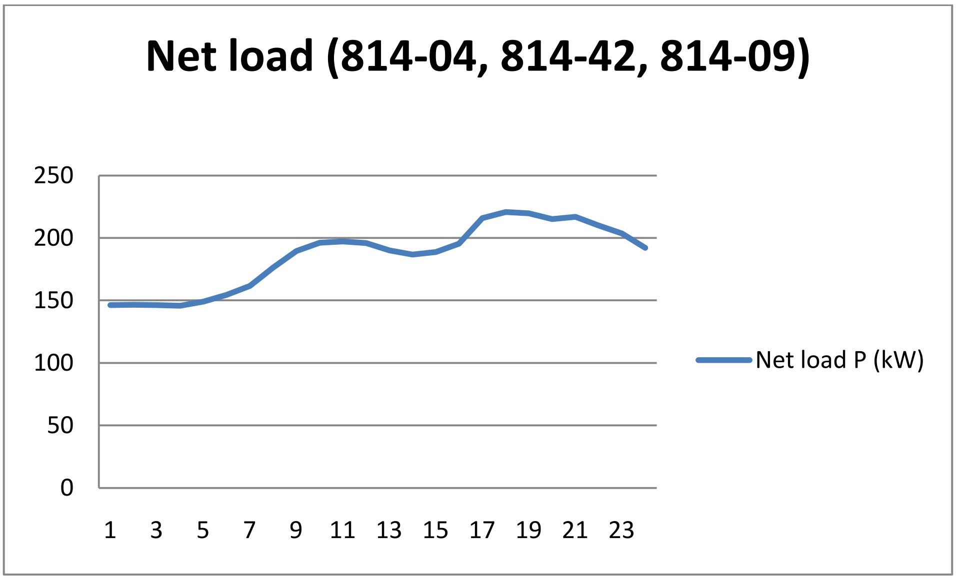


Figure 3.9: Net load.

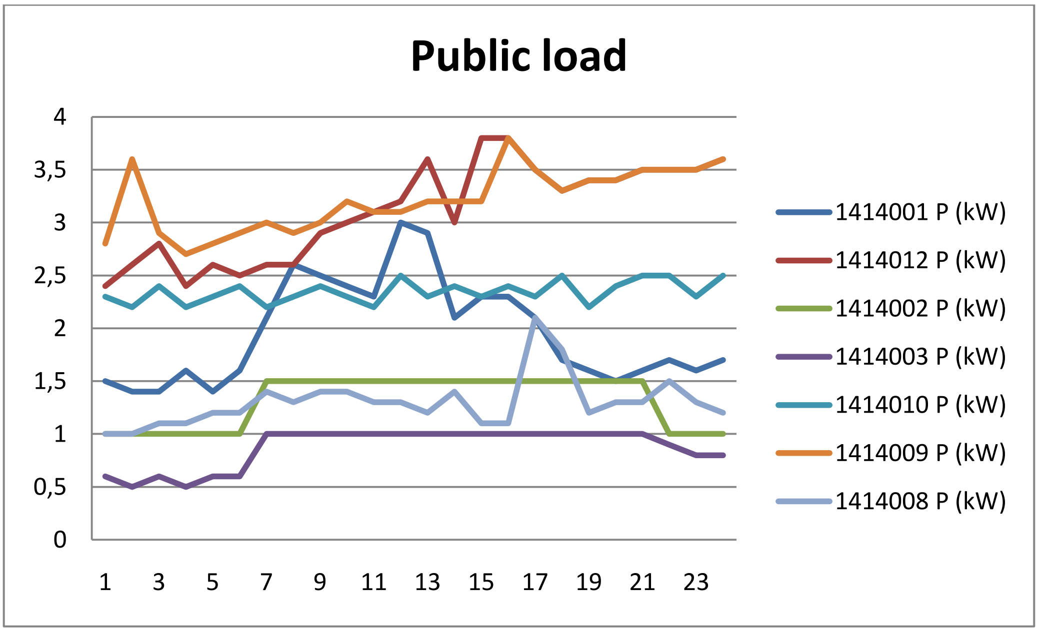


Figure 3.10: Public load.

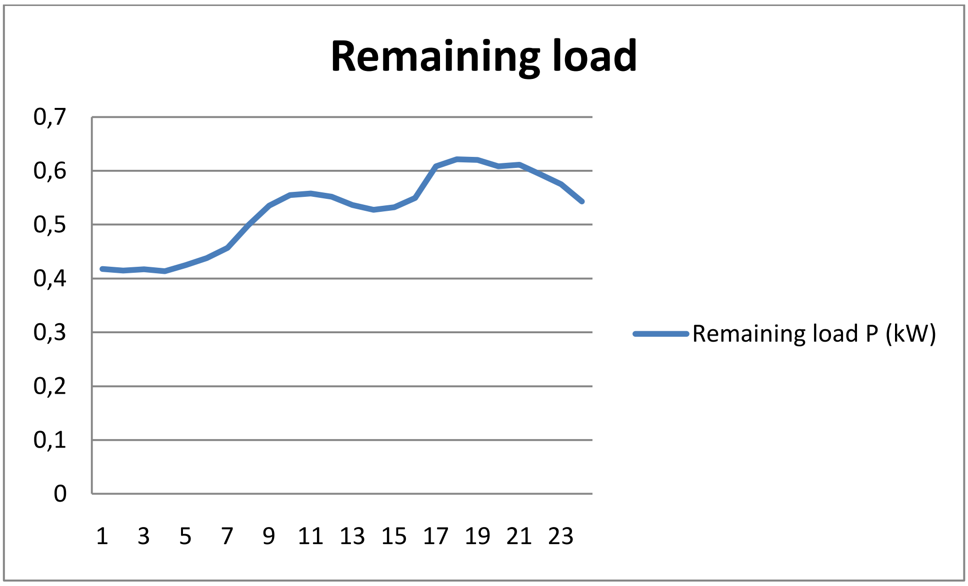


Figure 3.11: Remaining load

3.4. Wind power generation

In this part we will present the countryside system after the addition of wind power generation. The aim is to calculate the maximum wind power that we can inject to the system without exceeding the voltage limit. In order to do this, we will connect a generator in the bus 814-14, just before the transformer T2. In the next figure we see the new model.

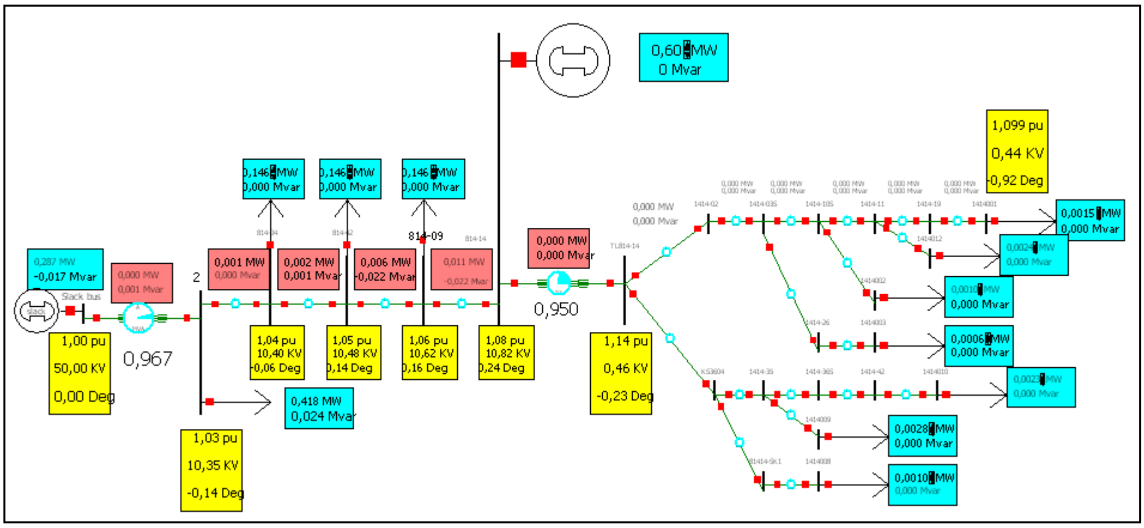


Figure 3.12: Countryside system with wind power generation.

With this generator we can inject just active power in the system and we cannot control the voltage in any point. Usually wind farms are able to control the voltage with the reactive power but, in this case, we will have a several turbines with low power so we will not have this possibility.

4. Simulations

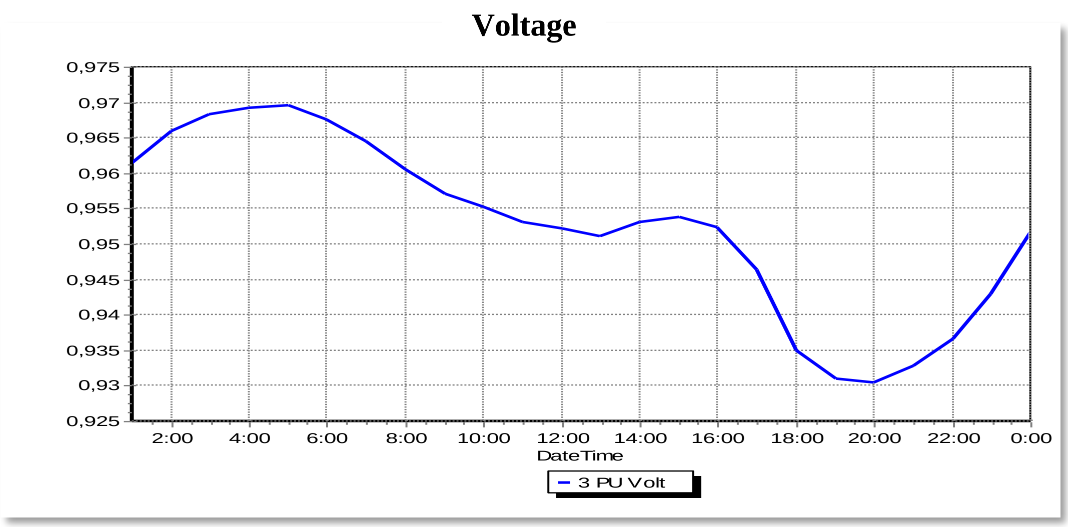
4.1. Generic system

The goal of these simulations is to see how we can control the voltage in the load point. We run several different simulations of the same model and load profile, modifying various control settings such as the voltage deadband or tap changer features. Finally, we analyze the behavior of the load voltage, the tap changer and the losses.

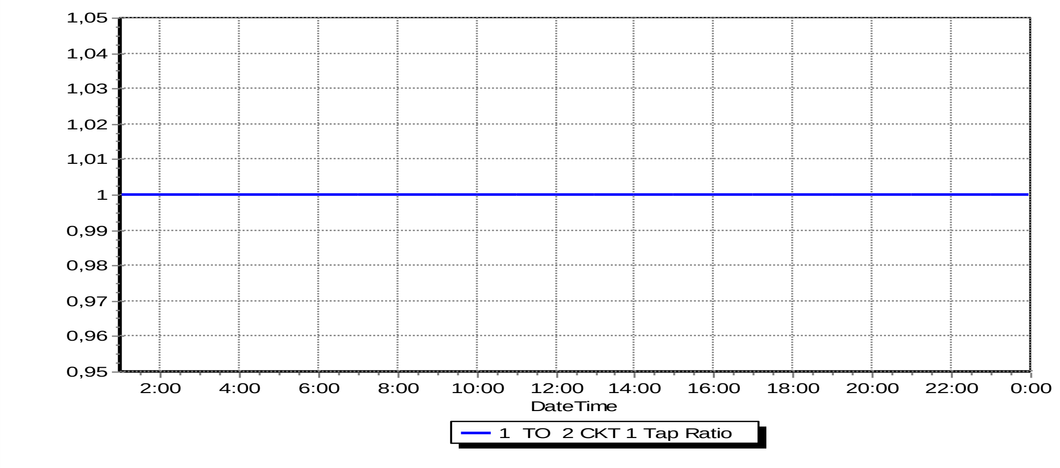
The losses are shown in average power. To calculate the energy losses it is necessary to multiply the average active power by 24 hours, obtaining the energy losses in MW·hour.

Table 4.1 presents a summary of each simulation with the most important information. For a more detailed description refer to Appendix B.1 where each case is presented separately. Case 1 is presented below as an example.

Case 1: No Tap Changer



Tap Ratio Position



Average Power Losses

Active: 0.0452 MW

Reactive: 0.0515 MVar

Case	Tap ratio	Deadband	Active losses (MW)	Reactive Losses (Mvar)
1. No tap changer	1.000	No	0.0452	0.0515
2. No automatic control	0.9625	No	0.0415	0.0473
3. Automatic control a	4 changes	0.02 p.u.	0.0405	0.0462
4. Automatic control b	2 changes	0.04 p.u.	0.0406	0.0463
5. Automatic control c	10 changes	0.01 p.u.	0.0405	0.0462

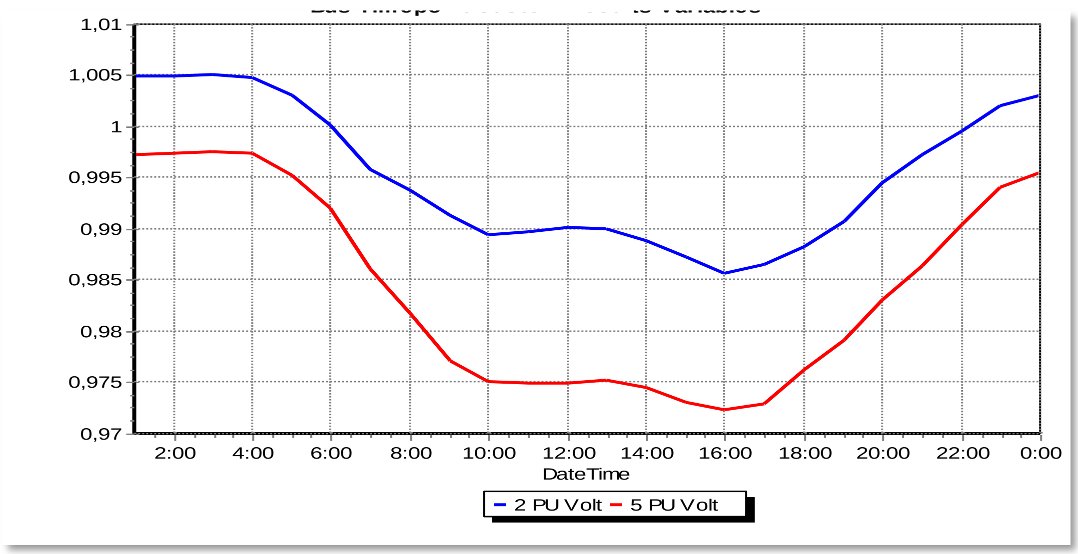
Table 4.1: Simulations results

4.2. City system

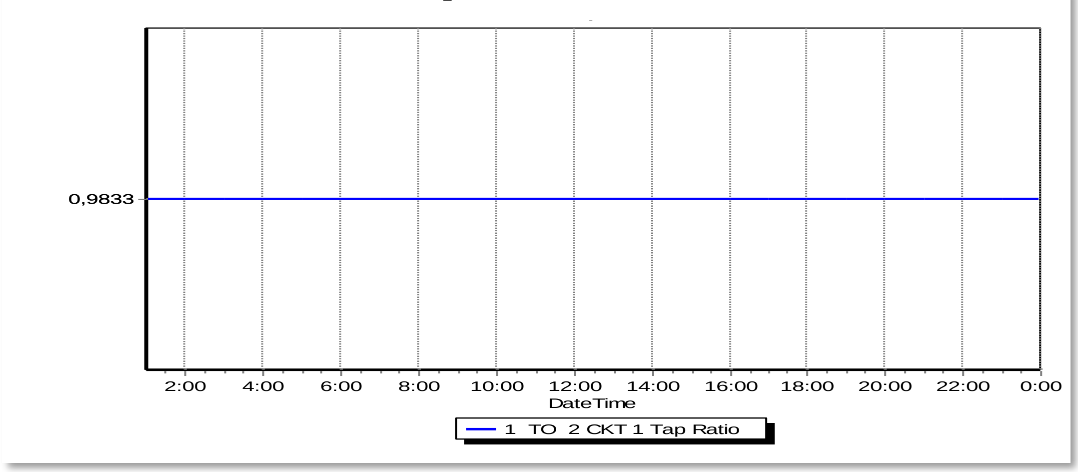
We run different simulations of the city system with the load profile defined in the preceding section. We modify the voltage deadband in the bus 2, which is the controlled bus. In each simulation, we show the behavior of the voltage in the public load bus (red line), in bus 2 (blue line) together with the deadband limits, the tap changer and the losses.

- **Case 1: Deadband 0.1 p.u.**

Voltages



Tap Ratio Position



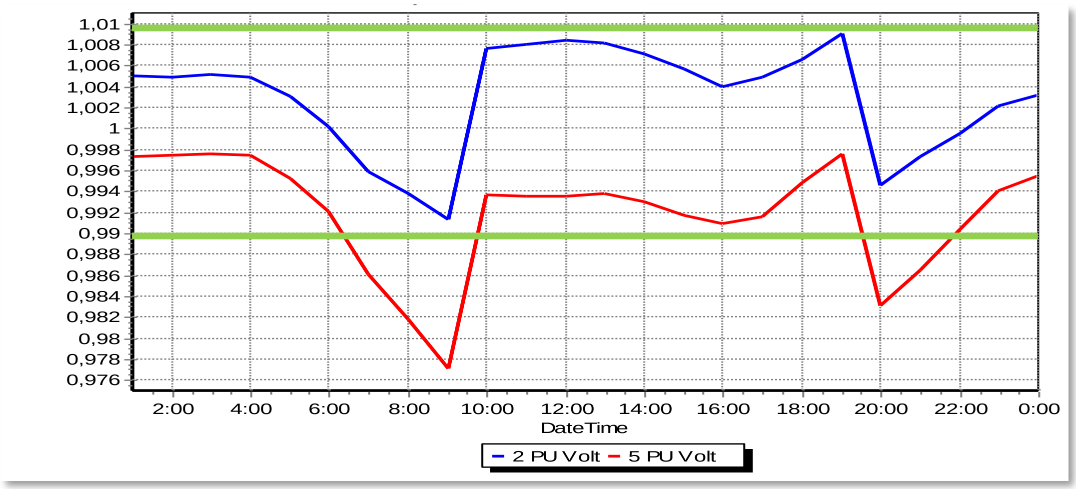
<u>Average Power Losses</u>

Active: 0.0667 MW

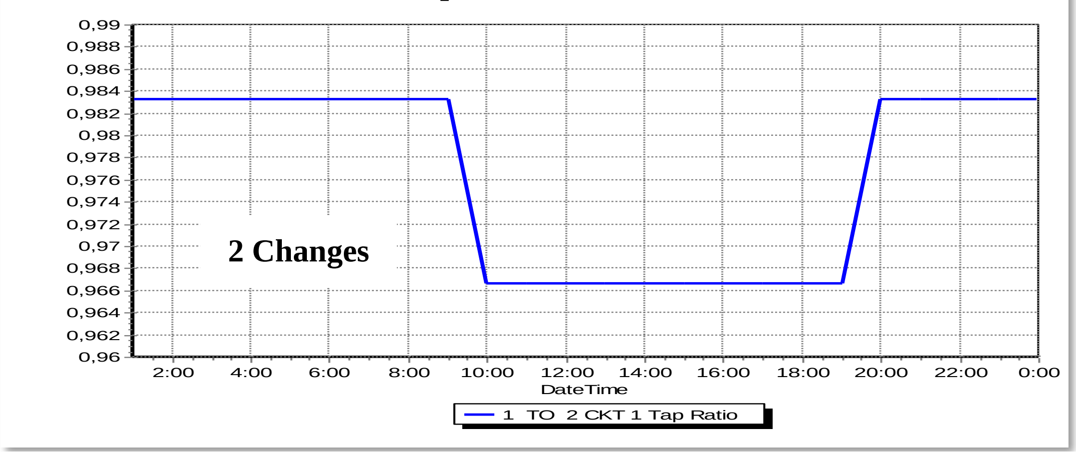
Reactive: 1.4787 MVar

- **Case 2: Deadband 0.02 p.u.**

Voltages



Tap Ratio Position



<u>Average Power Losses</u>

Active: 0.0656 MW

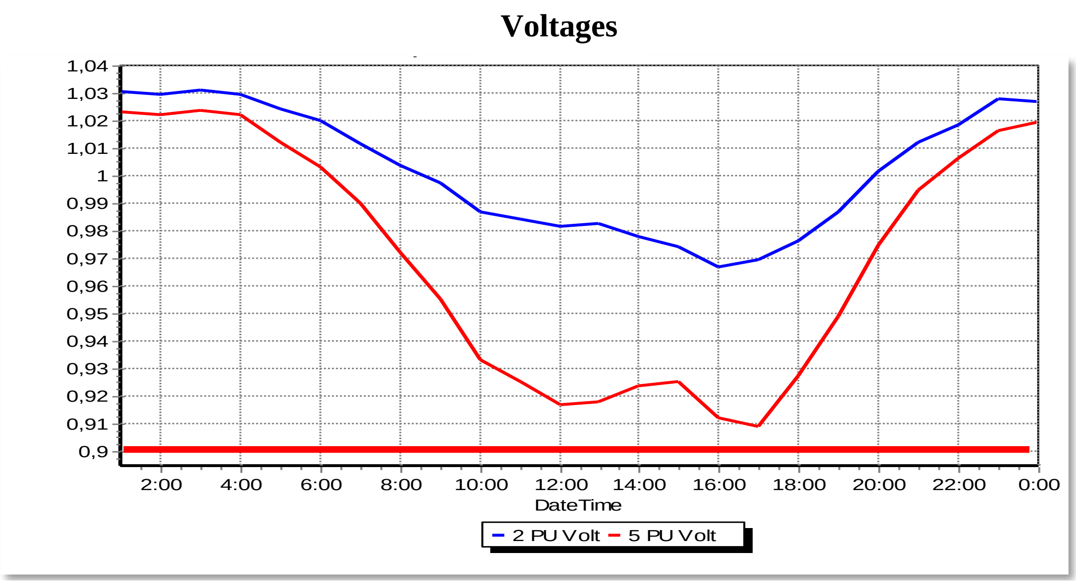
Reactive: 1.4402 MVar

4.2.1. Alternative

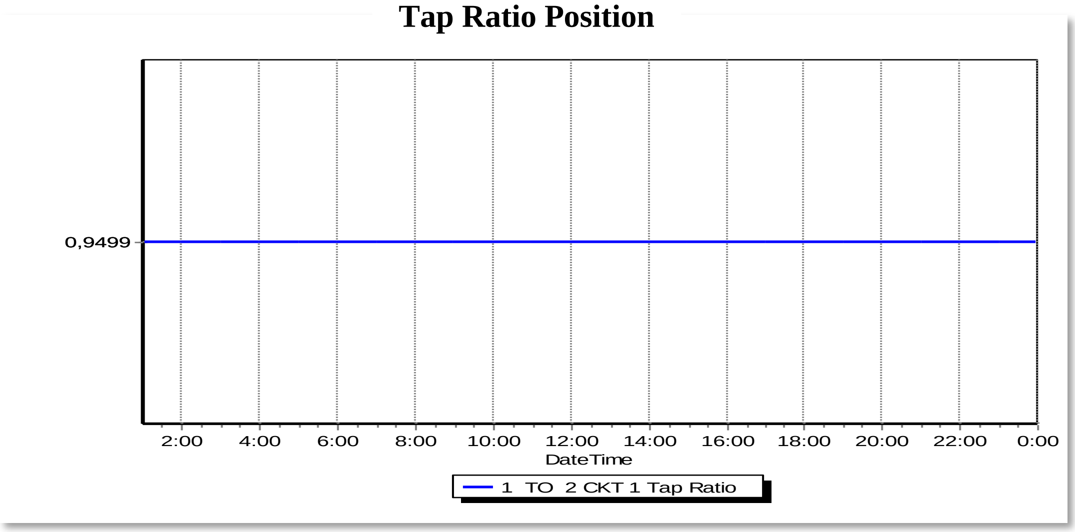
We have run four simulations varying the deadband to see how the tap changer works and how the losses are affected. In the results of the simulation we present the same voltages we used in the previous section, the deadbands limit (green straight lines) and the limits of the voltage magnitude variation, which are ± 10% for 95% of the week as we have seen in the theory of voltage quality presented before (red straights lines).

In this section we illustrate just the first. For further information refer to Appendix B.2 where the others cases are presented separately.

Case 1: Deadband 0.1 p.u.



Tap Ratio Position



Average Power Losses

Active: 0.1345 MW

Reactive: 3.1010 MVar

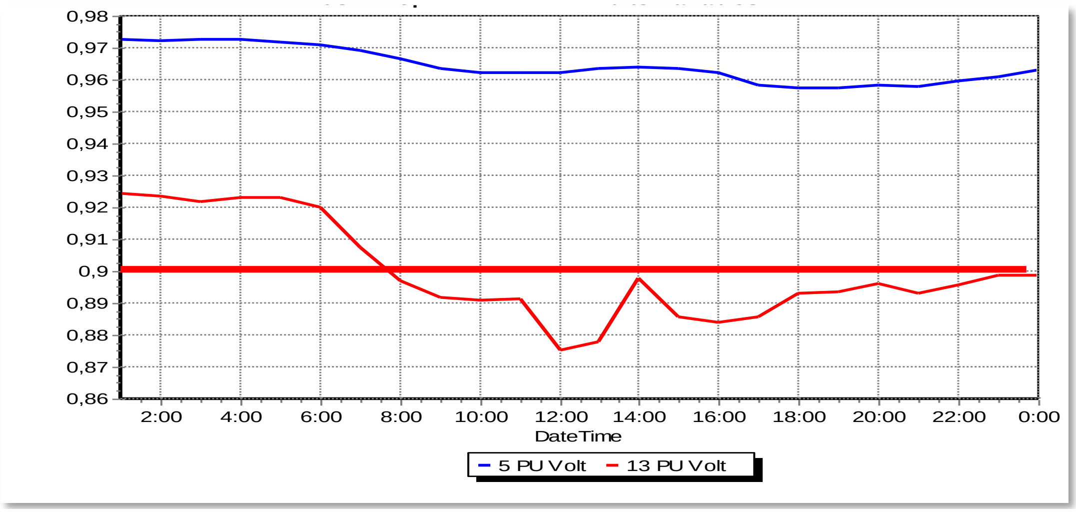
4.3. Countryside system

In this case, we do not have a tap changer in any transformer. The alternative is to change the fixed tap ratio of both transformers manually in order to show different behaviors of both the losses and the voltage quality for the customers. In the results we present the voltage in the bus 814-09 for the net load (blue line), and the bus 1414001 for the public load (red line) because they have the lowest load voltages. Also, we will see the limit of voltage magnitude variation, which is ± 10% for 95% of a week (red straights lines). The losses will be shown in average power.

We have run five cases. Next, we present the first one. The information about the others is contained in Appendix B.3.

Case 1: T1 Tap ratio: 1.000 (50 kV/10 kV)
T2 Tap ratio: 1.000 (10 kV/400 V)

Voltages



Average Power Losses

Active: 0.0179 MW

Reactive: -0.0150 MVar

4.3.1. LDC system

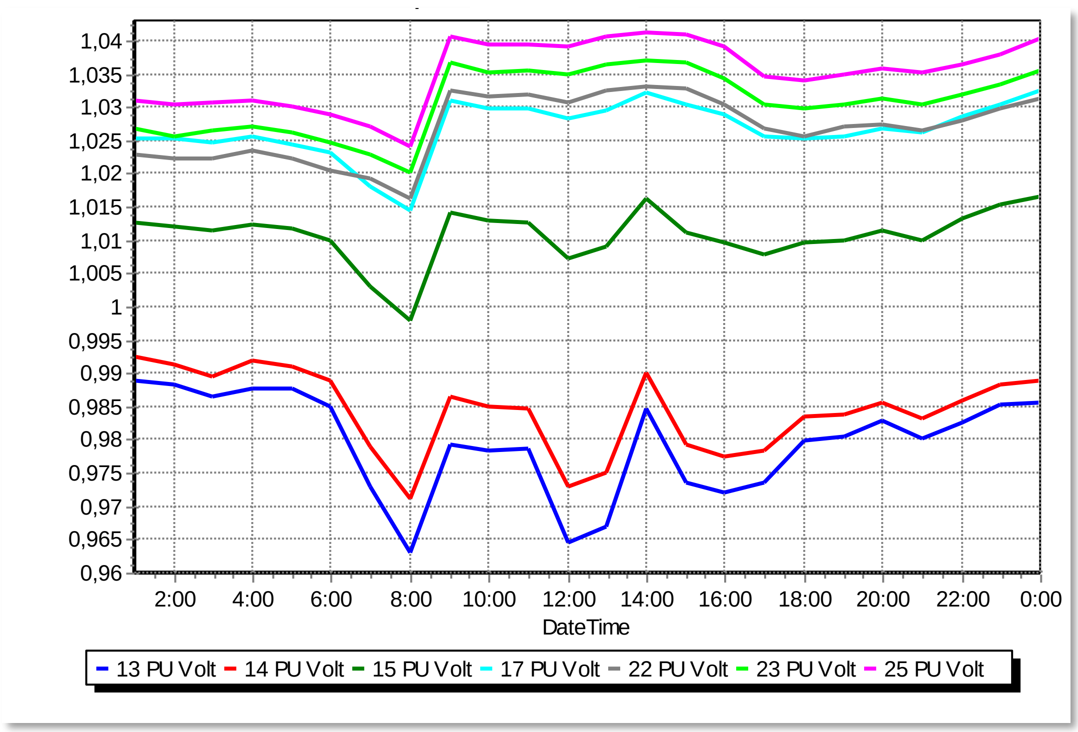
Now, the LDC system is included in the simulations. In PowerWorld, we simulate LDC considering that we can control the voltage in other buses separated from the transformer T1 with the automatic tap changer. So, we just have to specify the bus we want to control and the deadband. Of course, this system works better than the real LDC system because we are not taking into account the error we would have when calculating the losses in the lines, but it is a good approximation to see the effects of LDC on the system performance.

We leave the tap ratio of the transformer T2 fixed on 0.9750, and the automatic tap changer of the transformer T1 activated. The results of the simulation are shown below.

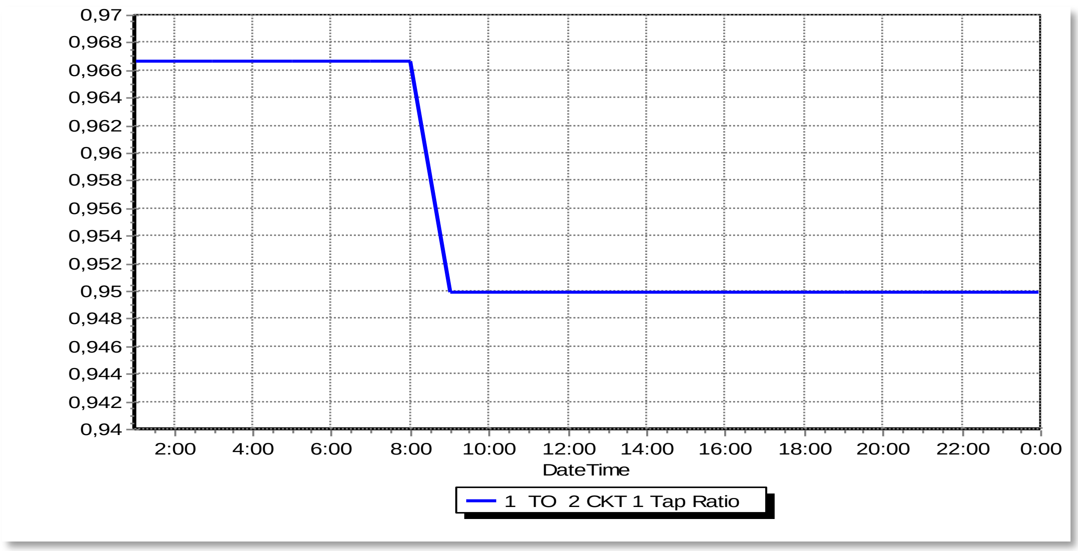
Case 1: Controlled bus: 814-14

Deadband: 1.00 p.u. – 1.025 p.u.

Voltages



Tap Ratio Position



<u>Average Power Losses</u>

Active: 0.0161 MW

Reactive: -0.0209 MVar

4.3.2. Constant impedance load

If we run one simulation with a constant impedance load we can see some differences compared to a constant power load. We run the point at 13:00 of the load profiles. The results are illustrated in the table 4.2.

Tap ratio T1	Tap ratio T2	Losses active power (kW)	Voltage Bus 814-09	Voltage Bus 814-09
1,0000	1,0000	16,4	0,97	0,9
0,9833	1,0000	16,9	0,98	0,91
0,9666	1,0000	17,5	1	0,93
0,9666	0,9750	17,6	1	0,96
0,9666	0,9500	17,7	1	0,98

Table 4.2: Results for a constant impedance load

4.4. Wind power generation

Taking into account the simulations of the countryside, we use the consumption point at 1:00 in the load profiles since it is the one that provides the highest voltages. Hence, we calculate the maximum power we can inject in the system without exceeding the voltage limit, which is set at ±10% for 95% of a week.

We run simulations with different tap ratio position of both transformers. In the results we show the maximum active power that we can generate and the voltage in some of the buses. We emphasize the voltages that are in the limit.

The next table shows the summary of the simulation results.

Tap ratio T1	Tap ratio T2	Maximum active power (MW)	Voltage Bus 814-14	Voltage TL 814-14
1,0000	1,0000	1,06	**1,100**	**1,100**
0,9833	1,0000	0,91	**1,100**	**1,100**
0,9666	1,0000	0,76	**1,100**	**1,100**
0,9666	0,9750	0,48	1,068	**1,100**
0,9666	0,9500	0,32	1,049	**1,100**

Table 4.3: Results part 1.

In the previous table, we present the results obtained for the tap ratios that we used in the original countryside system. Obviously, if we want to increase the amount of power that we can generate we need to reduce the voltage with the transformer T1 using the negative steps of the tap changer. However, we have to take care of the voltage just after the transformer, which is the point with the lowest voltage. So it does not go below the limit of 0.9 p.u. In Table 4.4, we show also the voltage after this transformer. The tap ratio for transformer T2 should be set to the lower step (1.05) since the voltage raise problem will occur in the bus 814-14. We emphasize in red the voltages that are outside the limits.

Tap ratio T1	Tap ratio T2	Maximum active power (MW)	Voltage Bus 2	Voltage Bus 814-14	Voltage TL 814-14	Voltage Bus 1414001
1,0167	1,0500	1,20	0,984	**1,100**	1,047	1,003
1,0334	1,0500	1,34	0,968	**1,100**	1,047	1,003
1,0501	1,0500	1,47	0,952	**1,100**	1,047	1,003
1,0668	1,0500	1,60	0,937	**1,100**	1,047	1,003
1,0835	1,0500	1,73	0,922	**1,100**	1,047	1,003
1,1002	1,0500	1,85	0,908	**1,100**	1,047	1,003
1,1169	1,0500	1,97	**0,895**	**1,100**	1,047	1,003

Table 4.4: Results part 2.

5. Results summary

5.1. Generic system

The analysis of the simple models built in PowerWorld can help us to find the best strategy for our real systems.

The addition of the voltage control with automatic tap changer provides some advantages to the system. Firstly, we can keep the voltage in the load within a certain deadband, so the quality of the power supply for the costumers is much better. Also, we can decrease the losses, although it depends on the fixed tap position we decide, the higher the tap ratio is the higher the losses are.

Analyzing the simulations, we have many different possibilities to control the voltage. Depending upon the requirements of each system (losses, voltage quality, tap changes…) we could find the optimum settings and, in this way, satisfy the needs. For example, increasing the deadband the number of tap changes decreases, which is positive for the tap changer’s lifetime, but lowers the voltage quality. On the other hand, if we decrease the deadband the number of tap changes increases but we have better quality. Regarding losses, if we raise the voltage set point the losses decrease and vice versa.

So, we can conclude that the number of tap changes depends on the amplitude of the deadband and the losses are related to the voltage level.

5.2. City system

Looking at the results, there are two possibilities for the tap changer operation. It could work either without changes or with two changes. Analyzing these two options, both of them are correct. To select one of them we have to consider our preferences. The option with no tap changes is positive for the lifetime of the tap changer in the transformer. The one with two changes leads to lower losses in the system and also improved voltage quality for the public load.

Analyzing the simulations of the city system alternative part makes the case more interesting. Table 5.1 presents a summary of the results where we see the voltage quality, the losses and the tap changes.

Deadband (p.u.)	Min. Public load voltage	Active losses (MW)	Reactive losses (MVar)	Tap changes
0,1	0,91	0,1345	3,1010	0
0,065	0,92	0,1315	3,0114	4
0,05	0,93	0,1323	3,0604	6
0,02	0,93	0,1320	3,0470	6

Table 5.1: Results of alternative city system.

In terms of voltage quality, there is a direct relation with the deadband. The smaller the deadband is the better the voltage quality is. The same happens with numbers of tap ratio changes. The smaller the deadband is the more tap changes are needed.

The optimal solution for this system is a deadband of 0,065 because we have fewer losses, less tap changes, and the lowest voltage in the public load is 0.92 p.u. which is within limits. It is not an extremely good value since it is close to the quality limit of 0.9 p.u., but decreasing the deadband will not improve much the voltage level.

5.3. Countryside system

In Table 5.2 we present a summary of all the simulations where we compare the active losses and the voltage quality. We have decided to represent the voltage in the buses 814-09 and 1414001 because they have the lowest voltage compared to their respective group of loads. The drawback is that we have to take care not to raise too much the voltage in the other buses. We will discuss about that in the followings conclusions.

Tap ratio T1	Tap ratio T2	Losses active power (kW)	Max-Min voltage Bus 814-09	Max-Min voltage Bus 1414001
1,0000	1,0000	17,9	0,97-0,96	0,92-0,88
0,9833	1,0000	17,3	0,99-0,98	0,94-0,90
0,9666	1,0000	16,6	1,01-0,99	0,96-0,92
0,9666	0,9750	16,6	1,01-0,99	0,99-0,94
0,9666	0,9500	16,6	1,01-0,99	1,02-0,97

Table 5.2: Countryside system simulation results.

Regarding losses, they decrease when we are increasing the voltage with the tap ratio. We can say that the losses are proportional to

$$1/V^2$$

when we have a constant power load. As we have seen in the simulations, if we set constant impedance load the losses are proportional to

$$V^2.$$

We do not see big differences with the changes in transformer 2 because the lines and the impedances after this transformer are very low. We cannot reduce the losses more because the voltage level would raise too much.

As for the voltage quality, there are some corrects solutions depending on which load buses we are taking into account. The important thing is that the voltage must be between the deadband limits in all the costumer buses. In our case, looking at the buses 814-09 and 1414001, it seems that the optimal alternative is to set T1-0.9666 and T2-0.9500. With this solution the voltage in all the buses is within limits and the losses are as low as possible. Nevertheless, from the costumers perspective, the best solution is T1-0.9666 and T2-0.9750 because the average error in all the voltages at the costumers' side is as low as possible. The figure 3.1 shows those voltages.

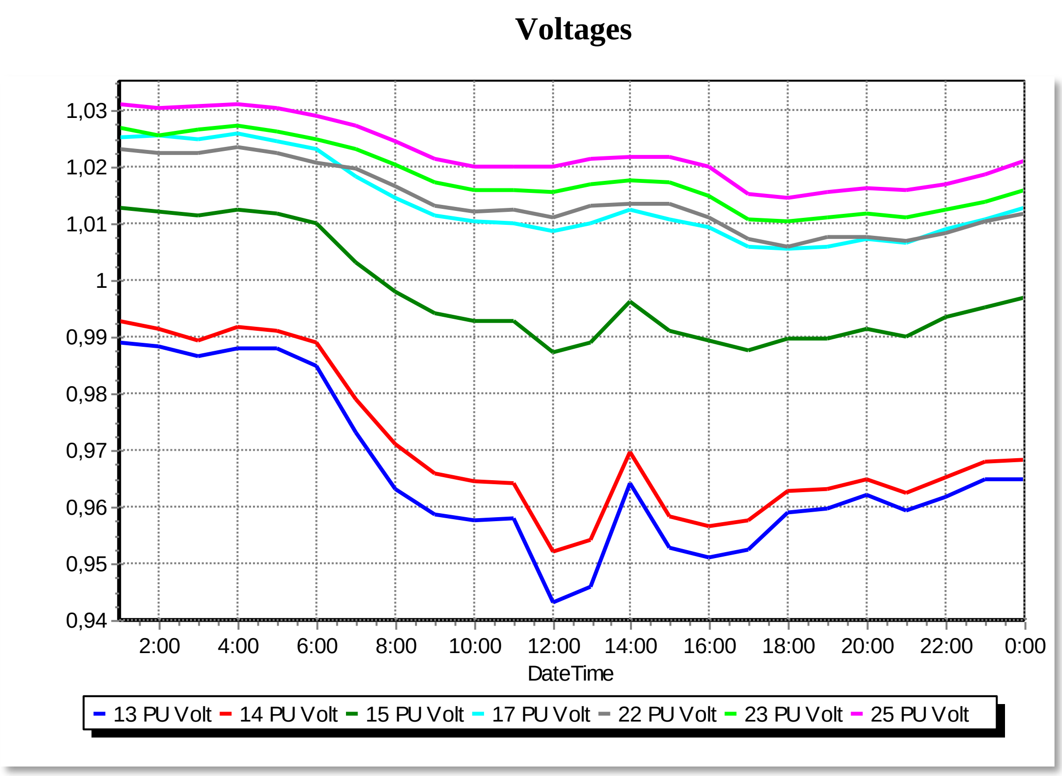


Figure 5.1: Voltages of the public load buses with T1-0.9666 and T2-0.9750.

The addition of the line drop compensation (LDC) system controlling the voltage in bus 6 is positive for the voltage quality, and also leads to reduced losses. In Figures 5.2 and 5.3 we see a comparison of the voltage in the buses 1414001 and 1414008 since they have the more extreme voltage values. In this case, the advantages are not very significant, but, in a different situation with larger differences in the power consumption during the day or the year, we could see higher benefits in the voltage quality and in the losses too. On the other hand, we have two movements of the tap changer per day and, without LDC system, we do not have any. So, globally, the LDC system is not interesting in this case.

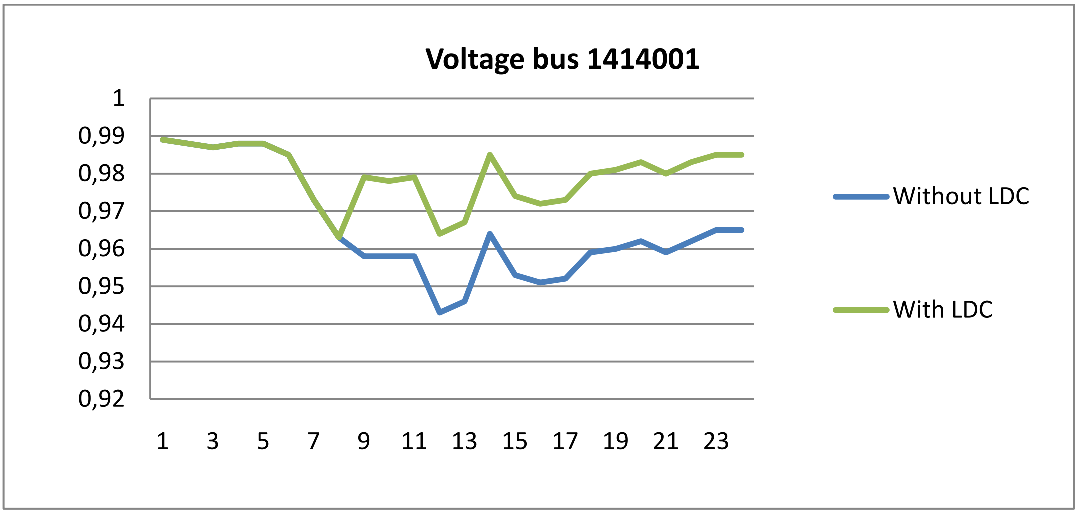


Figure 5.2: Comparison bus 1414001

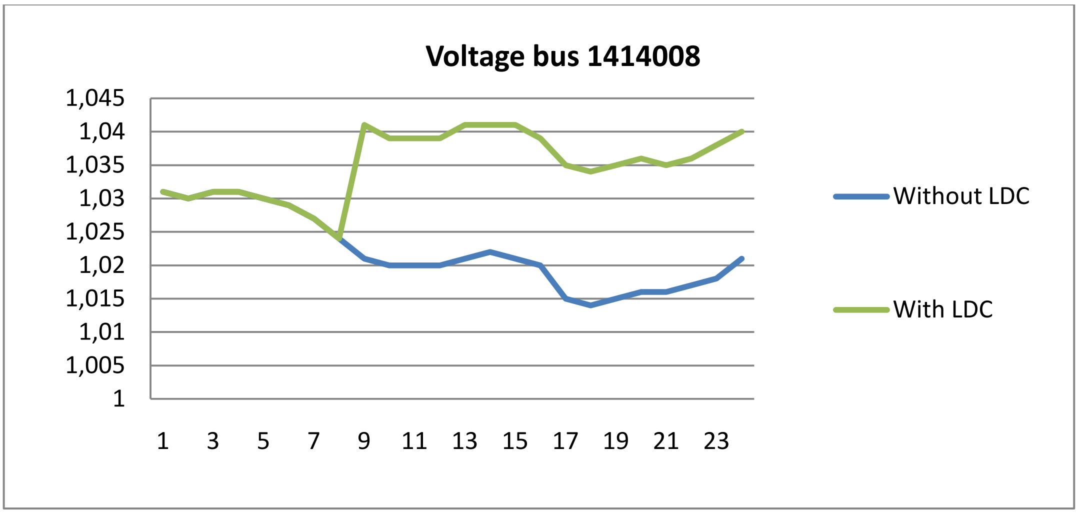


Figure 5.3: Comparison bus 1414008.

5.4. Wind power generation

The best solution for the maximum generated power is T1-1.1002 and T2-1.0500. With these settings, we can generate up to 1.85 MW in bus 814-14 with the wind turbines, which is enough power to feed all the loads in the system.

We know the maximum power that we can inject to the net, so we could look for suitable products in the market for this system. Table 5.3 shows the products of Vestas and Gamesa that are interesting for our application.

Company	Name	Power	Wind
Gamesa	G52	850 kW	Medium, High
Gamesa	G58	850 kW	Low
Vestas	V52	850 kW	Medium, High
Vestas	V60	850 kW	Medium, Low
Vestas	V82	1.65 MW	Medium, Low
Vestas	V90	1.8 MW	Medium
Vestas	V100	1.8 MW	Low

Table 5.3: Wind turbines of Gamesa and Vestas. [9] [10]

Depending on the wind conditions that we have, we can decide which turbines are suitable. As we calculated, the maximum power we can connect is 1.85 MW in the bus 814-14. Table 5.4 represents the possible choices of turbines for the different types of wind.

Wind	Name	Number	Power
Low	G58	2	1.7 MW
	V60	2	1.7 MW
	V82	1	1.65 MW
	V100	1	1.8 MW
Medium	G52	2	1.7 MW
	V52	2	1.7 MW
	V60	2	1.7 MW
	V82	1	1.65 MW
	V90	1	1.8 MW
High	G52	2	1.7 MW
	V52	2	1.7 MW

Table 5.4: Solutions for the different types of wind.

6. Conclusion

Based on the data received from Lunds Energi, we have built three systems with the simulation tool PowerWorld. Firstly, we have built a generic system to extract conclusions that could be useful for the voltage problems in the real systems. Then, we have built the city system and the countryside system with the characteristics of the lines, the transformers, the generation and the loads. Finally, we have added the wind power generation to the countryside system. The load profiles used for the simulation are made up of 24 values over one day.

Looking at the simulation results for the city system, we do not find any problem with the voltage. The main conclusion is that the system can work with a fixed tap ratio during the day without going out of the quality limits specified for the voltage level. This is positive for the lifetime of the tap changer. However, if we make the conditions more extreme, we see more movements in the tap changer which makes the case a bit more difficult to analyze. Regarding the countryside system, we have found voltage problems with some costumers because the voltage level is very low. A possible change that improves the voltage quality is to move the fixed tap position in both transformers to raise the voltage at the customer's end. Particularly, the case with tap ratios T1-0.9666 and T2-0.9750 seems to be the best in a global view for the costumers. The addition of line drop compensation systems is positive because we can control the voltage in a bus closer to the costumers. The next tables show a summary of the results.

Deadband (p.u.)	Min. Public load voltage	Active losses (MW)	Reactive losses (MVar)	Tap changes
0,1	0,91	0,1345	3,1010	0
0,065	0,92	0,1315	3,0114	4
0,05	0,93	0,1323	3,0604	6
0,02	0,93	0,1320	3,0470	6

Table 6.1: Results of alternative city system.

Tap ratio T1	Tap ratio T2	Losses active power (kW)	Max-Min voltage Bus 814-09	Max-Min voltage Bus 1414001
1,0000	1,0000	17,9	0,97-0,96	0,92-0,88
0,9833	1,0000	17,3	0,99-0,98	0,94-0,90
0,9666	1,0000	16,6	1,01-0,99	0,96-0,92
0,9666	0,9750	16,6	1,01-0,99	0,99-0,94
0,9666	0,9500	16,6	1,01-0,99	1,02-0,97

Table 6.2: Countryside system simulation results.

Analyzing the results of the different systems we can confirm a direct connection between the voltage set point and the losses and, also, between the deadband amplitude and the tap changer operation and lifetime. When we increase the voltage level with the tap changer we reduce the losses in the system if we are working with a constant power load. This reduction is bigger in the countryside system than in the city system because the lines are longer, so the impedances are higher. But if we work with constant impedance load when we increase the voltage the losses increase as well. Hence, depending on the type of the load, we have a different relation between the voltage and the losses. Concerning the deadband, we can come to the conclusion that the wider the deadband is the fewer tap changes are needed. In the next figure we present a summary with these conclusions.

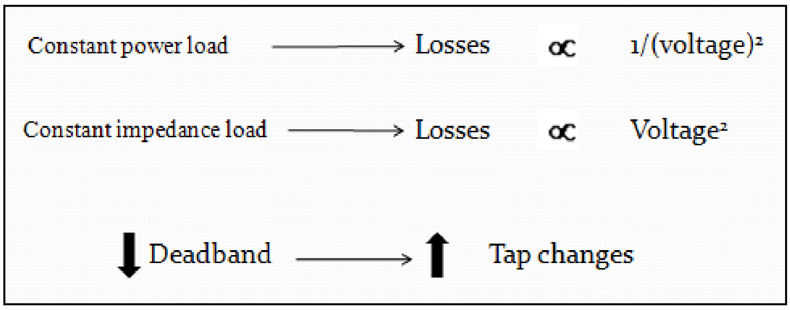


Figure 6.1: Summary

With the hourly data available, we observe that we do not have too many tap position changes during a day. But, in real operation, it would be more of them because there will be noise and others perturbations in the grid that could generate big variations in the voltage in a small period of time. That means that the tap changer can modify its position going up and down within one hour and we are not taking into account these movements.

Related to the wind power generation, there are many changes in the voltage when we connect wind turbines in a countryside system. Specifically, the more wind power we inject, the bigger the voltage rise is. Therefore, it is necessary to calculate how many turbines you can introduce at each point of the system without going above the voltage limit. Also, the tap changer position should be readjusted in order to be able to increase the power we can inject in that bus. The best solution for our system is T1-1.1002 and T2-1.0500, allowing us to generate up to 1.85 MW in bus 814-14 with the wind turbines. This energy is enough to feed all the loads in the system. So it is a good idea to install them because we can generate renewable energy respectful with the environment. Another advantage of the wind power generation in this system is that we generate close to the loads, reducing a lot the losses since the generation point is near the consumer point. The drawback is that you could have problems of too high voltage in some nodes of the system, and too low voltage in some other nodes at the same time. Table 5.4 in the results chapter suggests some turbines from Vestas and Gamesa that are actually in the market and are suitable for our situation depending on the type of wind.

7. Future work

As we said in the conclusions, in this thesis we have worked with hourly values for the load profiles. This is interesting to find the main operation of the tap changer during the day. However, for future work, load profiles with higher resolution should be used, like minute values, which will cause another operation in the tap changer of the transformer with faster changes due to the noise or any disturbance. The Figure 7.1 shows the tap changer movements of a Lunds Energi transformer during 24 hours. We can check that there are several steps in one hour so working with a resolution higher than hour is desirable.

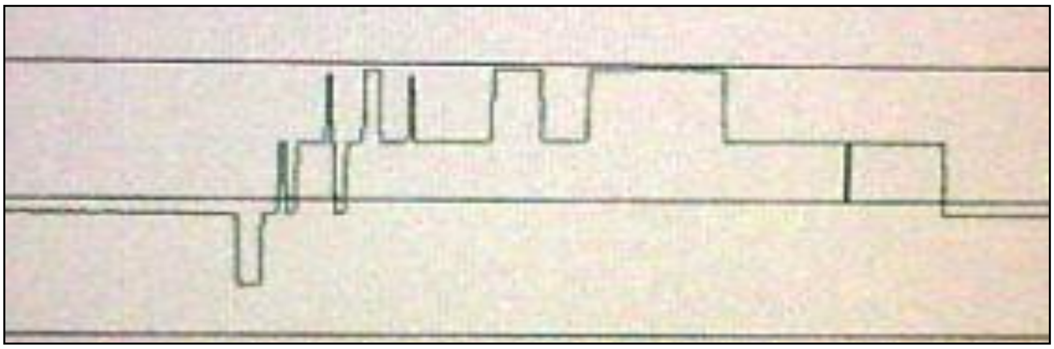


Figure 7.1: Tap changer movements during 24 hours

Another interesting point for the future work is to add the measurements of the voltage in the 130 kV line. We have worked assuming a constant 130 kV voltage in the bus before the transformer, slack bus in the figure 7.2. However, in a real system there are variations in this value that could lead to a different operation of the system. In the next figure we see the city system and it is marked where we have to add the measurements.

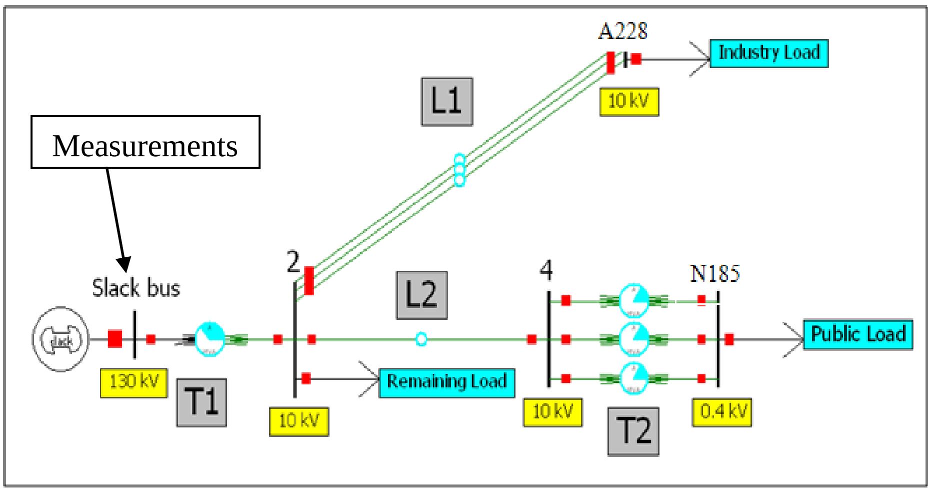


Figure 7.2: City system.

We have confirmed that depending on the type of load, the system works in a different way, specially the relation between the losses and the voltage level. In our simulations, we have focused on constant power loads. For future works, an analysis with a constant impedance load could be of interest.

8. Bibliography

[1]. Welch, Lee E. (2004). Taking Control of Voltage Drop and Reactive Power. Primedia Business Magazines & Media Inc.

[2]. E. Lakervi, E.J.Holmes. (1995). Electricity Distribution Network Design. The Institution of Engineering and Technology, London, United Kingdom.

[3]. L.L. Grigsby. (2000). The Electric Power Engineering Handbook. CRC Press and IEEE Press.

[4]. Qing Tian, Xin Guo, Xiangning Lin. (2008). Improvement in the scheme of voltage control regulator. IEEE

[5]. Elena Gimenez Romero. (2007). Voltage Control in a Medium Voltage System with Distributed Wind Power Generation. Department of Industrial Electrical Engineering and Automation, Lund University.

[6]. Henryk Markiewicz & Antoni Klajn. (2004). Voltage Disturbances
Standard EN 50160 - Voltage Characteristics in Public Distribution Systems. Wroclaw University of Technology.

[7]. Southern California Edison Website. (2009).
http://www.sce.com/005_regul_info/eca/DOMSM09.DLP

[8]. PowerWorld official website. (2010). www.powerworld.com

[9]. Gamesa official website. (2010).
http://www.gamesacorp.com/en/products/wind-turbines/catalogue

[10]. Vestas official website. (2010).
http://www.vestas.com/en/wind-power-plants/procurement/turbine-overview.aspx#/vestas-univers

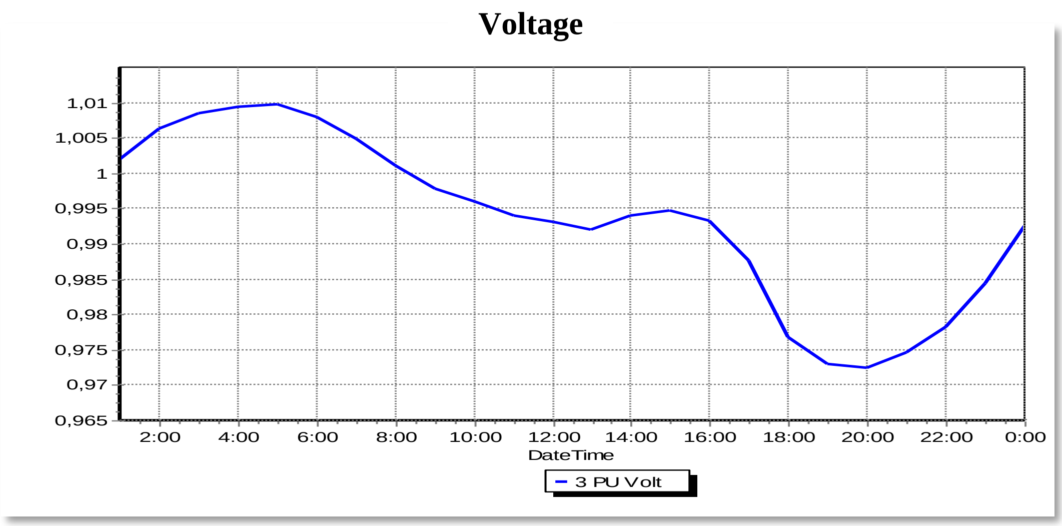
Appendix A: Matlab function

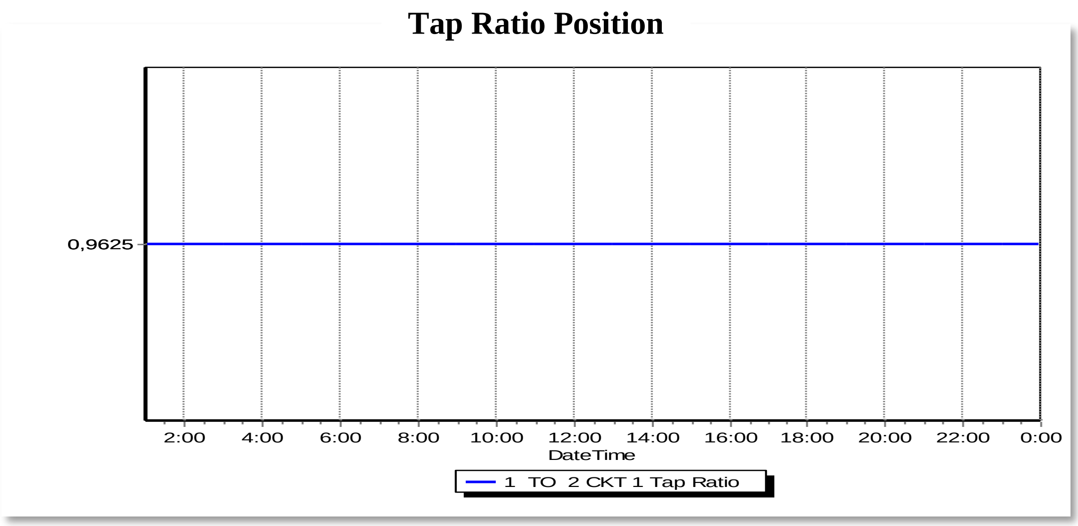
```
% Parameters of thevenin equivalent
    %Sbase=1.5MVA Ubase=10Kv
    %(All the values are in per unit)
U1=1;
l=8; % length of the cable
Zt=0.00375i; % impedance transformer
Zl=(0.00504+0.0053055i)*l; % impedance line
Z=(Zl+Zt); %total  impedance
R=real(Z);
X=imag(Z);

%Calculation of the load
S=[0.9+ 0.4359i];
day=[0.655,0.581,0.542,0.527,0.522,0.553,0.606,0.669,0.725,0.755,0.790
,0.804,0.821,0.790,0.777,0.802,0.894,1.071,1.132,1.139,1.104,1.047,0.9
48,0.813];
S=day*S;
P=real(S);
Q=imag(S);

%Solution
a=1;b=-U1;c=P*R+Q*X; % parameters equation 2° grade approximation
U2a= (-b + sqrt(b^2-4*a*c))/2*a;
a=1;b=-U1;c=conj(S)*Z; % parameters equation 2° grade
U2c= (-b + sqrt(b^2-4*a*c))/2*a;
U2c= sqrt(real(U2c).^2+imag(U2c).^2);

%Draw solution
t=1:1:24;
plot(t,U2a,'-',t,U2c,'--'),grid on
title('Comparison of voltages')
xlabel('Time');
ylabel('Voltage');
legend('approximation', 'normal');
```

Appendix B: Simulations

B.1 Generic system

Case 2: No automatic control voltage





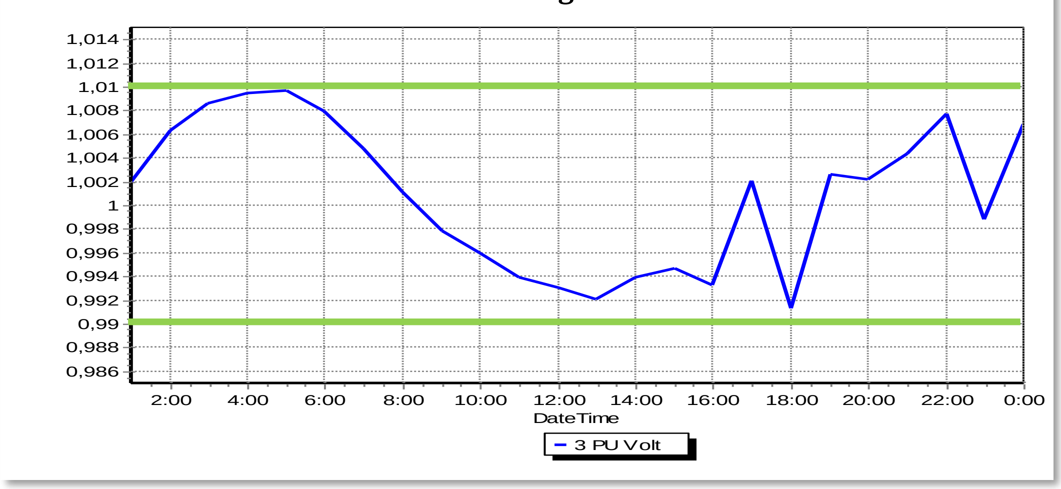
<u>Average Power Losses</u>

Active: 0.0415 MW

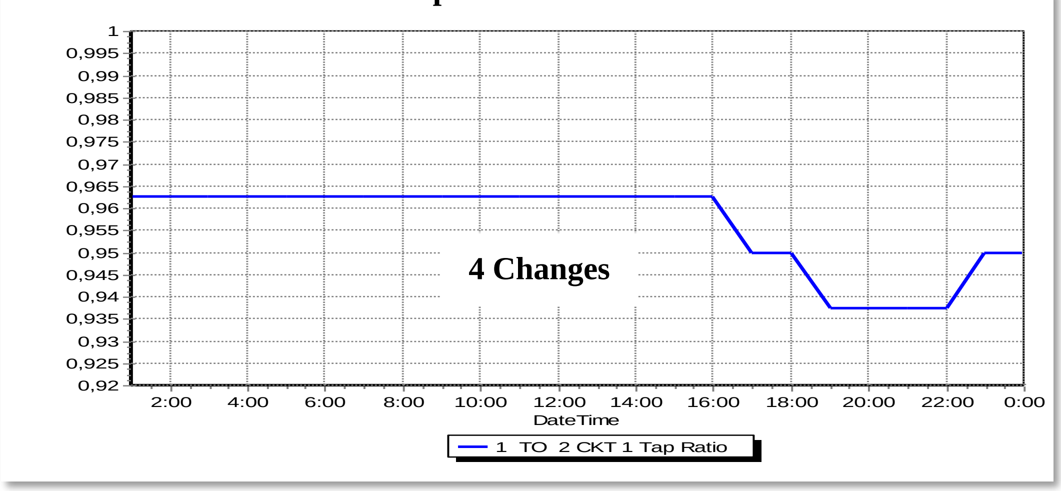
Reactive: 0.0473 MVar

Case 3: Automatic control voltage a

Voltage



Tap Ratio Position

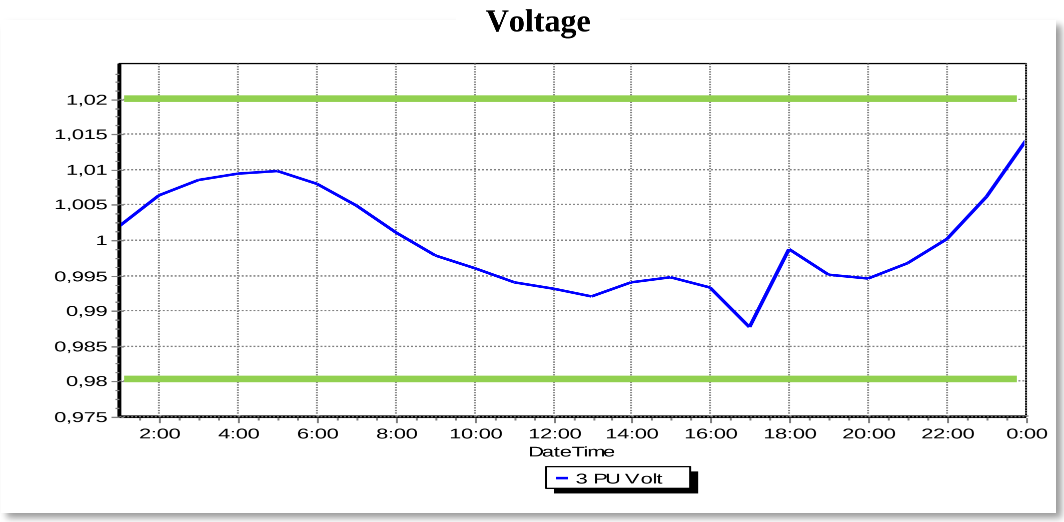


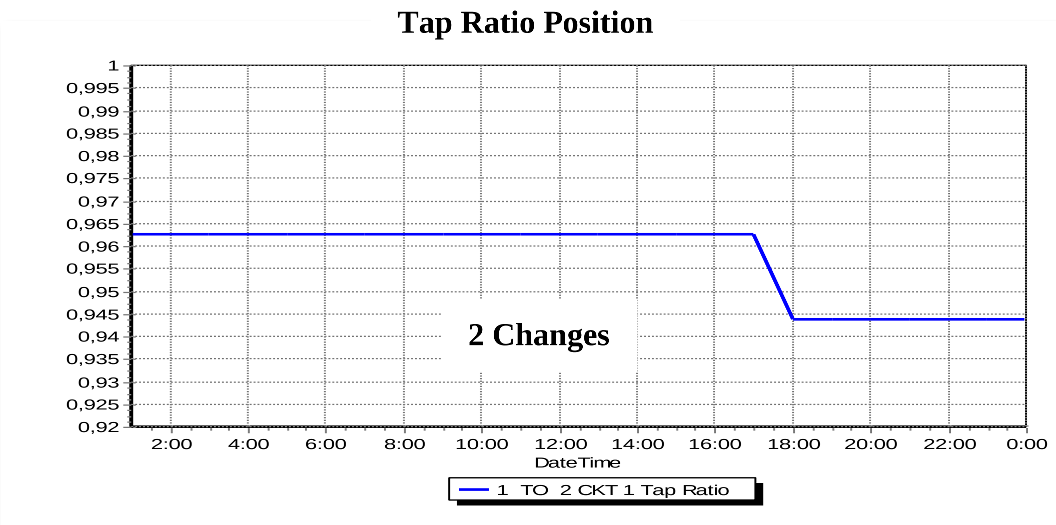
Average Power Losses

Active: 0.0405 MW

Reactive: 0.0462 MVar

Case 4: Automatic control voltage b





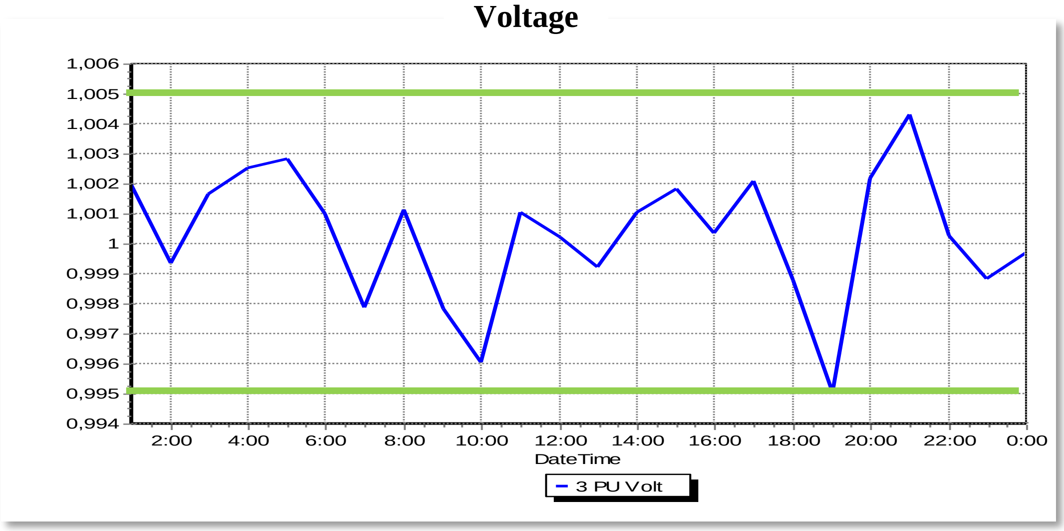
Average Power Losses

Active: 0.0406 MW

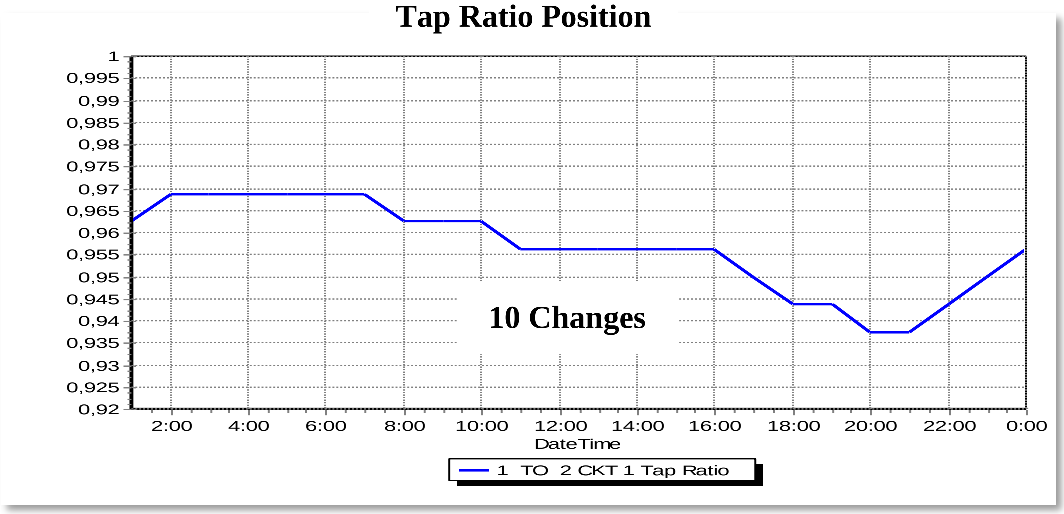
Reactive: 0.0463 MVar

Case 5: Automatic control voltage c

Voltage



Tap Ratio Position



<u>Average Power Losses</u>

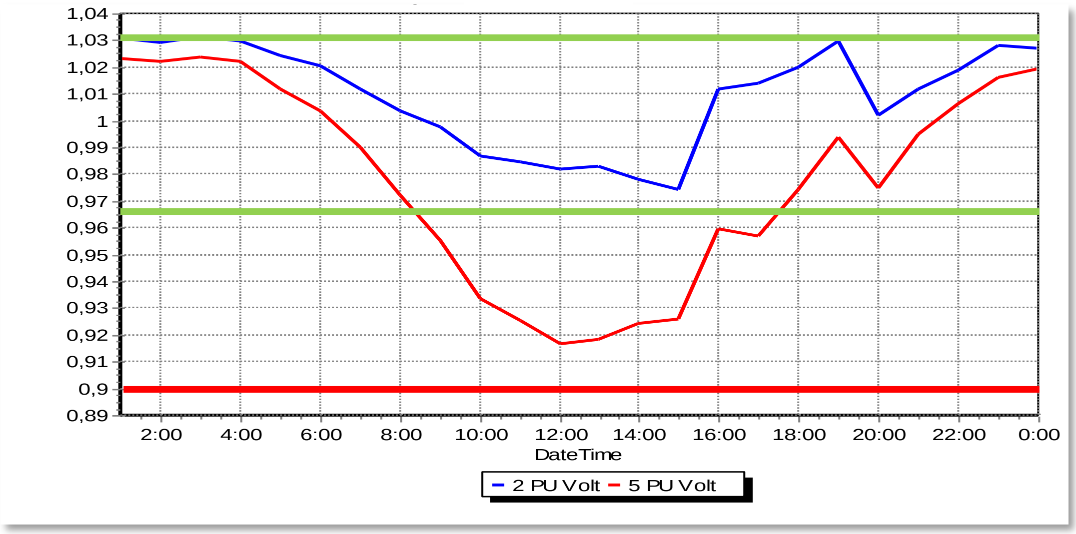
Active: 0.0405 MW

Reactive: 0.0462 MVar

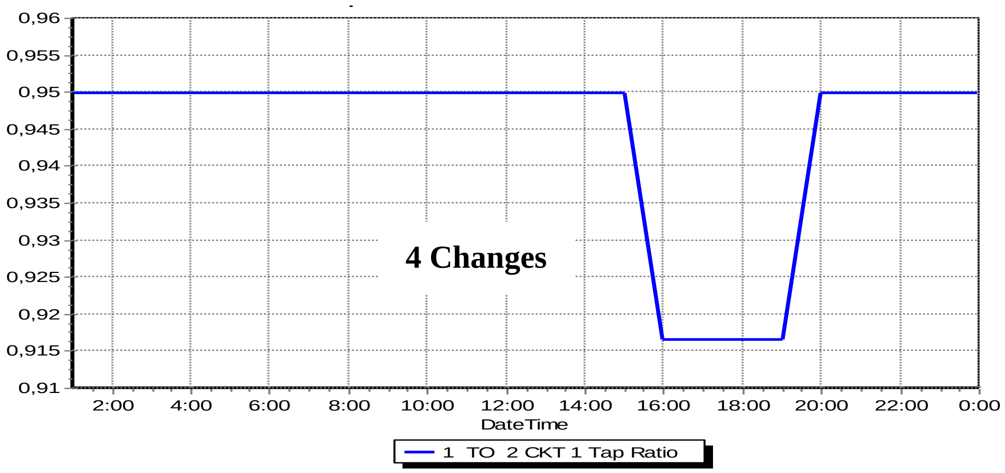
B.2 Alternative city system

Case 2: Deadband 0.065 p.u.

Voltages



Tap Ratio Position



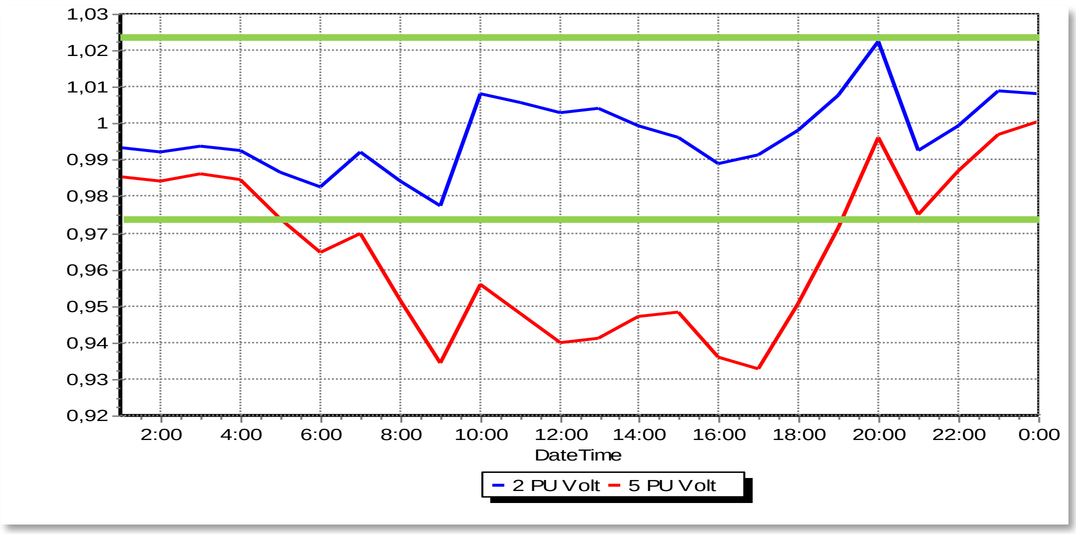
Average Power Losses

Active: 0.1315 MW

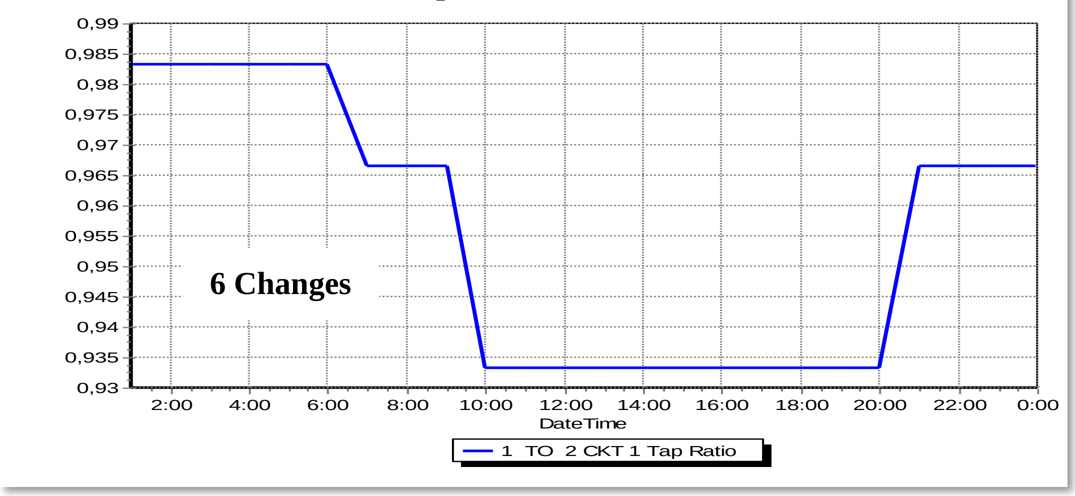
Reactive: 3.0114 MVar

Case 3: Deadband 0.05 p.u.

Voltages



Tap Ratio Position



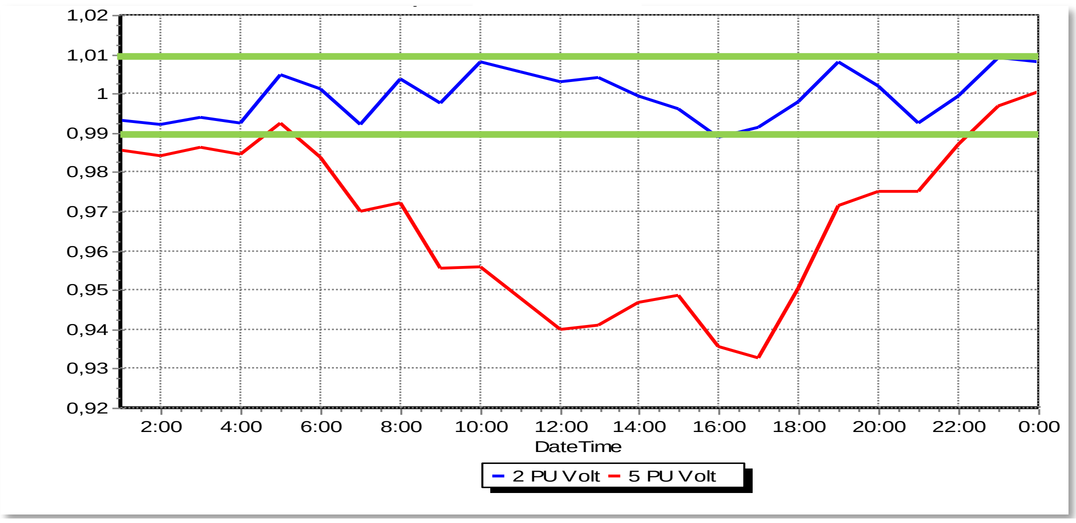
<u>**Average Power Losses**</u>

Active: 0.1323 MW

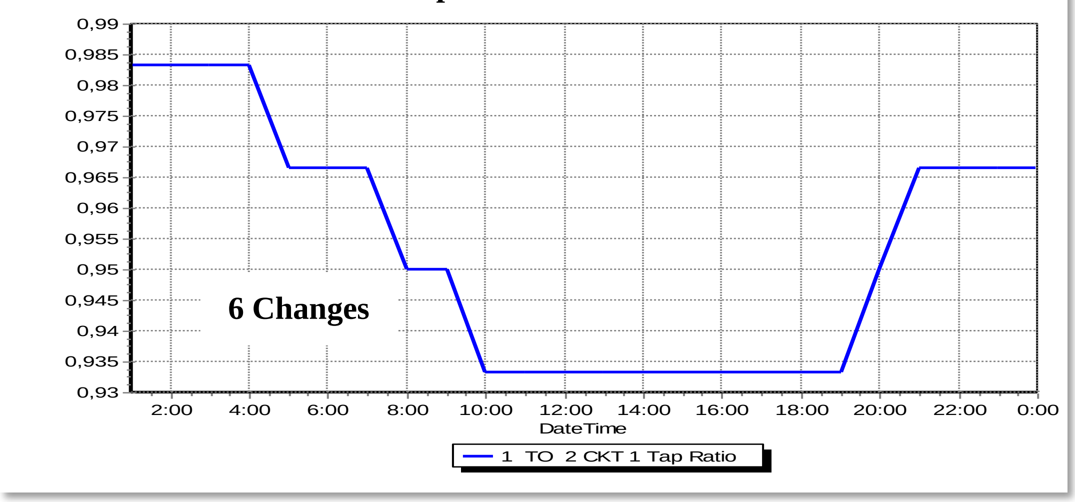
Reactive: 3.0604 MVar

Case 4: Deadband 0.05 p.u.

Voltages



Tap Ratio Position



<u>Average Power Losses</u>

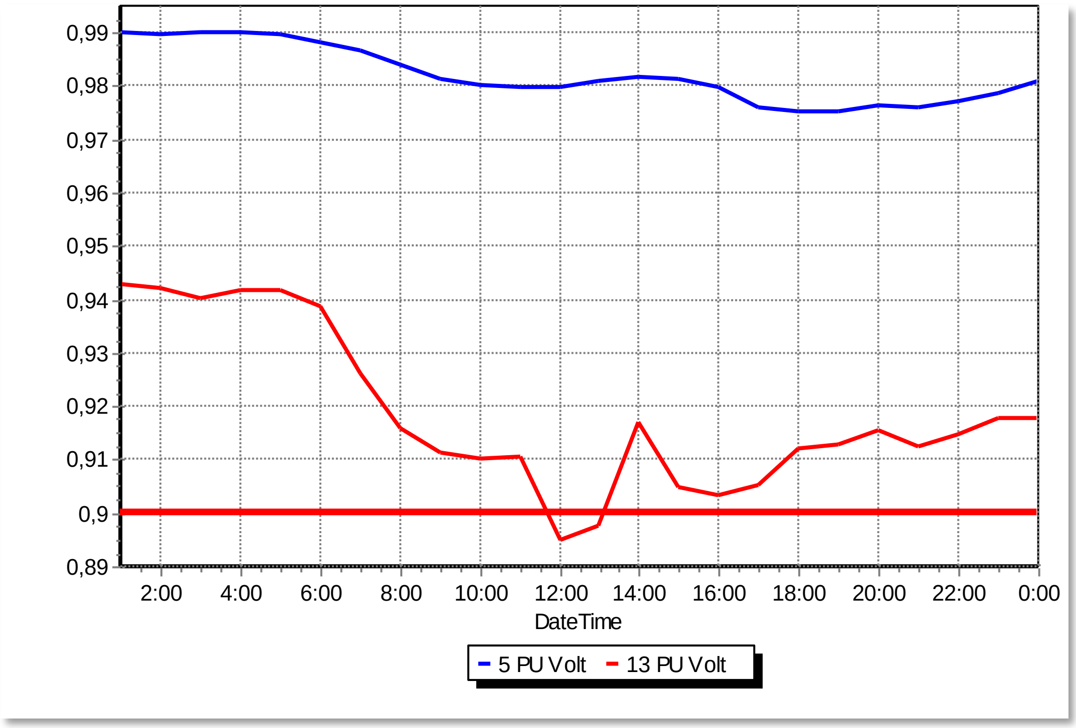
Active: 0.1320 MW

Reactive: 3.0470 MVar

B.3 Countryside system

Case 2: T1 Tap ratio: 0.9833
T2 Tap ratio: 1.000

Voltages



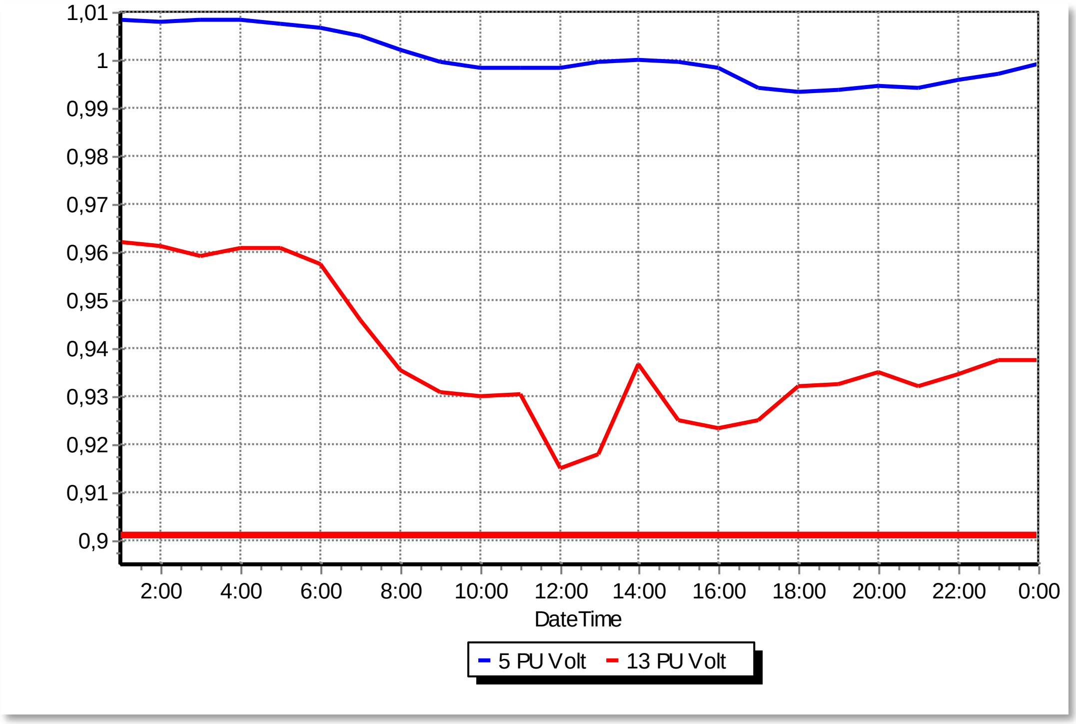
<u>Average Power Losses</u>

Active: 0.0173 MW

Reactive: -0.0171 MVar

Case 3: T1 Tap ratio: 0.9666
T2 Tap ratio: 1.000

Voltages



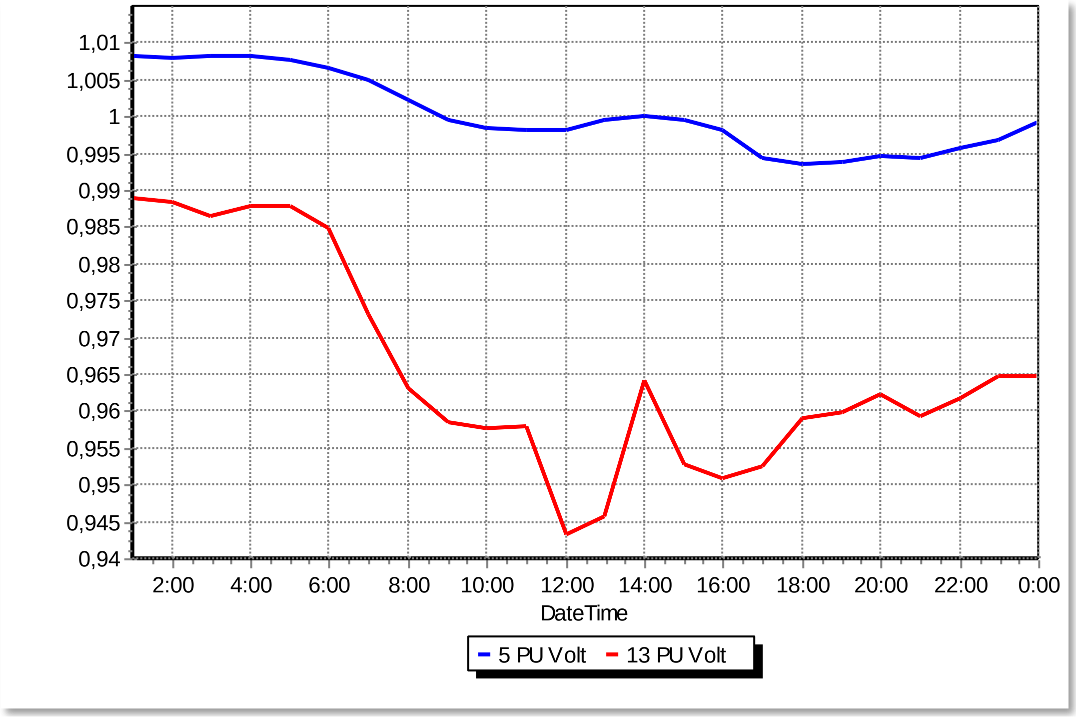
<u>Average Power Losses</u>

Active: 0.0166 MW

Reactive: -0.0193 MVar

Case 4: T1 Tap ratio: 0.9666
T2 Tap ratio: 0.9750

Voltages

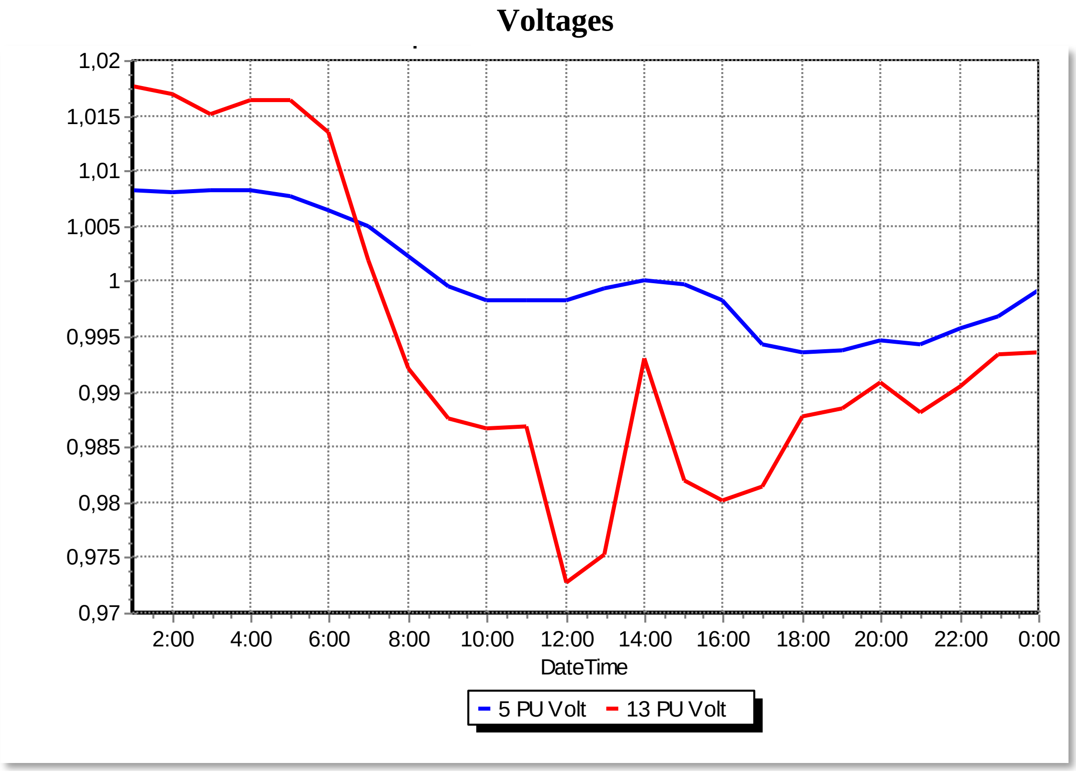


Average Power Losses

Active: 0.0166 MW

Reactive: -0.0193 MVar

Case 5: T1 Tap ratio: 0.9666
T2 Tap ratio: 0.9500



<u>Average Power Losses</u>

Active: 0.0166 MW

Reactive: -0.0194 MVar

Appendix C: Lines characteristic

FeAl 62
- Series resistance: 0.535 Ω/km
- Series reactance: 0.356 Ω/km
- Shunt charging: $1.92 \cdot 10^{-6}$ Mhos/km

FeAl 31
- Series resistance: 1.065 Ω/km
- Series reactance: 0.38 Ω/km
- Shunt charging: $1.92 \cdot 10^{-6}$ Mhos/km

FeAl 19
- Series resistance: 1.738 Ω/km
- Series reactance: 0.38 Ω/km
- Shunt charging: $1.92 \cdot 10^{-6}$ Mhos/km

AXCEL 3x25mm^2
- Series resistance: 1.2 Ω/km
- Series reactance: 0.116 Ω/km
- Shunt charging: $59.7 \cdot 10^{-6}$ Mhos/km

N1XV 95
- Series resistance: 0.32 Ω/km
- Series reactance: 0.075 Ω/km
- Shunt charging: $175.93 \cdot 10^{-6}$ Mhos/km

N1XV 50, ALUS 50
- Series resistance: 0.641 Ω/km
- Series reactance: 0.075 Ω/km
- Shunt charging: $157.08 \cdot 10^{-6}$ Mhos/km

N1XV 10, EKKJ 10
- Series resistance: 3.08 Ω/km
- Series reactance: 0.091 Ω/km
- Shunt charging: $100.53 \cdot 10^{-6}$ Mhos/km