CODEN:LUTEDX/(TEIE-5243)/1-68/(2007)

Industrial Electrical Engineering and Automation

Voltage Control in a Medium Voltage System with Distributed Wind Power Generation

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ACKNOWLEDGEMENTS

First of all, I would like to express my most sincere gratitude to my supervisor Magnus Akke. His help with the simulation program, his interesting ideas and the proof reading of my work have been very important to accomplish this thesis. I would like to thank him for being always so kind and patient.

Olof Samuelsson also deserves my gratitude for co-supervising my work, for reading and correcting this report. His suggestions together with Magnus' have contributed to make this thesis more interesting.

The department IEA is a nice place to work. I am so thankful to everyone in the department for providing a nice atmosphere.

I would also like to thank Ǻke Juntti from E.ON for giving us the data of the generation in Högseröd. I am also thankful to E.ON for their interest in the results of my work.

Spending ten months in Sweden has been a great experience; I would like to thank all my friends who have been with me trough this time. Especially I am thankful to Julia and Erik for letting me train the presentation with them several times.

Last but not least I would like to thank my parents, Timoteo and Carmen, for their support even when we are far away.

Lund, June 1, 2007

Elena Giménez Romero

ABSTRACT

In this thesis we investigate different methods to control the voltage in a system with distributed generation (DG). In this case we consider two wind power plants of 6 and 8 MW installed power. Lately the interest for DG is increasing. This technology is quite new and needs more investigation to develop cost-competitive alternatives.

The major advantage with DG is that the power is produced close to consumers. Therefore the losses are reduced in transmission and distribution systems. Also, DG gives the opportunity for autonomous island operation.

For conventional radial feeders, without any DG, the power flows only in one direction: from the feeding grid towards the loads. Therefore the voltages decrease towards the end of the feeder.

When DG is added in a system, we have to consider the situation when the DG exceed the local load and power flows in reverse direction, that is, towards the high voltage grid. Hence, the power flow can either be from the grid toward loads, or vice versa. Then we have two very different load flow situations to consider in the power system analysis. The opposite load flow conditions give totally different voltage distribution in the system. Hence, the conventional voltage control systems and protections might be inappropriate when we have DG.

When the DG is producing active power, the voltage at its connection point will increase which might lead to an overvoltage. On the other hand, when the DG is inactive and with heavy local load, the voltage might drop, giving low voltage. Therefore we have to avoid all abnormal voltage conditions, both undervoltage and also overvoltage.

This thesis starts with some background information of wind power and distributed generation. After that we simulated a 24-hour cycle of operation for a small system under different conditions. The simulation results are commented, and we try to make some general conclusions about the best options for each technology.

The simulated system is based in a real system located in Högseröd, Sweden. It is a 130kV/ 20kV system consisting of a transformer with on-load tap changer (OLTC). The transformer station has two 15 km feeders that connect to local buses with a combination of DG and local load. Due to variations in load and generation, it was suspected that this transformer could have problems with excessive wear of the taps. One objective was to minimize the number of tap operations per day.

We have studied two different wind turbine technologies, namely Doubly-fed Induction Generator (DFIG) and Squirrel cage induction generator (SCIG).
Another important aspect to study was the effect of reactive compensation. To do this, we simulated the DFIG without compensation (zero reactive power input and output) and in voltage control mode (to model this we used a STATCOM). For the compensation of the SCIG we used capacitors, either in three steps or one fixed value. To get some insight of how the voltage control is affected by connection type, the simulation cases were run with underground cable and repeated for overhead line.

Inspired by the objective to reducing the number of tap changes, we also added a simulation case where the transformer OLTC was blocked.

An analysis of the simulations results can help to find a good control strategy for the system in Högseröd.
The number of tap changes is higher with SCIG because the reactive power through the transformer is higher than with DFIG.
DFIG technology gives better results in voltage control mode (with STATCOM) rather than with zero reactive power output.
SCIG technology works better with fixed capacitors instead of step capacitors. Step capacitors compensate 100% at full load causing a high overvoltage.
Using underground cables the number of tap changes is reduced and also the voltages are closer to nominal values. An exception is when DFIG is used in voltage control mode (with STATCOM). Then the node voltages are more sensitive to reactive power variations with an overhead line. The reason is that an overhead line gives the STATCOM more control authority.
Depending on the load location it could be a good solution in some cases to block the transformer.

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CHAPTER 1: INTRODUCTION

Due to the environmental impact of electricity and the increasing demand there is a strong need of alternative technologies that can assure not only the needed electricity supply with good quality and low price, but also the efficient use of the natural resources.

One of those alternative technologies is to generate the electricity close to power consumers. This technology is known as distributed generation (DG).

There are several DG technologies that are gaining more attention all around the world. Some of the existing renewable energies are included in those technologies.

Due to the large amount of wind resources available the potential for distributed and large scale generation is huge.

Thus, technology development is needed so that DG become cost competitive and more efficient.

1.1 Voltage profile with distributed generation

In the usual networks the power flows only in one direction, from the generation station to the loads.

When we include DG it might be that the power flows from the DG system to the generator when the load is low.

The voltage profile of the line also varies if there is DG installed. The voltage in the connection point depends not only on the load but also on the active and reactive power generated or absorbed by the DG. The combination of high DG power and low load can cause overvoltage in the connection point.

Voltage outside of the acceptable range must be avoided. Also the voltage variation as such should be minimized. There are several methods to achieve it, which will be discussed in chapter 3.

There are limits for the maximum DG that can be integrated in a feeder. Some limits depend on the maximum allowed voltage variation, thermal design of the conductor and the transformer rating.

Improved voltage control of the DG feeder is one option to increase the integration limit. Smart voltage control of the DG feeder can also be used to reduce the voltage variations at various points of the system, for example at the DG connection point or at the feeding transformer station.

Concerning distributed wind studies there are some typical problems that are discussed below:

- Voltage regulation
    - The main concern is the impact of the fluctuating output from the turbine on system voltage.
    - Fixed and semi-variable speed machines use switched capacitor banks.
    - Variable speed wind turbines can adjust the power factor.
    - There is a need to coordinate the voltage control devices in the feeder. Lack of coordination could lead to excessive switching of capacitors and voltage regulators.

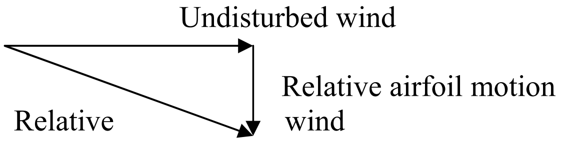
- Flicker:
    - This phenomenon can be described as a fluctuation in system voltage that can result in observable changes in light output.
    - These fluctuations can be caused by the changes in the turbine output.
    - Flicker occurs on weak systems with low short-circuit ratio.
    - There are some causes of the voltage flicker like the tower shadow effect (each time one blade passes the tower there is a temporary torque reduction),
    - Variations in wind speed and turbine start-up and shutdown.

- Fault current contribution:
    - With turbine sizes above 1MW contribution to faults current must be considered.
    - The turbines can cause some problems like reduction of reach of relays, difficulties on fuse lifetime and incompatibilities with fault clearing processes.

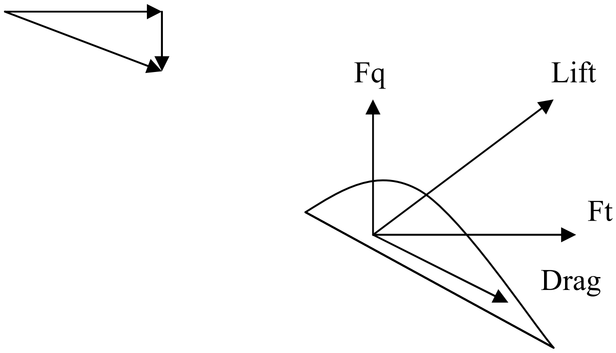
CHAPTER 2 : BASIC IDEAS OF WIND POWER

2.1 Aerodynamics of wind turbines

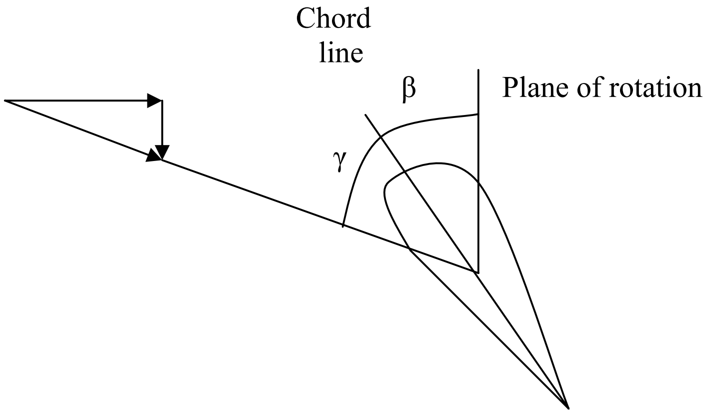
When the wind reaches the turbine it changes its direction due to the airfoil motion.



The forces caused by the wind on the airfoil can be divided in two: a lift and a drag force, perpendicular and parallel to the undisturbed wind direction.



The force Fq is the one that moves the blades in a rotatory movement. The force Ft is undesirable because it is normal to the plane of rotation and contributes to thrust.
The output from a wind turbine has to do with the orientation of the blades. There are two important parameters to evaluate this, the pitch angle (β) and the angle of attack (γ).



From the lift and drag force we can obtain the lift and drag coefficients (Cl, Cd).

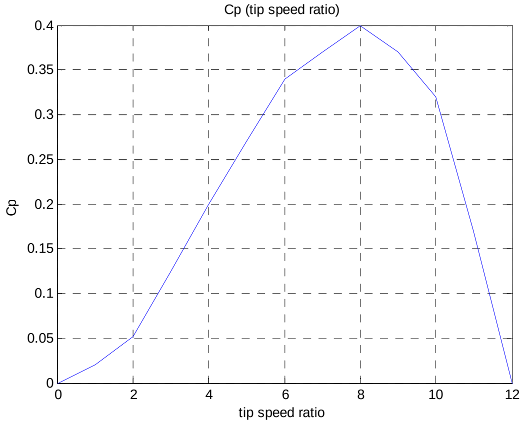
The coefficient Cp gives the fraction of power that is extracted from the available power in the wind. We can obtain it by measuring the power from the turbine or by the lift and drag coefficients.
The mechanical output is:

$$P = 0.50 \cdot C_p(\lambda, \beta) \cdot \rho \cdot A \cdot \omega^3; \qquad \lambda = \frac{\Omega \cdot r}{\omega}$$

Where:

- λ is the tip speed ratio
- ω is the wind speed
- Ω is the rotor speed
- r is the rotor blade length
- ρ is the air density
- A is the area swept by the rotor

Cp depends on the wind speed, the rotational speed of the turbine and aerodynamic parameters of the blades.
We can represent Cp (λ) at different wind speeds.
The diagram below illustrates the Cp (λ) curve of a 225 kW wind turbine with a rotor diameter of 20 m.



Calculation example:

With the data of the wind speed, turbine diameter and the Cp (λ) diagram is simple to obtain the mechanical output. The calculations are shown here for the wind turbine described above.
The wind speed in this example is 10 m/s and the turbine speed is 6 rad/s.

$$\lambda = \frac{\Omega}{\omega} \cdot r = \frac{6 \cdot 10}{10} = 6$$

With this value for λ we can obtain Cp=0.34 from the graphic above.

$$P = 0.50 \cdot C_p(\lambda, \beta) \cdot \rho \cdot A \cdot \omega^3 = 0.5 \cdot 0.34 \cdot 1.225 \cdot \pi \cdot 100 \cdot 10^3 \approx 65 \text{ kW}$$

2.2 Classification of wind turbine generators

Wind turbine configurations can be classified depending on their ability to control speed and depending on the blade control that they use.
Here, we will only discuss four typical wind turbine designs.

2.2.1 Fixed speed

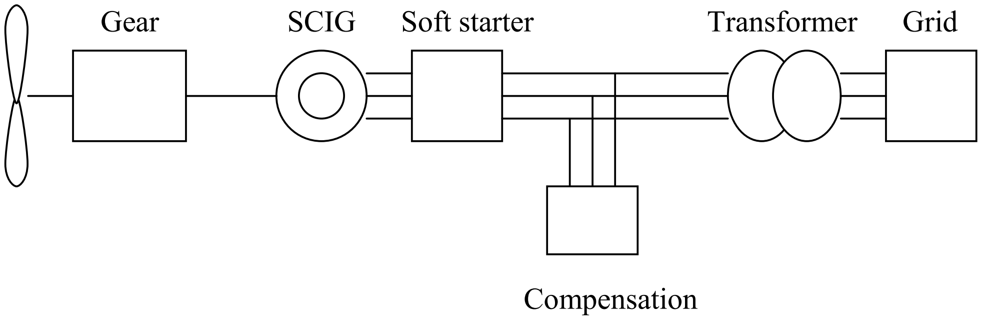
This kind of machines is designed with an asynchronous squirrel cage induction generator (SCIG). The generator is connected to the grid via a transformer. It can also use a soft starter to avoid high inrush currents during startup.
The induction generators always draw reactive power from the grid. To limit the reactive power drawn from the grid, this configuration uses a capacitor bank.
Due to the fixed speed the wind fluctuation cause mechanical and thus electrical fluctuations.
Wind fluctuations cause voltage variations, which also show up as variations in reactive power consumption. Thus this system requires reactive compensation and a stiff grid.
In order to increase the power production, the generator of some fixed-speed wind turbines has two sets of stator windings, one for low speed and another for medium speed.

The output power must be controlled in case of high wind speeds. To do this, there are different methods.

- Passive stall control: it uses the geometry of the rotor blades. When the wind speed becomes too high the life force is limited by creating turbulence on one side of the blade. Wind turbine manufacturers like Ecotecnia and Made use this type of control method.

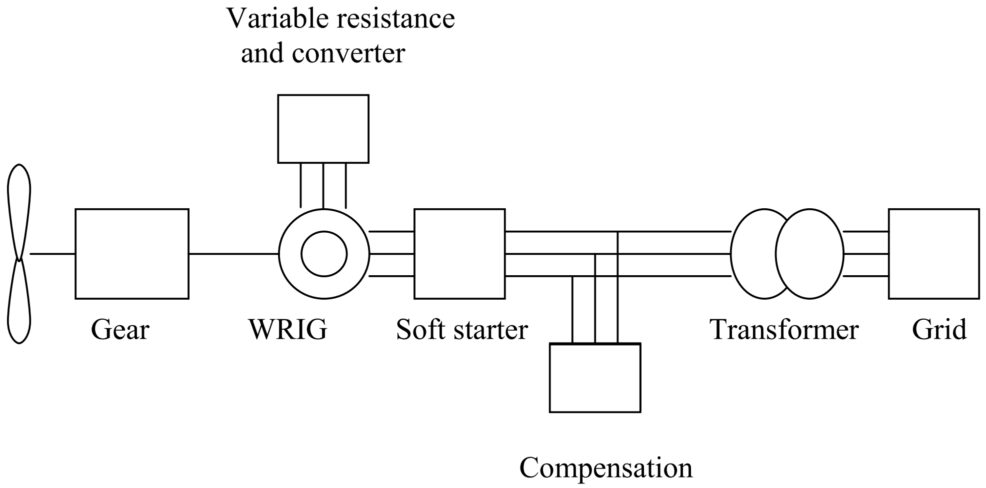
- Pitch control: the output power is limited by turning the rotor blades. During high wind situations, the pitch angle can be increased and thus the angle of attack is reduced.

- Active stall control: at low wind speed the blades are pitched like in the pitch-controlled wind turbine to achieve maximum efficiency. At high wind speeds the blades are pitched into the opposite direction (increasing the angle of attack.)



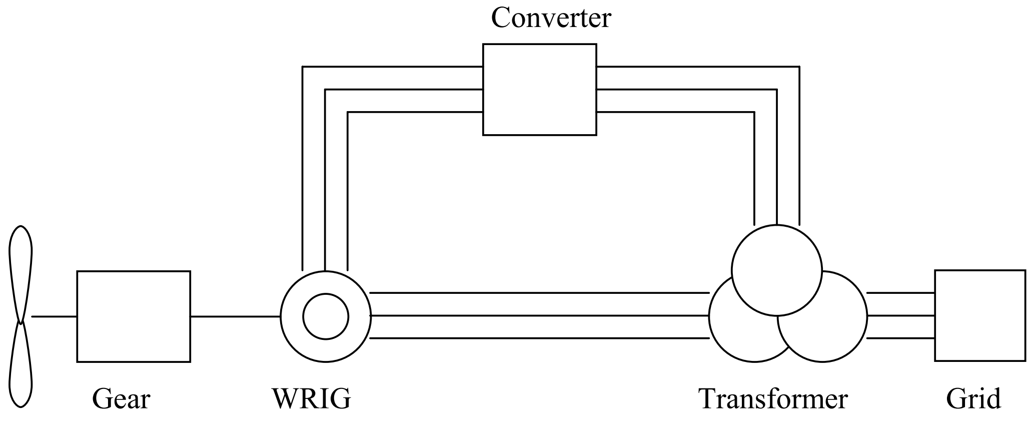
2.2.2 Limited variable speed

This design uses a wound rotor induction generator (WRIG) with a variable rotor resistance. The resistance is controlled with a power electronic converter.
The power output is controlled by changing the resistance. The range of speed variation depends on the size of the rotor resistance. For variable speed wind turbines only pitch controlled mechanisms are used. That is because the passive and active stall controlled wind turbines do not have the capability for a fast reduction of power.



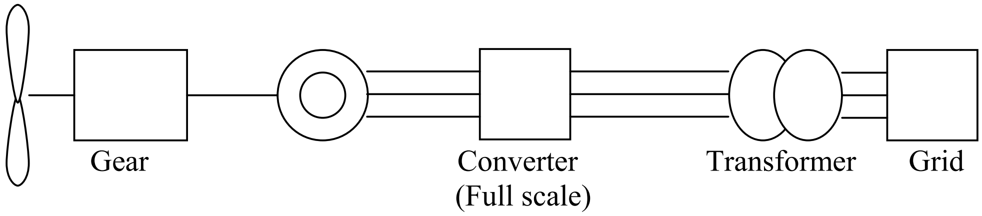
2.2.3 Variable speed with partial scale frequency converter

This method is known as doubly feed induction generator (DFIG).
It uses a WRIG. The stator is connected to the grid via a transformer and the rotor is connected to a small scale frequency converter.
The converter performs the reactive power compensation and gives a smoother grid connection. The range of speed variation is larger than previous methods.



2.2.4 Variable speed with full-scale frequency converter

A full-scale frequency converter gives the possibility to use different generator types and make them operate in a similar way as a wound rotor synchronous generator. Some generators commonly used are, rotor induction generator or permanent magnet synchronous generator.
The generator is connected to the grid through a full-scale frequency converter. With this method we can have a full-scale speed range.
One of the advantages is that we can skip the gear box with this method.
The companies Enercon, Made and Lagerway use this configuration.



CHAPTER 3: VOLTAGE CONTROL

In this chapter we present different methods to control the voltage. The methods are:

- STATCOM
- STATCOM
- Tap changing transformers
- Line drop compensation
- Series capacitors
- SSSC

3.1 Compensation by controlled reactive elements

Since the voltage is strongly correlated with the reactive power one way to affect the node voltages is to connect capacitors or reactors in the nodes where we want to control the voltage. A connected capacitor will increase the voltage at the connection point by producing reactive power. In contrast, a connected inductor will decrease the voltage at the connection point by consuming (absorbing) reactive power.

When using this kind of regulation, we have to consider that depending on the R/X ratio of the line, the changes in reactive power affect the voltage in different ways. Transmission networks often use overhead lines and transformers, with low resistance, so the R/X ratio is low, around 0.1. For systems where R/X is low, reactive power has a large impact on voltage and is therefore an important tool for voltage control.

Nevertheless in distribution lines that often consist of a combination of overhead lines and underground cables, the R/X ratio is higher, around 0.5-1. For that reason the sensitivity of the node voltages to changes in reactive power is less. In spite of this, compensation methods are also used in distribution systems along with other methods. In order to control the power from the reactive elements there are different methods. We will emphasize two of them; the Static Var Compensator (SVC) and the static synchronous compensator (STACOM)

3.1.1 Static Var Compensator (SVC)

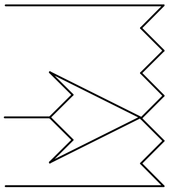
The SVC regulates the voltage by controlling the reactive power injected into or absorbed from the system.
It measures the voltage that we want to control. Using the difference between the measured voltage and the voltage reference the voltage regulator calculates the reactive power needed.
Depending on the reactive power needed the capacitor and inductor banks are switched on and off by thyristor switches. This method uses a phase-angle control

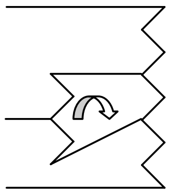
3.1.2 STATCOM

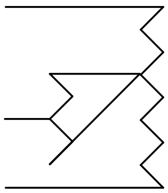
Basically the STATCOM performs the same function as the STATCOM, when the system voltage is low it generates reactive power and when the voltage is high it absorbs reactive power.
The STATCOM has a voltage source converter (VSC) connected to the secondary side of a coupling transformer. This converter uses GTOs, IGBTs or IGCTs.
A capacitor connected on the DC side of the VSC acts as a DC voltage source.
The circuits are often controlled by a digital signal processor (DSP) system.
There are some advantages of STATCOM over STATCOM. The STATCOM can generate more reactive power than the STATCOM. This can be useful during a fault and also to improve system stability. Another advantage is that the compensating current in the STATCOM does not depend on the voltage level of the connecting point, thus when the voltage drops the current is not decreased. Moreover, the STATCOM has a faster response because it has no delay associated with the thyristor firing. This can be useful during fast transients.

3.2 Tap-changing transformers

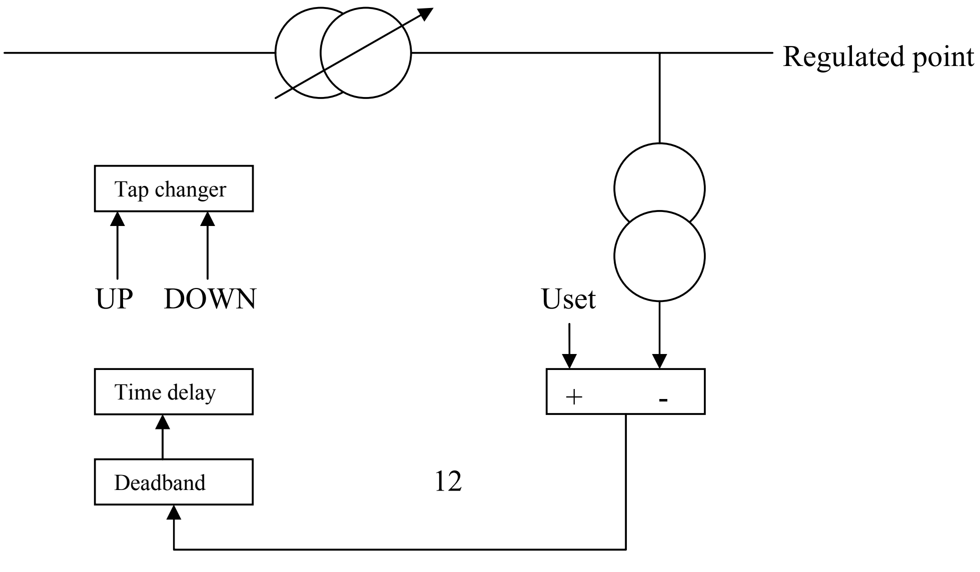
A tap changer can change the number of turns in the transformer and thereby adjust the transformer ratio.
The transformers with tap changers can shift reactive power between the primary and secondary sides and thus regulate the voltage of the secondary side.
The basic operation of a tap changer is shown on the following picture.







Those movements are performed by mechanical switches. The possible tap ratio change is ±10-15% in steps of 0.6-2.5%. Each tap operation takes 0.1-0.2 seconds.
The conventional control for the OLTC is an integrator control with a time delay and a dead band. The dead band sets the tolerance or long term voltage deviations and the time delay is intended for noise-rejection.



This method to change the taps causes arcing between the arms and the connectors.
To solve the problems associated with mechanical switches new designs have been proposed.
One of them is to replace the mechanical switches by power-electronics. This method provides faster compensation of voltage dips and continuous regulation of the voltage. The drawback is that they are more expensive and less robust; also they have higher power losses.
Another idea is to use thyristor-assisted tap changers, this method avoids arcing during the switching and thereby the wear on the tap changer is reduced; however, the control with this method is not as fast and continuous as the one that replaces the switches for power-electronics.

For a traditional system without DG, the highest voltage is at the feeding transformer and the lowest voltage is at the receiving bus located at the end of the feeder. The conditions for OLTC regulation are:

- Ensure that the sending-end voltage is below the maximum allowed voltage.
- Ensure that the receiving-end voltage at the feeder end is above the minimum allowed voltage.

For a new system with one, or more, DG at any location along the feeder, the load flow and voltage drop are non-trivial. Hence we have to reformulate the conditions for OLTC regulation:

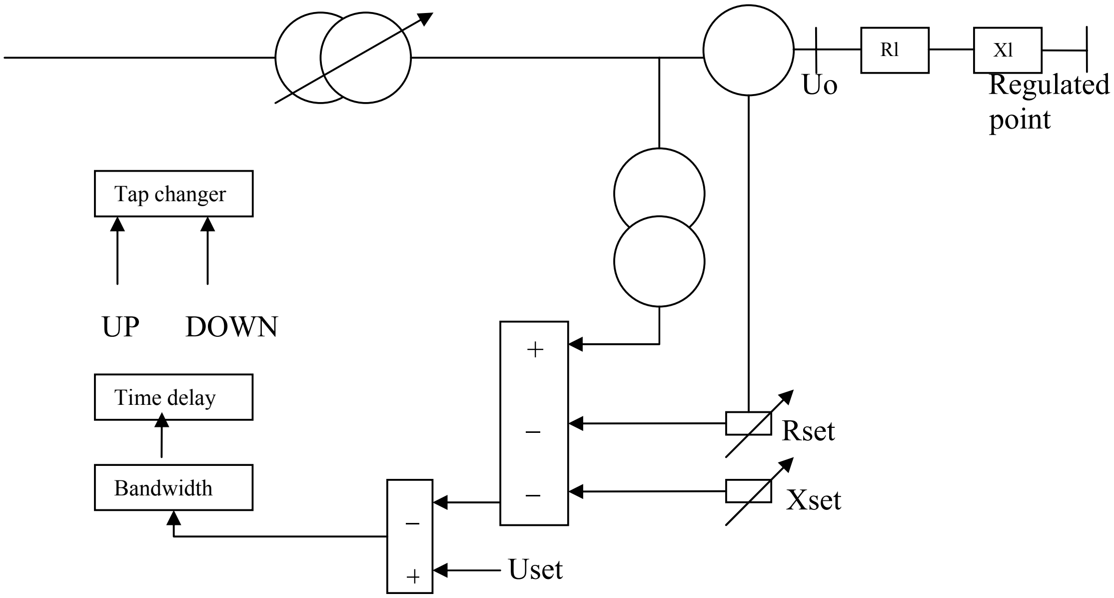
- Ensure that the sending-end voltage is within acceptable range for **all operation condition of DG**.
- Ensure that the receiving-end voltages at **all feeder locations** are within acceptable range for **all operation condition of DG**.

For systems without DG, OLTC regulation has been used to keep the sending end voltage constant at highest allowed magnitude. Hence the system has been operated with minimum losses at any load condition.

Conventional OLTC regulation gives one large advantage. It simplified the voltage analysis by de-coupling the feeder voltage profiles from each other. The steady state value of the controlled voltage will remain unaffected by changes in power factor or power reversal. When the OLTC controls the sending end voltage at the feeding transformer to be constant, the load on one feeder will not affect the voltage on the neighboring feeders. Therefore multiple feeders controlled by the same OLTC can be treated separately, independent of the load on other feeders. This “feeder de-coupling” greatly simplifies the analysis of the steady-state voltage profile in the system. Note that voltage transients that are faster than the OLTC control dynamics have to be analyzed separately.
Conventional OLTC regulation has the drawback that the DG integration limit is rather low. Since the sending end voltage is kept constant, there is a risk that the voltage profile along the feeder might be high for the combination of light load and high generation from DG. Thus there is a small margin before the power produced by DG causes over-voltage.

3.3 Line drop compensation (LDC)

Some customers can be far from the regulation location and due to the line voltage drop, voltages at the load location can be below specified limits.
The LDC system is based on calculating the line voltage drop based on the line current, resistance and reactance. With these values it performs voltage corrections to get the feeder voltage constant.
The basic operation is shown in the picture.



With this method the feeder can operate close to its nominal voltage at any load condition. Nevertheless minimization of losses at any load condition is not possible. Changes in power factor or direction of power flow will affect the regulation because LDC uses line and feeder parameters.
One drawback of LDC is that when there are several feeders controlled by the same LDC and their loads are different, the feeder with highest load will suffer undervoltage.

3.4 Series capacitors

Compensation with series capacitors reduces the resulting line reactance because the reactive generation from the series capacitors compensates for the reactive consumption of the line. This improves the system transfer capability.
Series capacitor reactive generation increases with the current squared, thus they are self regulated, they generate reactive power when most needed. This is an advantage over parallel capacitors were the reactive output increase with voltage squared.
However this kind of compensation requires complicated protection and control system and is therefore rather expensive. Hence it can only be economically justified in transmission networks.

3.5 Static synchronous series compensator (SSSC)

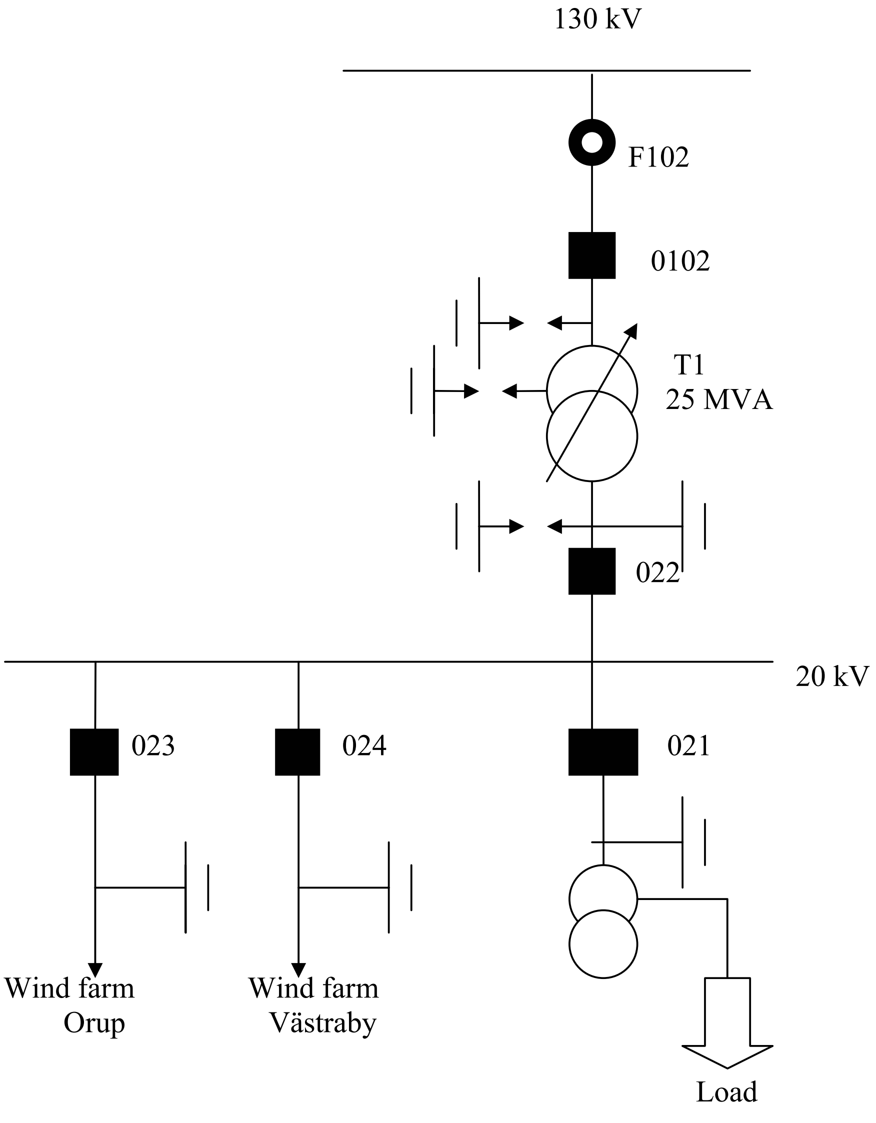
This device consists of a coupling transformer, an inverter and a capacitor. The SSSC is series connected to the line through the coupling transformer.
The power flow of the transmission line can be controlled. SSSC is able to reverse the power flow.

Since the purpose of this thesis is to study the impact of DG in a local network the last two methods will not be considered. Nevertheless they could be useful for transmission lines.

CHAPTER 4: SYSTEM TO BE STUDIED

4.1 SCHEME OF THE SYSTEM IN HÖGSERÖD

The chosen system is a real system located in Högseröd, Sweden. This is a simplified scheme of this system:



To get a more challenging system, we slightly modified the original model. Basically the main changes were:

- The transformer rating: we run the simulations with a 15 MVA transformer instead of 25 MVA.
- The loads: we included loads in the feeders where the wind farms are.
- Lengths of lines and cables: we used longer lines and cables to have more voltage drop.

4.2 Parameters

4.2.1 Transformer

We use a 130kV/20kV transformer with 17 taps. The taps are located in the secondary side. The most important parameters are the following:

- Nominal power Pn = 15 MVA
- Reactance of the primary winding X1= 0.05 p.u.
- Resistance of the primary winding R1= 0.001 p.u.
- Reactance of the secondary winding X2 = 0.05 p.u.
- Resistance of the secondary winding R2 = 0.001 p.u.
- Magnetizing resistance Rm= 1000 p.u.
- Magnetizing reactance Xm= 1000 p.u.

Parameters for the OLTC control:

- Time delay = 60 seconds
- Voltage change per tap = 0.01 p.u.
- Deadband = 0.0099 p.u.
- Reset ratio = 0.0098 p.u.

The bases for the data in p.u are the nominal voltages and power of the transformer.

4.2.2 Lines and cables

We simulated all the cases with overhead lines and with underground cables; both of them are copper conductors of 95 mm² and 15 km length.

Overhead line:

- Resistance per kilometer = 0.32 Ω
- Capacitance per kilometer = 8.6 nF
- Reactance per kilometer = 1.0 mH

Underground cable:

- Resistance per kilometer = 0.32 Ω
- Capacitance per kilometer = 220 nF
- Reactance per kilometer = 0.36 mH

4.2.3 Wind turbines

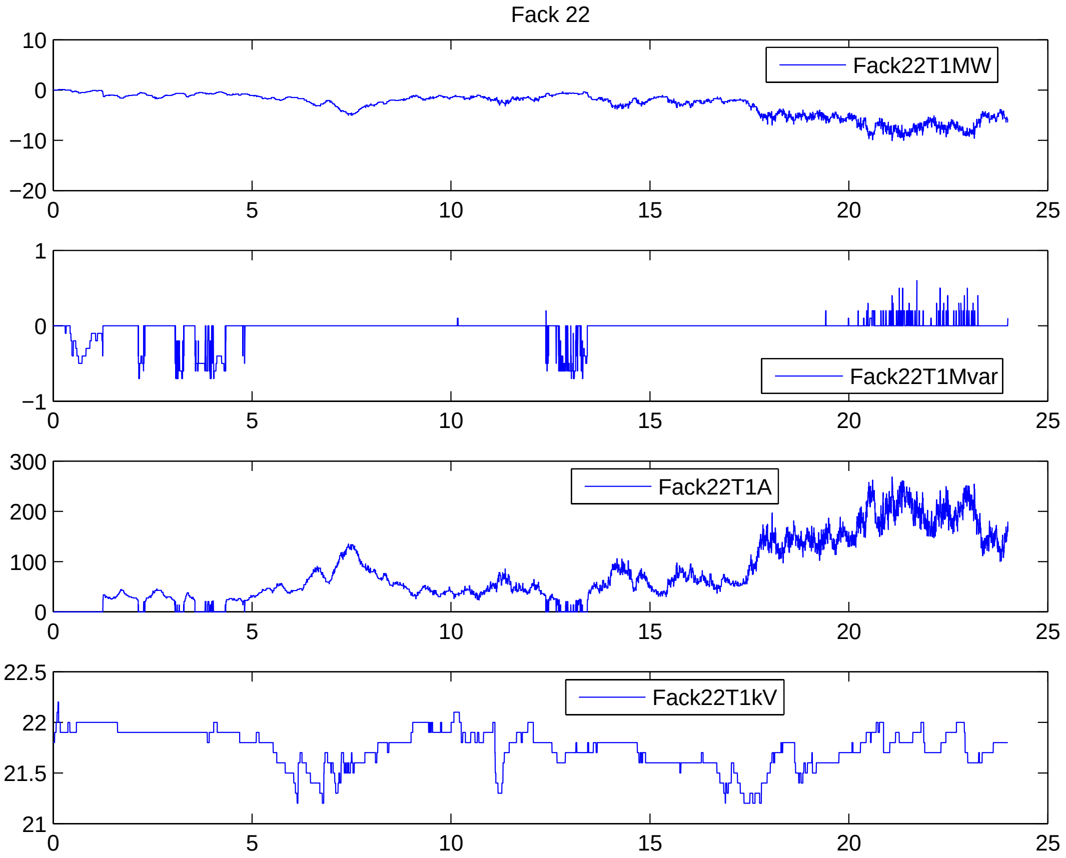
We used the same wind turbines for both wind farms in all cases. Each wind turbine is 2 MW, we have four turbines in Västraby (feeder 23) and three in Orup (feeder 24).
We tested two different technologies for wind turbines: Squirrel cage induction generator (SCIG) and doubly-fed induction generator (DFIG).

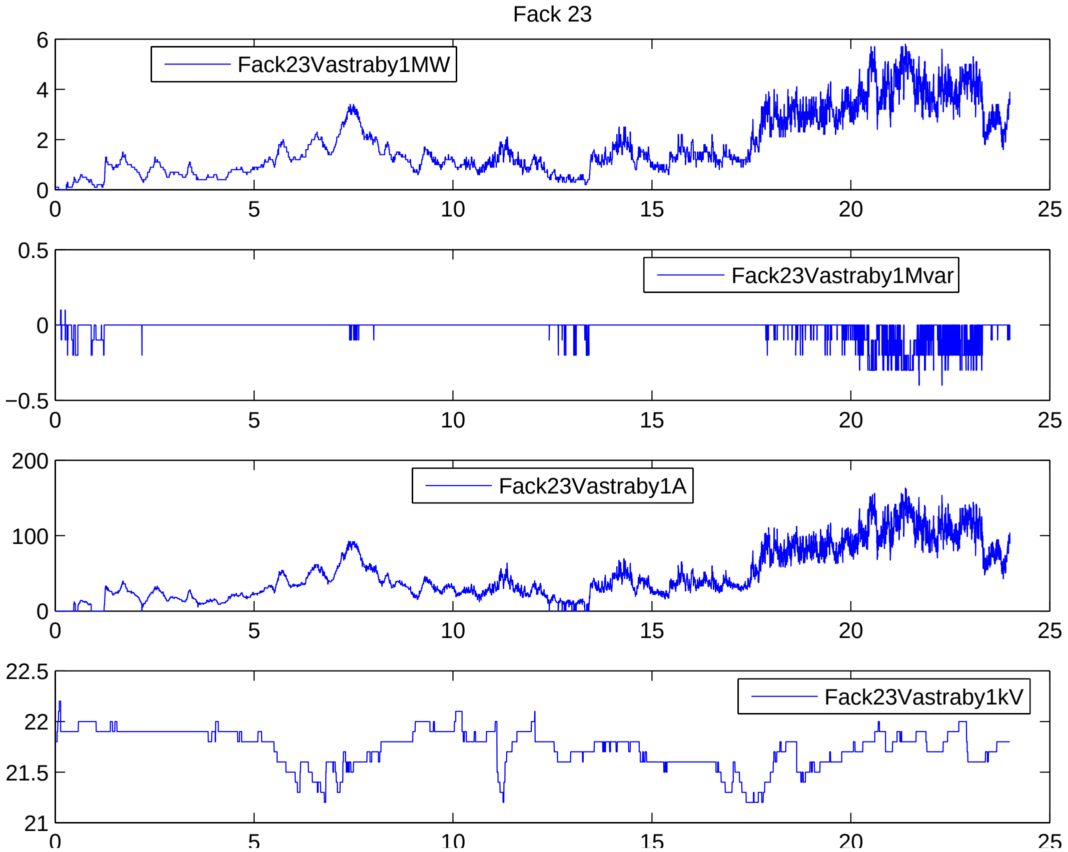
CHAPTER 5: INPUT DATA

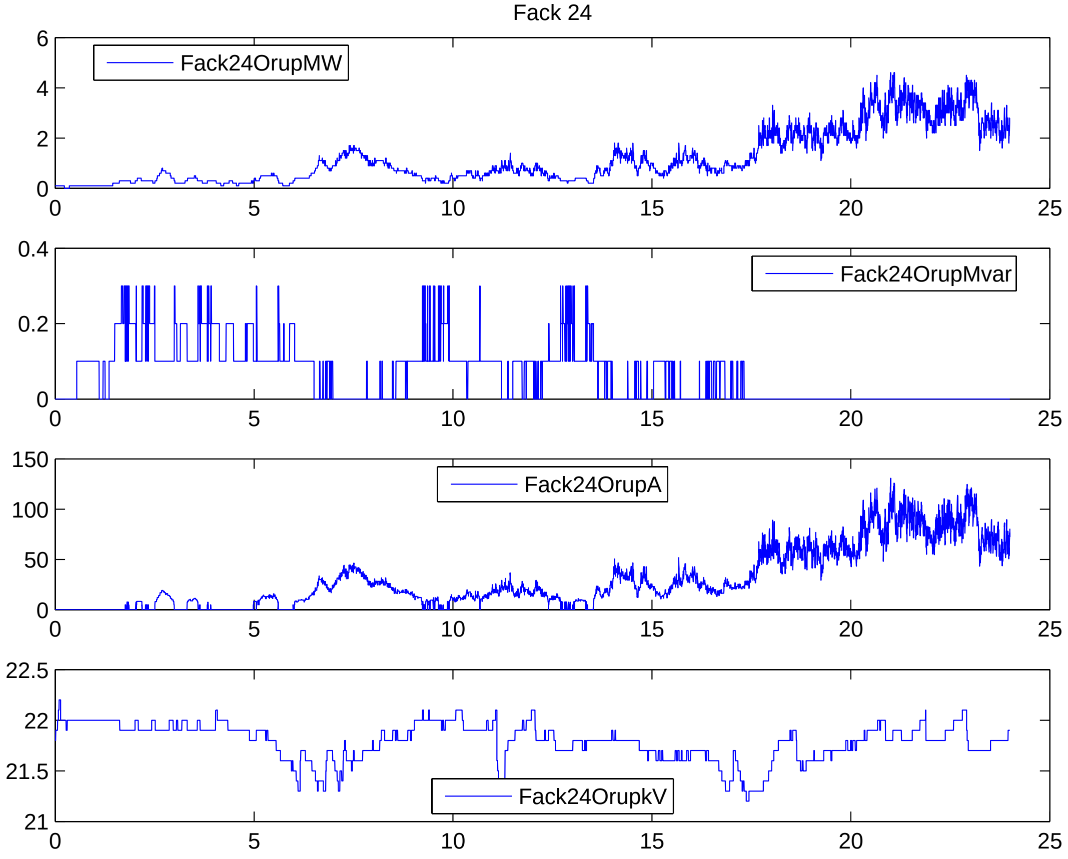
5.1 Wind power plant

Åke Juntti at E.ON Nät in Malmö, has kindly provided us with data measured at the 130/20 kV transformer station in Högseröd. The measurements of the active and reactive power for two feeders to the wind power farms are of most interest to us. Measurements were taken for four days. We decided to choose the data of February the 8th 2007 for our simulation study. During this 24-hour cycle, the generation varies from low generation during the day to high generation during the night.

Some plots for the active and reactive power, currents and voltages are shown below. All of them are from the measurements on February the 8th.




Fack 23
Fack23Vastraby1MW
6
4
2
0
Fack23Vastraby1Mvar
0.5
0
−0.5
Fack23Vastraby1A
200
100
0
Fack23Vastraby1kV
22.5
22
21.5
21
0
5
10
15
20
25


Fack 24
Fack24OrupMW
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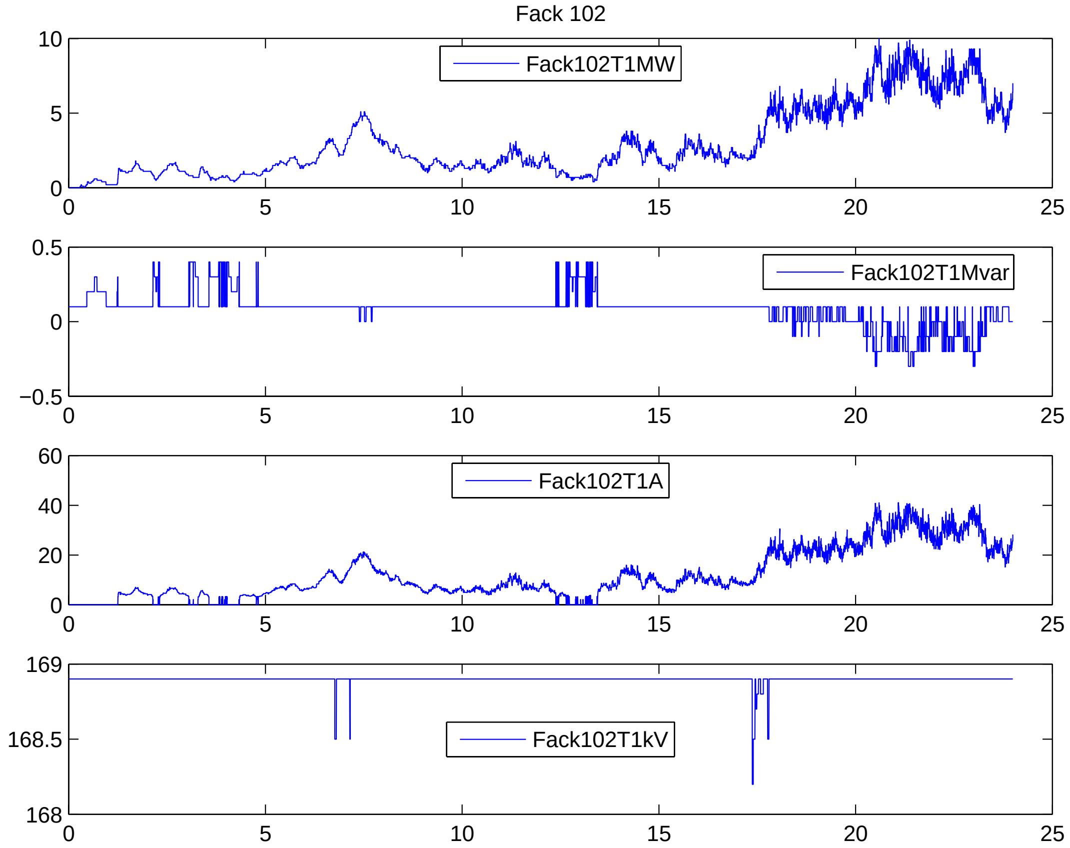
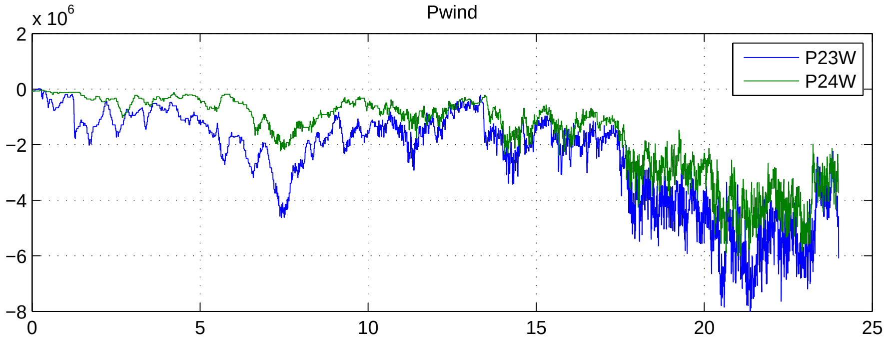
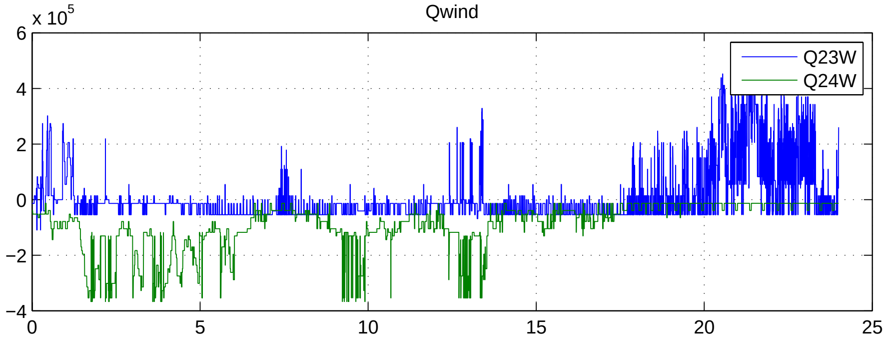
4
2
0
Fack24OrupMvar
0.4
0.2
0
Fack24OrupA
150
100
50
0
Fack24OrupkV
22.5
22
21.5
21
0
5
10
15
20
25



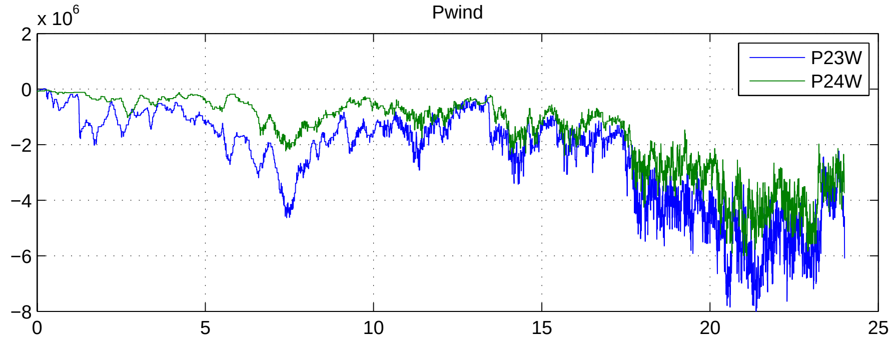
We have fabricated a 24-hour cycle that should represent a worst case scenario. The wind farm is located at the end of the feeder, were we also have added local load. During the day, we have high load and very low wind generation. During the night the situation is reversed, that is, no load and high wind generation. This means that the power flow through the transformer is high during most of the day, but the flow direction is reversed during the night.

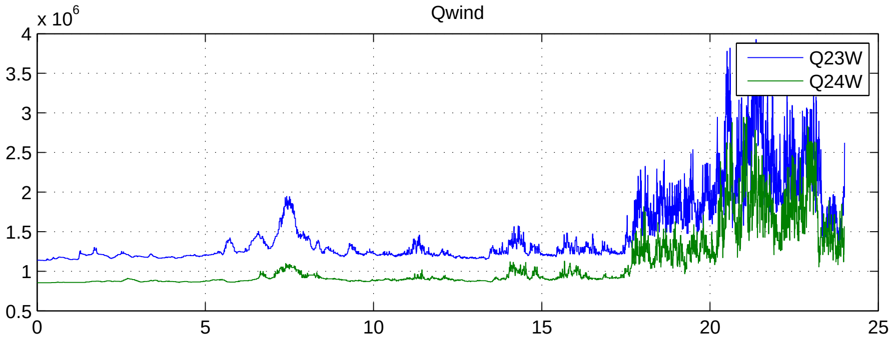
To clarify ideas here are the plots for the active and reactive power generated (negative) or absorbed (positive) by the wind power plants in both feeders:





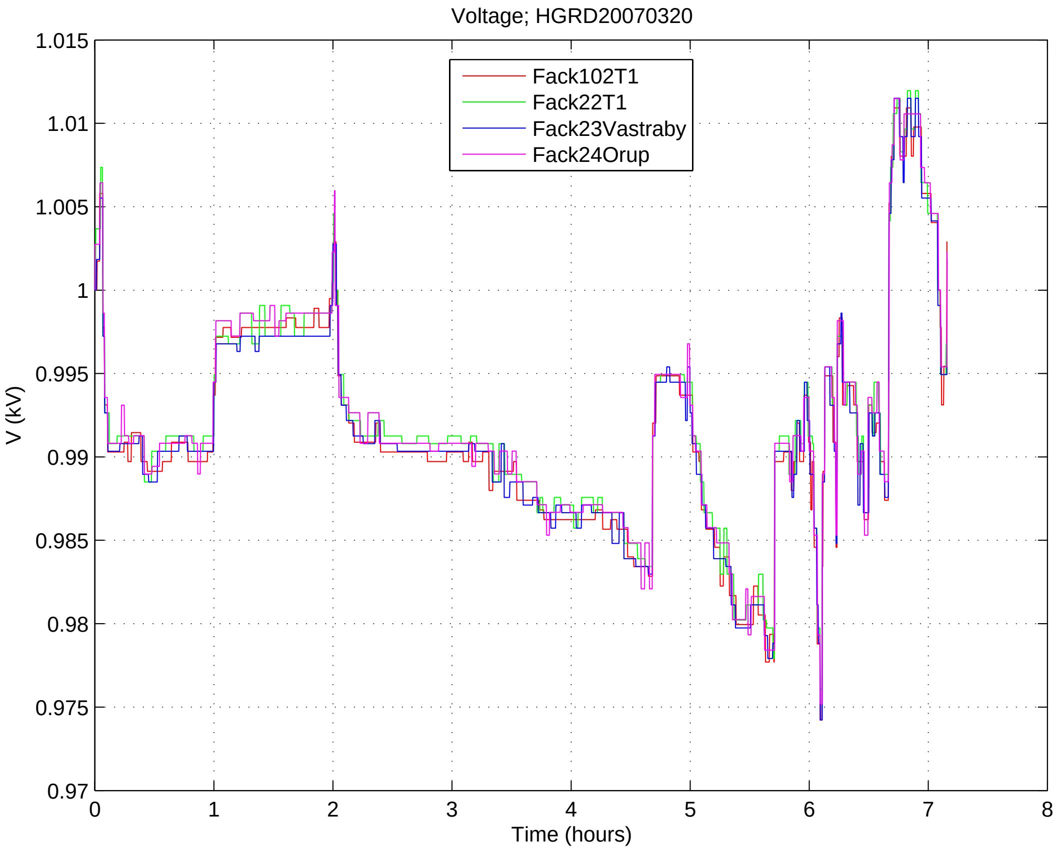
We used this data to simulate wind power plants with doubly-fed induction generators. For the simulations with the squirrel cage induction generators we used a look up table in MATLAB to get the reactive power output that a turbine with this generator would have had. The results are shown in the following picture.





5.1.1 Testing the measurements: voltage variations

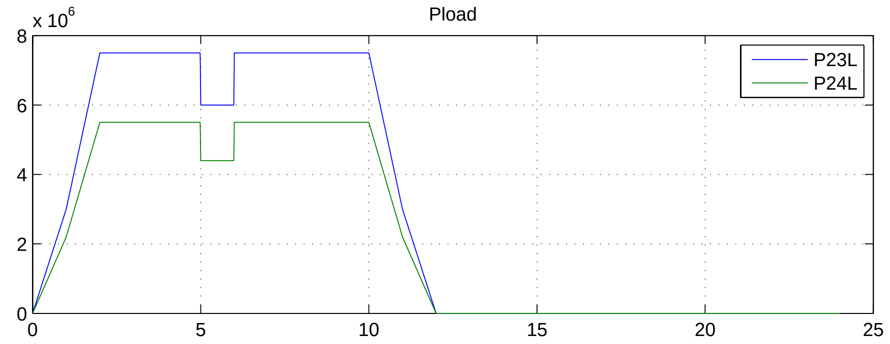
What caused the voltage variations on the low voltage side? Was it caused by the local wind power plants, or by variation in the feeding 130 kV grid?
The voltage measurement on the high voltage side was not operating on February the 8th. We got new measurements from E.ON for four days in March when the voltmeter was working correctly. These measurements were used to plot the voltages in p.u. in all the feeders. Here are the results:

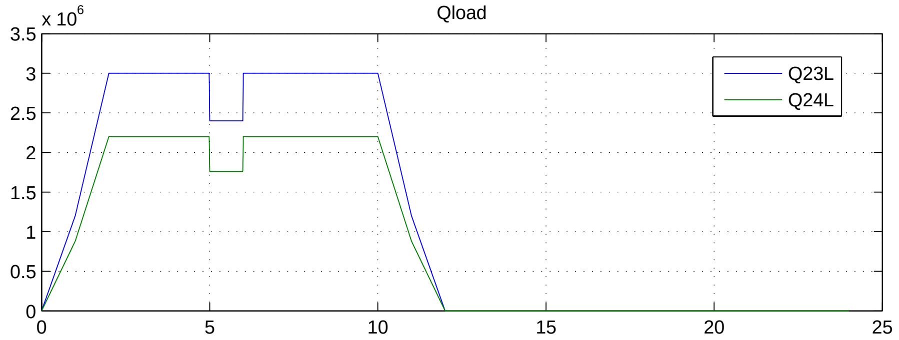


The plot shows that the voltage variations on the low voltage side are caused by the voltage variations on the high voltage side. We obtained the same result from the data for the other three days.

5.2 Load

The load model was implemented with a characteristic typically for a factory. The load increases during the first hours of the morning when people is arriving to work, it reaches its maximum value when everyone and all the machines are working, it decreases a bit in lunch time, increases again after lunch and decreases until zero when the fabric closes.
For the reactive power we took 40% the active power which would be the typical value.
The load is a bit higher in the feeder 23 where the wind generation is higher as well.


Pload
x 10^6
8
6
4
2
0
0
5
10
15
20
25
P23L
P24L


Qload
x 10^6
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
Q23L
Q24L

CHAPTER 6: MODELING THE SYSTEM IN SIMULINK

For modeling and simulation, we selected SimPowerSystems. The package aims at simulating power systems and is based on the program family of Simulink and Matlab.

6.1 Initial model

At the beginning we used the models that SimPowerSystems provides for the wind turbines, for the OLTC and the compensation.

We wanted to simulate the operation of the system during a whole day to see how the OLTC behaves with different load and wind generation conditions.

The problem with this model was the long simulation time required. The cause of this is the high precision with respect to fast dynamics that the models in SimPowerSystems have.

For our purpose we do not need to model fast dynamics because we are not interested in short transients. The control setting of the OLTC has dynamics in the order of 10-60 second. Hence, for our simulation study it is of minor importance to model fast transients with dynamics that can be measured in fractions of seconds.

6.2 Final model

To make the simulation time shorter we used a simplified models for the OLTC and the compensation.
The wind power turbines were implemented as variable loads that deliver power, instead of absorbing it. The recorded data for the P and Q were used as input to control the variable load. In this way the controlled load “replayed” the recorded P and Q for the wind plant.

With these modifications we did not have to use the models from SimPowerSystems’ library, which had continuous states with fast dynamics. Hence, we can use the phasor method with a discrete solver. This shortened the simulation times from days to some minutes.

The models used for the transformer and compensation are shown in detail in Appendix A.

CHAPTER 7: SIMULATIONS

Our main objective with the simulations is to discover how the transformer works and how do the voltages vary under different operating conditions.

We decided to simulate a limited number of cases that could be representative for a typical class of problem. The cases were selected to be representative for difficult operating conditions. The idea is that if we understand and can handle these difficult cases, then we have a good foundation to also control the system under less severe operating conditions.

In order to have more challenges we slightly modified the original model.
The original transformer had spare capacity , so the transformer rating was reduced to15 MVar which is enough for the 14 MW of wind power installed.
We also changed the lengths of the lines to have more voltage drop; we used lines and cables of 15 km long.

For a system with distributed generation, we can get two extreme cases. The first case is minimum generation combined with maximum load. The second case is maximum generation combined with minimum load.
In both situations the power flow through the transformer is high. We took this into account to choose the load profile and the data for the wind generation. The idea was to have both situations in the same day. We took the data for generation in a day when the generation was low during the day and high during the night. The load profile is at the opposite, high during the day and low during the night.

In the simulated cases there are mainly four variables that are combined. These variables are: the technology used for the wind turbine (doubly-fed induction generator or squirrel cage induction generator), the compensation (no compensation, STATCOM, step capacitors, fixed capacitors), to have the OLTC on or off, and to use overhead lines or underground cables.

7.1 Descriptions of the components included in the models

7.1.1 Wind turbines

The turbines have 2 MW nominal power. One feeder had 4 turbines and the other feeder had 3 turbines.
To simulate the DFIG system we used the recorded data for P and Q from the wind farms and input them in a variable load model.
For the SCIG we used the same data for the active power and a look-up table for Q. The table was made from the operation characteristic of the SimPowerSystems' induction generator model. These P,Q data was used to control the variable load model.

7.1.2 Lines and cables

The same length, material and area were used for both line and cable. Hence the results should be directly comparable. The parameters for the line and cable are:

Cable:

R1=0.32 Ω/km
C1=0.22 μF/km
L1=0.36 mH/km

Line:

R1=0.32 Ω/km
C1=8.6 nF/km
L1=1.0 mH/km

7.1.3 Compensation

We used three different kinds of compensation: STATCOM, step capacitors and fixed capacitors

The doubly-fed induction generator has been simulated with voltage control mode and with zero reactive power. To simulate a controllable converter that keeps the voltage constant, an STATCOM is added to the wind power plant. The STATCOM measures the voltages in the feeders and calculates the reactive power needed to adjust the voltage; it can inject or absorb reactive power in the system.

The step capacitors system measures the active power output of the wind turbine and switch the suitable capacitor. It has three possibilities: to compensate zero load, medium load or full load.

The fixed capacitor follows the same principle than the steps capacitors system but it is just one capacitor to compensate at zero load.

7.2 Simulated cases

In order to avoid the excessive wear of the transformer the ideal would be as few tap changes as possible. With the OLTC on we can control the voltage. The voltage on the secondary side of the transformer can be kept constant by changing the taps.

Another method of controlling the voltages apart from the transformer would be to add compensation. We tried three different compensation systems.

For the next simulation cases the OLTC was blocked and the voltages were controlled by reactive compensation only.

We simulated all the cases with line and cable to study the differences in the voltage profile.

Two different wind turbine technologies are tested in these simulations to illustrate the advantages and disadvantages of using one or another.

The characteristics of the simulated cases are summarized in this scheme:

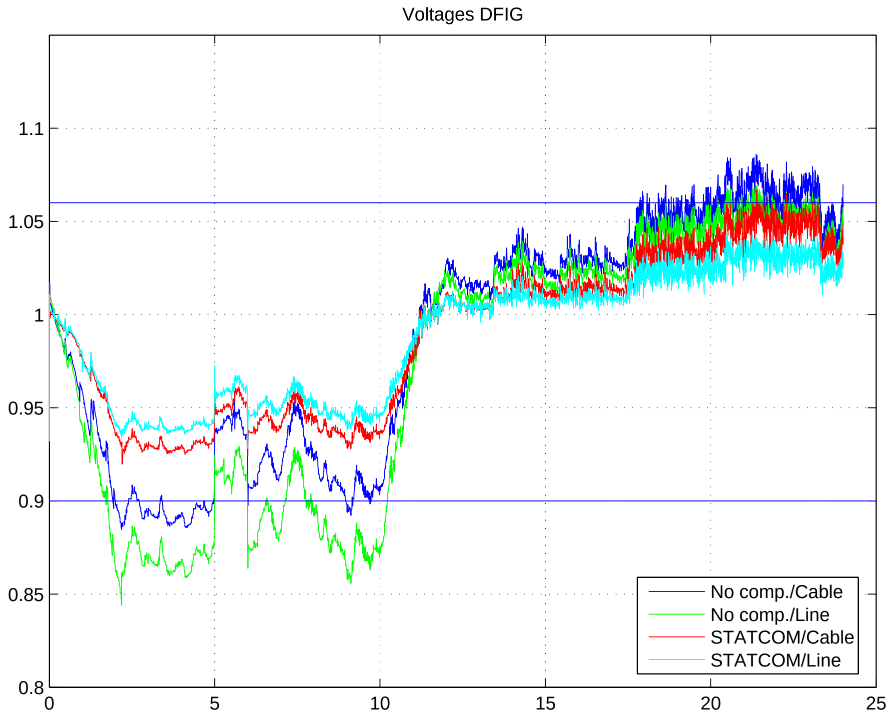
CASE	**WIND TURBINE**	**OLTC**	**LINE/CABLE**	**COMPENSATION**
1	DFIG	ON	CABLE	No compensation
2	DFIG	ON	LINE	No compensation
3	DFIG	ON	CABLE	STATCOM
4	DFIG	ON	LINE	STATCOM
5	SCIG	ON	CABLE	Fixed capacitors
6	SCIG	ON	LINE	Fixed capacitors
7	SCIG	ON	CABLE	Step capacitors
8	SCIG	ON	LINE	Step capacitors
9	DFIG	OFF	LINE	STATCOM

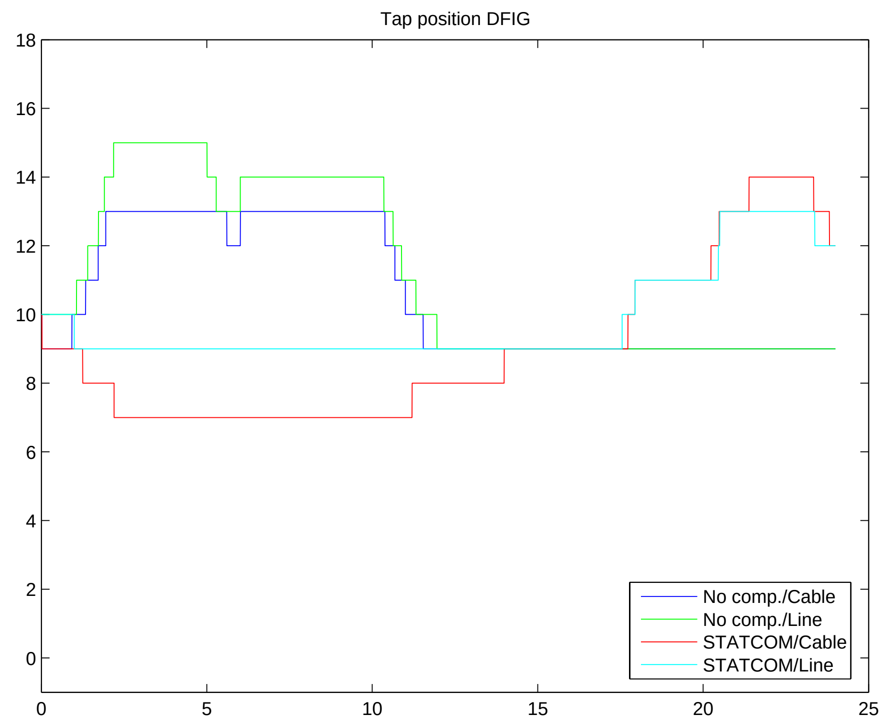
CHAPTER 8: RESULTS

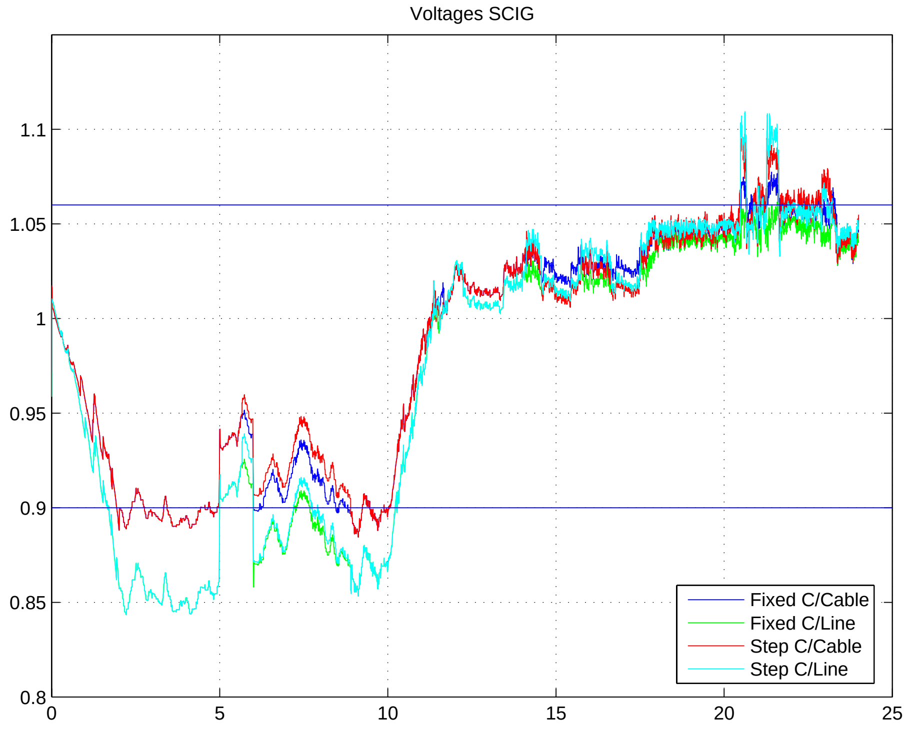
Our goal is to control the voltage with minimal tap operation. The simulation results are summarized with plots for the voltages and the tap position. The cases with DFIG are separated from the cases with SCIG.

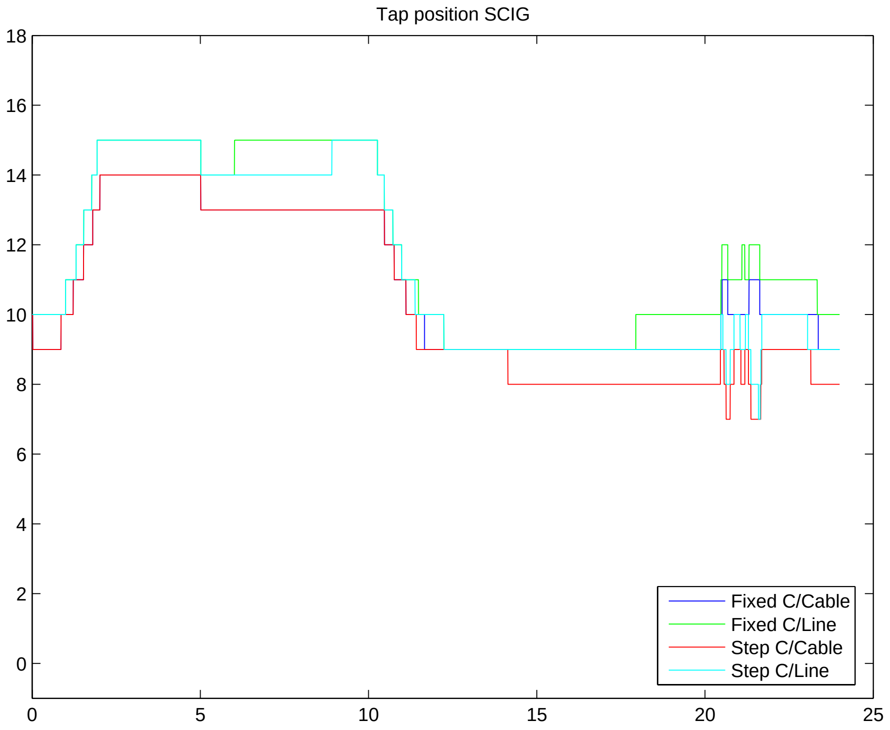
The plots present the voltages in the feeder 23 (Västraby). The conditions for the feeder 24 (Orup) are less severe (less load and less wind power) thus the voltages are closer to nominal values.

For more information consult the appendix where each case is presented separately.




Tap position DFIG
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
No comp./Cable
No comp./Line
STATCOM/Cable
STATCOM/Line


Voltages SCIG
1.1
1.05
1
0.95
0.9
0.85
0.8
0
5
10
15
20
25
Fixed C/Cable
Fixed C/Line
Step C/Cable
Step C/Line



The simulation results were evaluated with respect to number of tap changes, overvoltage and undervoltage. The scheme below summarizes the most important conclusions.

	Case description	Number of tap changes	Maximum and minimum values that reaches U3pu
CASE 1	DFIG, no compensation, cable	11	Max 1.086 8.6% overvoltage Min 0.8846 11.5% undervoltage
CASE 2	DFIG, no compensation, line	13	Max 1.0693 6.9% overvoltage Min 0.844 15.6% undervoltage
CASE 3	DFIG, STATCOM, cable	12	Max 1.0671 6.7% overvoltage Min 0.9198 8.3% undervoltage
CASE 4	DFIG, STATCOM, line	6	Max 1.0445 4.4% overvoltage Min 0.9281 7.1% undervoltage
CASE 5	SCIG, fixed capacitors, cable	17	Max 1.0774 7.7% overvoltage Min 0.8845 11.5% undervoltage
CASE 6	SCIG, fixed capacitors, line	22	Max 1.0628 6.28% overvoltage Min 0.8436 15.6% undervoltage
CASE 7	SCIG, step capacitors, cable	24	Max 1.0977 9.7% overvoltage Min 0.8845 11.5% undervoltage
CASE 8	SCIG, step capacitors, line	27	Max 1.1094 10.9% overvoltage Min 0.8436 15.6% undervoltage
CASE 9	Case 4 with the transformer blocked	0	Max 1.0318 3.1% overvoltage Min 0.9226 7.7% undervoltage

8.1 Comments to the simulation results

After simulating these nine cases we can have some conclusions based on the graphics. These graphics can be consulted in the appendix.

8.1.1 Voltage profile with line or cable

There are some differences in the voltages depending if we use line or cable.
This is due to the ratio R/X. For our overhead line this ratio is around 0.3 and for the cable it is around 1. If the resistance is smaller than the reactance, as in the case of the

line, the voltage drop is mainly caused by reactive power. For the cable the reactance and the resistance have almost the same value, so we have to consider both active and reactive power when calculating the voltage drop.

The simulation cases 1 and 2 can be used to illustrate how the flow of active and reactive power cause the voltages drop. When the power flow goes in the direction from grid to load, the voltages are closer to nominal values with cable. For the opposite direction the cable gives more voltage drop.

During the day, the load is high and the wind generation is low. The power comes from the grid and the load needs active and reactive power that goes trough the line or cable.

During the evening and night, the load is low and the powers produced by the wind farms exceed the local loads. Therefore the power flows from the wind farms to the high voltage grid. The produced power is mainly active power, since the wind farms draw little reactive power.

The conclusion is that when the power flow goes in the direction from grid to load we have reactive power circulating and when it goes in the other direction we have almost no reactive power flow. That explains why the voltages during the day are lower if we use line (more influenced by the reactive power flow) and during the night the voltages increase more if we use cable (more influenced by the active power flow)
Exactly the same conclusion can be taken from the comparison between the voltages in cases 5 and 6.

8.1.2 Voltage control with DFIG

The doubly-fed induction generator has been simulated with voltage control mode (STATCOM) and with zero reactive power (no compensation).
The STATCOM helps to keep the voltage much closer to the nominal value. Not only the voltages are better but also the number of tap changes is reduced drastically.
The diagram shows that the STATCOM gives a drastic change in the reactive power drawn from or injected into the grid. This is because the STATCOM uses reactive power to regulate the voltage towards the nominal value.
During the day, with high load and low wind, the voltages in both feeders tend to decrease. In this case the STATCOM acts as controllable capacitor injecting reactive power into the system. Part of this reactive power has to be absorbed by the grid.
During the night, with no load and high wind generation, the voltage tends to increase on both feeders. To keep the voltage close to 1 p.u. the STATCOM acts as a controllable reactance absorbing reactive power. That explains the high reactive power generated by the grid at this time of the day.
Due to the higher ratio R/X of the cable the sensitivity of node voltages to changes in the reactive power flow is less than for the overhead line. That is why the STATCOM has to use more reactive power to control the voltage for the cable connection.

Even though the STATCOM for the cable needs more reactive power, the result is still different compared to the line. The same STATCOM gets more control authority when used for an overhead line. Consequently, less compensation is needed to use an STATCOM for voltage control of an overhead line, compared to a cable. This agrees with the conclusion that Ferry August Viawan comes up with in his licentiate thesis

‘The reactive power absorption for overvoltage mitigation will be more effective if the feeder is an overhead line rather than an underground cable’.

8.1.3 Voltage control with SCIG

For the squirrel cage induction generator, two different devices have been used to keep the voltages close to 1 p.u.

One option is to use fixed capacitors on the feeders where the wind power plants and the loads are. The fixed capacitor is calculated to compensate the wind power plant at zero load; this means that if the voltage is 1 p.u the capacitor gives the reactive power that the wind power plant needs when it is producing zero power.

There might be a problem with the fixed capacitors because their reactive power output depends on the voltage of the feeder, the higher the voltage is the higher the reactive power will be. In this case this is not a problem because the voltages increase when the produced power increases and then the wind turbine needs more reactive power.

Comparison of DFIG without compensation, and SCIG with fixed capacitors, shows that the voltages are very similar, but the number of tap changes are higher for SCIG. We see a significant difference in reactive power when comparing the plots. The wind power plants with SCIG need more reactive power for the same amount of active power produced. The system with three step capacitors was the second method used to control the reactive power for the SCIG. The switching of these capacitors is controlled by the active power output of each wind turbines. One capacitor compensates for zero load, another for medium load and the last one for full load. The reason to use active power to control the switching, rather than voltage, is to avoid possible interactions between OLTC and the capacitors.
A comparison between the plots for the SCIG with fixed capacitors and step capacitors, shows that step capacitors does not improve voltage. Actually, the voltages are worse with step capacitors.
Using capacitors, the reactive power output is controlled only by the active power output of the turbine, not by the voltages. This is the reason that the voltages are not so close to nominal values.
The Q diagram shows that the reactive power drawn from the grid is lower for step capacitors than for fixed ones. Since the capacitors are controlled by active power, high wind power generation gives more reactive power. The combination of small load and high wind generation creates a problematic situation, where reactive power has to be absorbed by the grid. This situation becomes even more problematic if we use switched capacitors instead of fixed ones.

8.1.4 Active power

As expected the active power diagram does not change in the different cases. The resistance is the same for line and cable, the lengths of them are the same so the active power absorbed by the line or the cable has to be the same. We have the same active power production for SCIG and DFIG and also the same load for all the cases.

8.1.5 Apparent power

The graphics for the apparent power passing the transformer show some differences depending on the compensation and the kind of line used.
For the combination high load and low wind power generation, the apparent power through the transformer is highest for overhead line. For low load and high wind generation there is almost no difference between using line or cable.

The reason for this can be the higher reactive power absorption by the line. For high load and no wind generation the voltages in the feeders are below the nominal value. For high generation and no load the voltages are over the nominal values. Since the power is equal to the voltage multiplied by the current, the higher the voltages are the lower the current will be for the same power. The reactive power absorption in a line is proportional to the current squared ($X * I^2$) so higher voltages gives less reactive power absorption in a line. This can explain that the apparent power is similar for line and cable for the overvoltage case with high wind generation and no load.

The situation changes when we use STATCOM. Since the node voltages in a line are more sensitive to changes in reactive power than in a cable, the line requires less reactive power to control the voltage. Therefore the reactive flow trough the transformer is lower with the line.

If the active power flows from grid towards load, then the DFIG with STATCOM will help to reduce the reactive power flow. When the active power flow is reversed, i.e., from wind power towards the grid, the reactive power flow is less influenced. This is logical because the STATCOM compensates the reactive power in the feeders where the wind plants are and then less reactive power is drawn from the grid. The losses in the transformer are reduced when we use STATCOM due to the decreased flow of reactive power.
For the SCIG technology there is almost no difference in the apparent power when using step capacitors or fixed capacitors.

8.1.6 Number of tap changes during the day

Our main goals are to keep the voltages close to nominal values and minimize the number of tap changes. The number of tap changes is related to the amount of reactive power that goes through the transformer. If we compare the plots the relation is clear: the more reactive power flow trough the transformer the more number of tap changes. Between the DFIG and the SCIG it is clear that the SCIG system requires more tap changes due to the higher amount of reactive power that the turbines need.
In almost all the cases the number of tap changes is higher with the line. This is because the line absorbs more reactive power than the cable, and this reactive power is drawn from the grid. Cases 3 and 4 are an exception for this. The STATCOM has to work harder when we are using a cable, which means that it has to inject or absorb more reactive power in the system. This reactive power has to go trough the transformer causing more tap changes for the cable case.

The compensation for the SCIG works in a different way since it is controlled by the active power. The compensation does not vary much with line or cable because the active power is the same in both cases. The difference is caused by the higher reactive absorption by the line.

8.1.8 Blocking the transformer

We have simulated different cases using the OLTC to control the voltage at the secondary side of the transformer. Since our goal is to reduce the number of tap changes we simulate a ninth case with the transformer blocked. To control the voltages at the feeders we use an STATCOM.

As expected, without the tap changing action the voltage at the secondary side of the transformer is more variable. However, thanks to the STATCOM the voltages in the feeders are kept very close to their nominal values, even closer than when we use the OLTC.

Comparing the operation of the STATCOM for cases 4 and 9 we notice that with the transformer blocked the STATCOM has to inject and absorb less reactive power. That is because the voltage on the secondary side of the transformer can vary more, since the OLTC is blocked.

CHAPTER 9: CONCLUSIONS

An analysis of the simulations results can help us to find the best control strategies for this type of system.

The SCIG requires more reactive power than DFIG technology. This means that SCIG increase the number of tap changes. The reactive power drawn from the grid is also higher with the SCIG even if compensation is used.
For this reasons the DFIG seems to be more appropriate for this system. This agrees with the general trend in the wind turbine market. Nowadays the DFIG is the most common choice. In the book 'Wind power in power systems' by Thomas Ackermann we can find a scheme of the most used turbine technologies between the years 1998 and 2002.

World market share of wind turbine concepts (%)

	1998	**1999**	**2000**	**2001**	**2002**
SCIG	39.6	40.8	39	31.1	27.8
DFIG	26.5	28.1	28.2	36.3	46.8

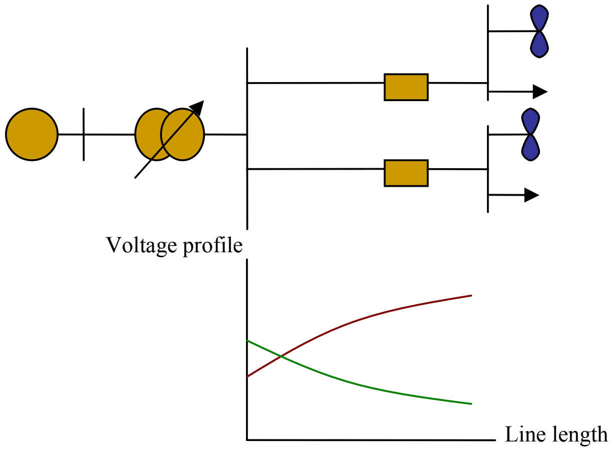
Concerning the compensation it is clear that the best results are with DFIG and STATCOM. For the SCIG we obtain better results with fixed capacitors compensation at zero load. The step capacitor system gives high overvoltages at high wind generation.

In chapter 8 we explained the differences in reactive power absorption between line and cable. We conclude there that the line absorbs more reactive power than the cable. The number of tap changes is directly related to the reactive power flow through the transformer. For this reason we get more tap changes when we use line; the only exception for this is when we use an STATCOM, then the node voltages are more sensitive to voltage variations when we use line.
Thus the conclusion is that for this system is best to use a cable except, when we use compensation that controls the voltage with reactive power injection or absorption.

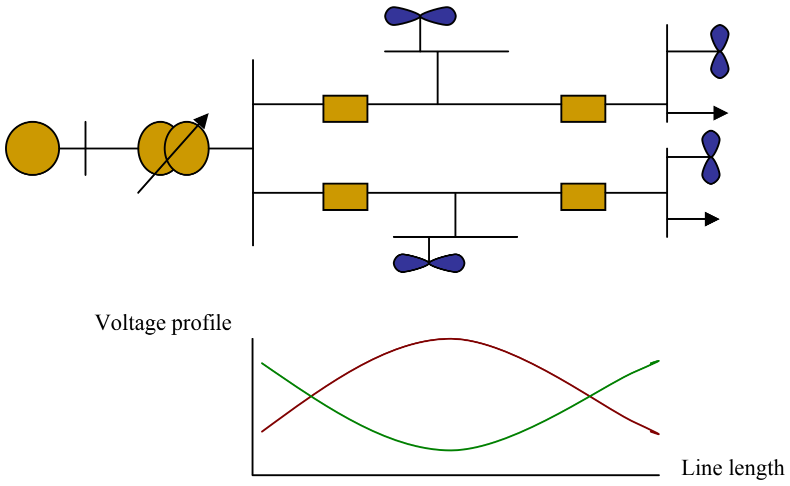
When we compared cases 4 and 9 (both with DFIG and STATCOM, case 4 with OLTC on and case 9 with OLTC off) we noticed that the voltages in the feeders are closer to nominal values with the OLTC off . However on the secondary side of the transformer the voltages are closer to nominal with the OLTC on, as expected.
Depending on the load location, it can in some cases be a good solution to block the transformer's OLTC. However, it seems worthwhile to reconsider the control setting for the OLTC. If all loads are located at the wind power plants, there is no need to control the voltage at the secondary side of the transformer. It would be sufficient to keep the voltages at the load buses within acceptable boundaries. On the contrary, if we have load at the secondary side of the transformer, this must be taken into account when deciding acceptable voltage variations.

CHAPTER 10: FUTURE WORK

The studied system has the loads and the wind power plants in the end of the feeders. In this case the voltage profile can vary depending on the generation and the load.



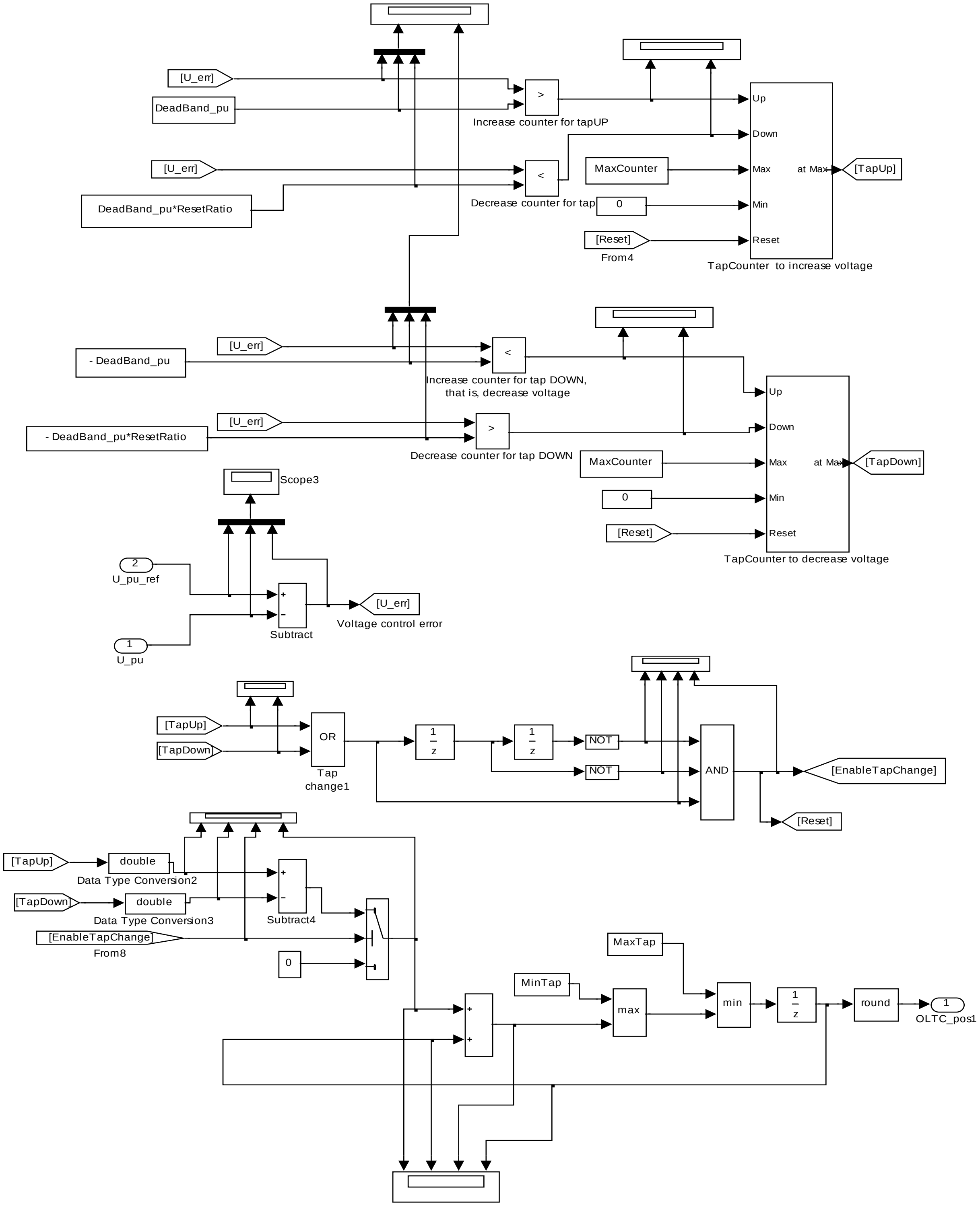
However the situation would be much more complicated when having generation or load in between the lines or cables. Then the voltage profile would be more unpredictable.



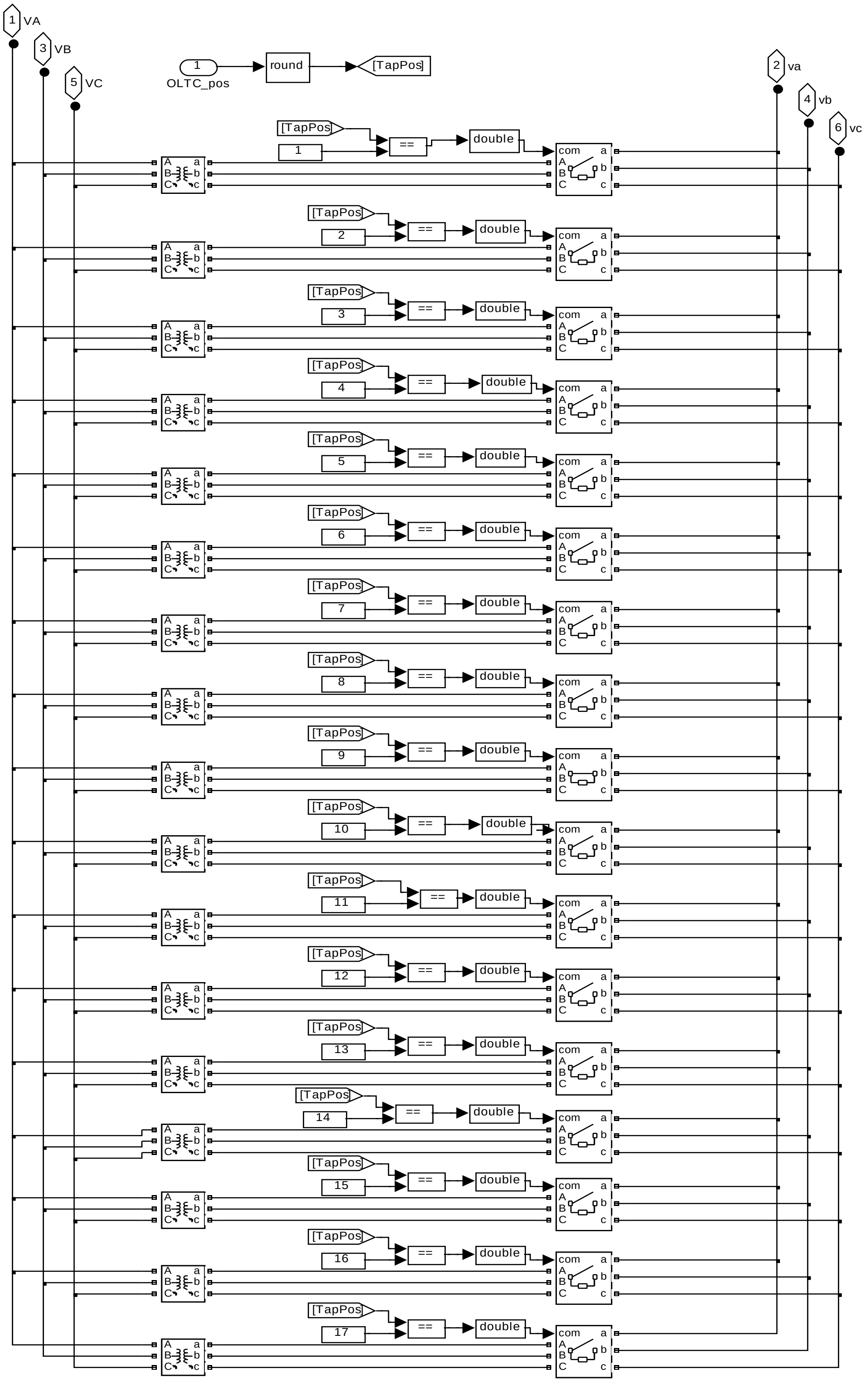
For this second case the voltage control strategies would need to be modified.

APENDIX A : MODELS

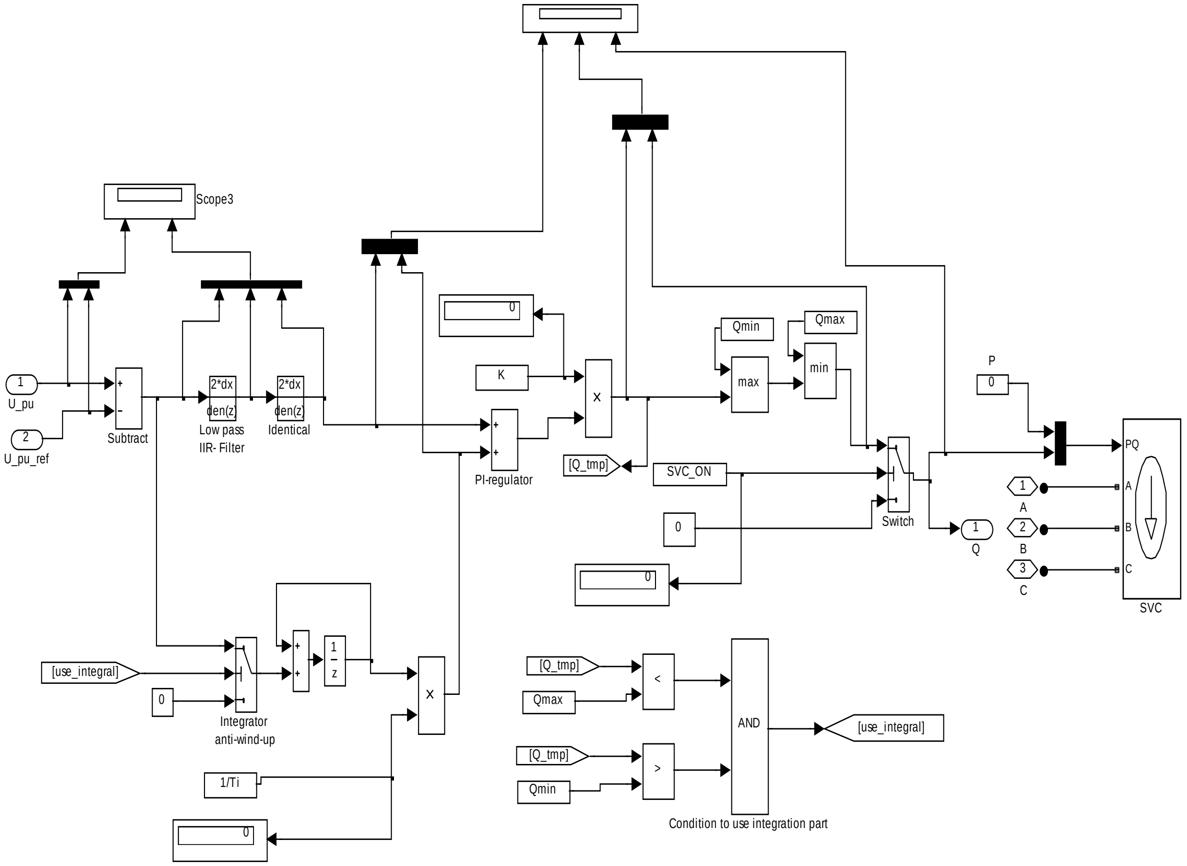
A.1 OLTC control



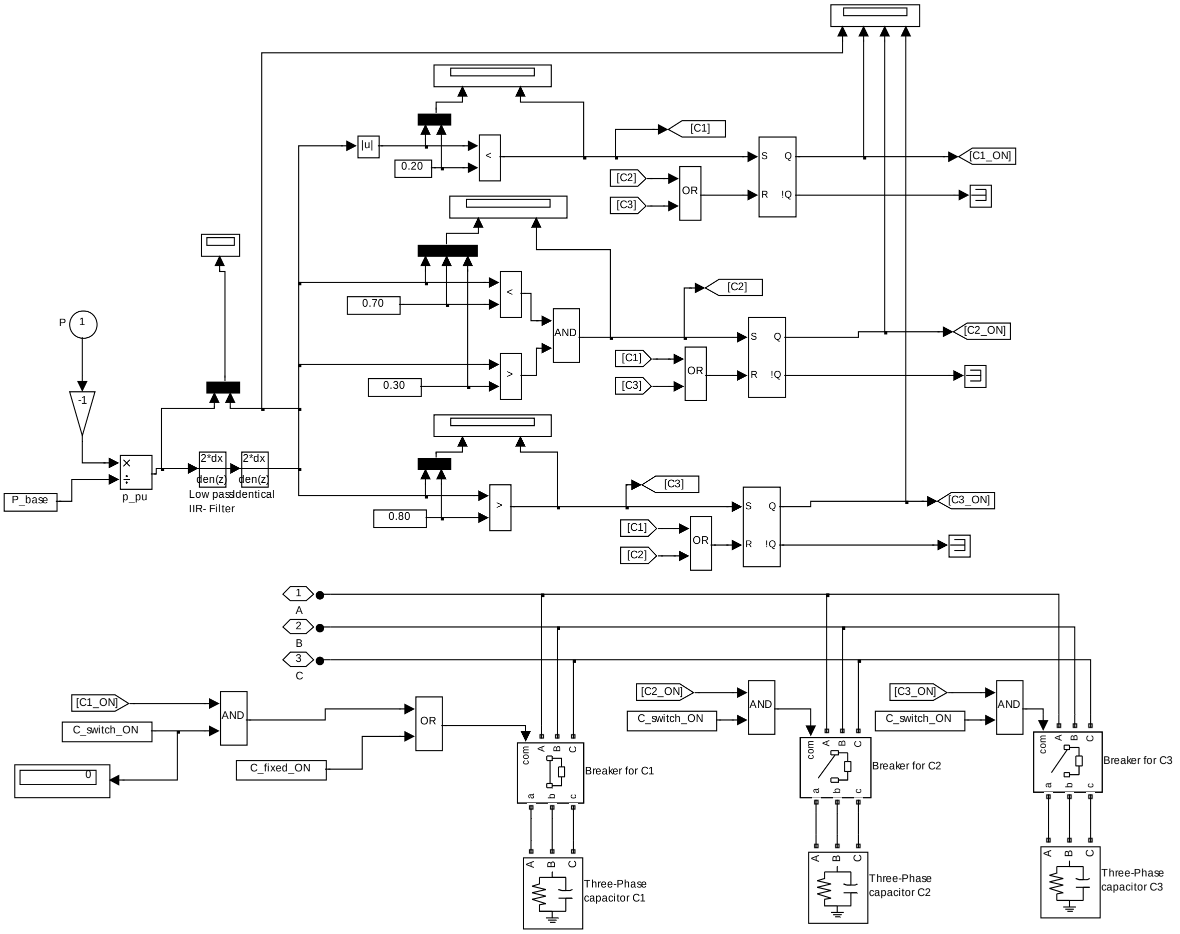
A.2 Transformer



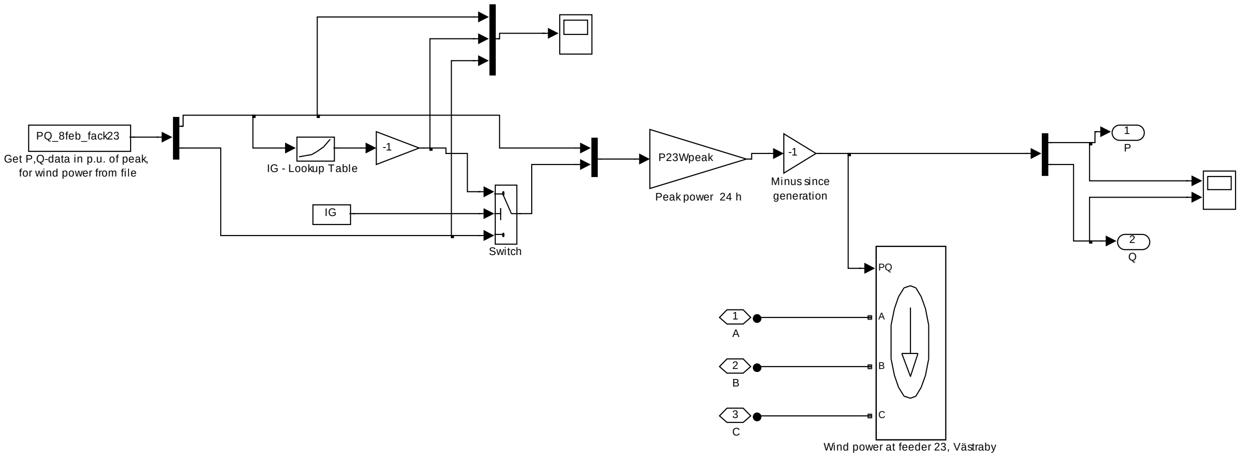
A.3 STATCOM


Scope3
0
K
Qmin
Qmax
min
max
x
P
0
PQ
1
U_pu
2
U_pu_ref
+
-
Subtract
2*dx
den(z)
Low pass
IIR- Filter
2*dx
den(z)
Identical
+
+
PI-regulator
[Q_tmp]
SVC_ON
0
0
Switch
1
Q
1
A
2
B
3
C
A
B
C
SVC
[use_integral]
0
Integrator
anti-wind-up
+
+
1
z
x
1/Ti
0
[Q_tmp]
Qmax
<
[Q_tmp]
Qmin
>
AND
[use_integral]
Condition to use integration part

A.4 Switched capacitors

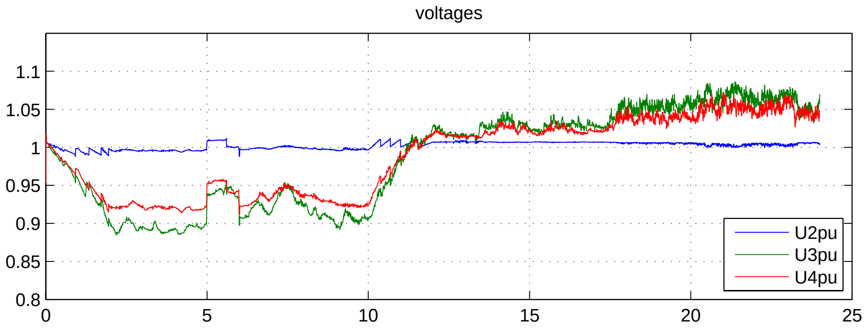


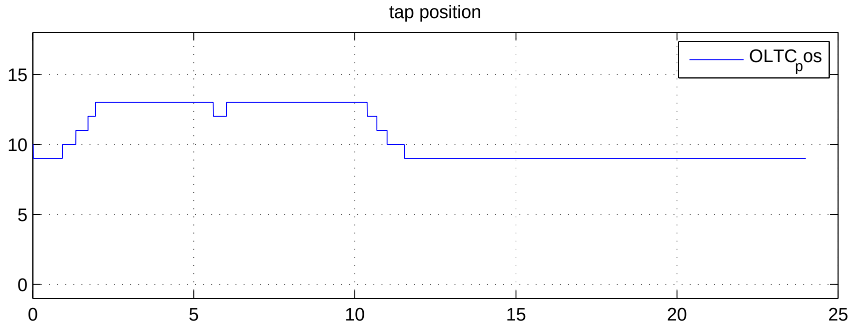
A.5 Wind turbine

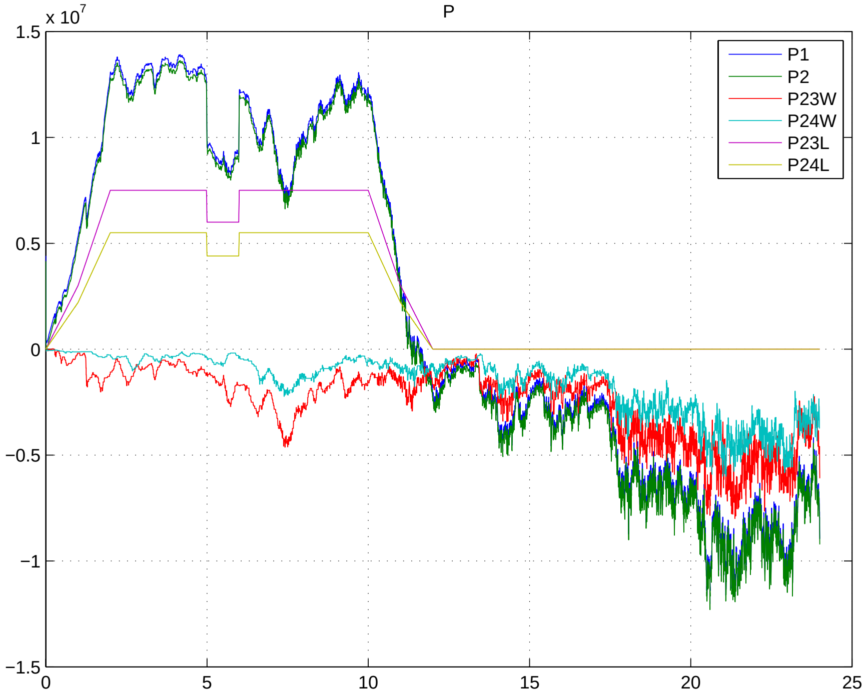


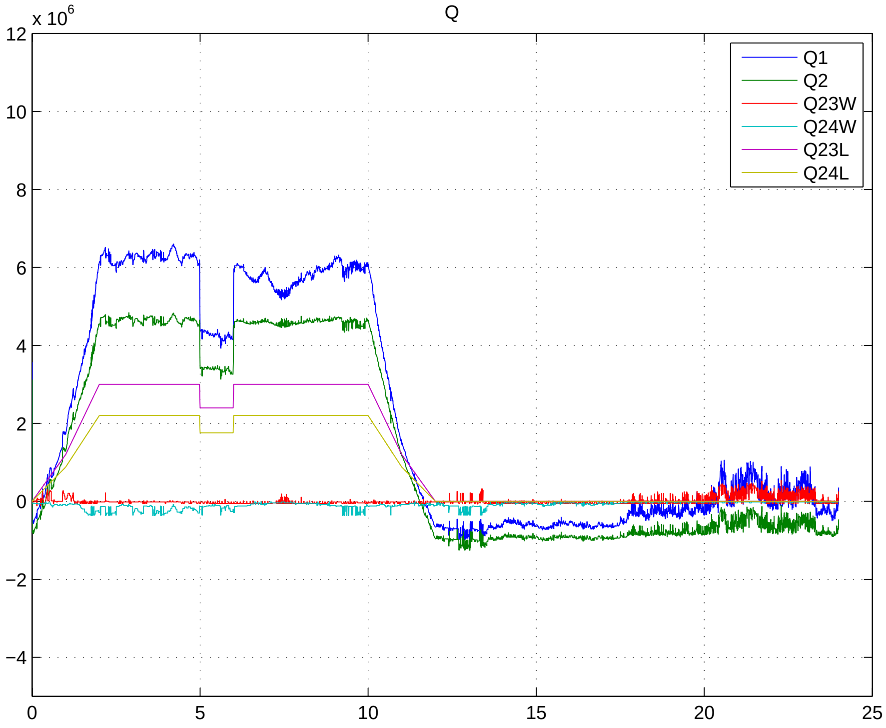
APENDIX B: GRAPHICS

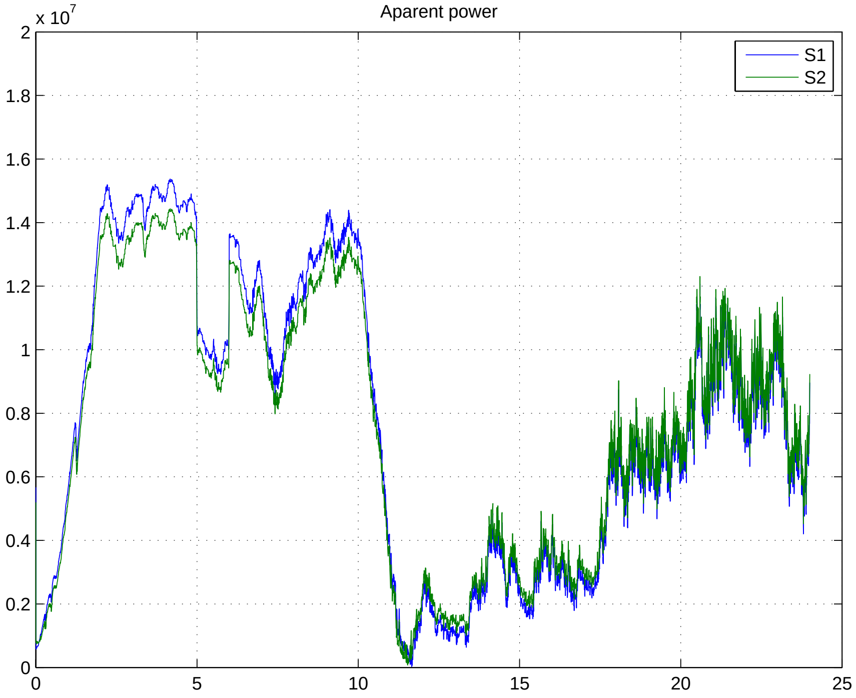
CASE 1: DFIG, Q=0 (any compensation), cable



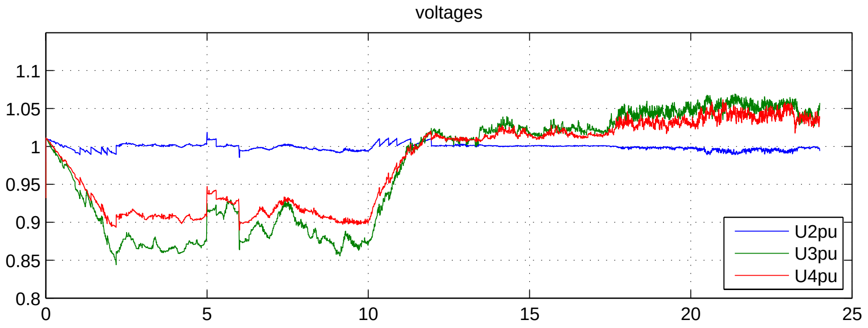


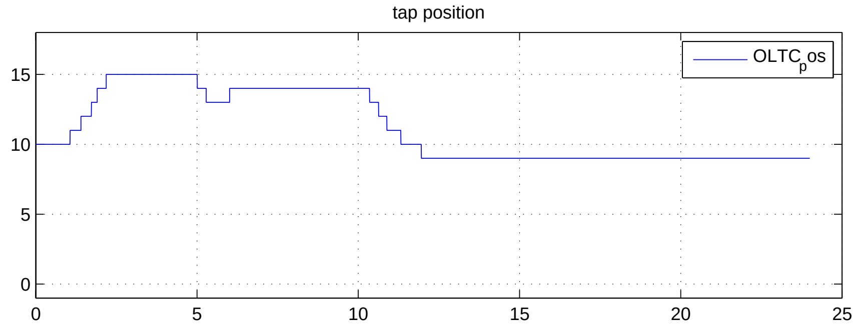


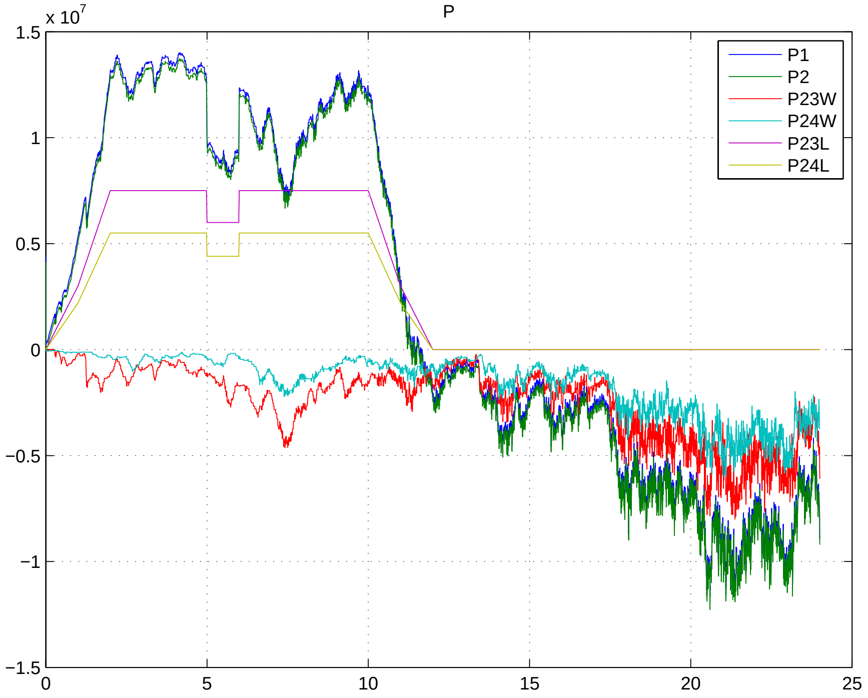

Q
x 10^6
12
10
8
6
4
2
0
−2
−4
0
5
10
15
20
25
Q1
Q2
Q23W
Q24W
Q23L
Q24L

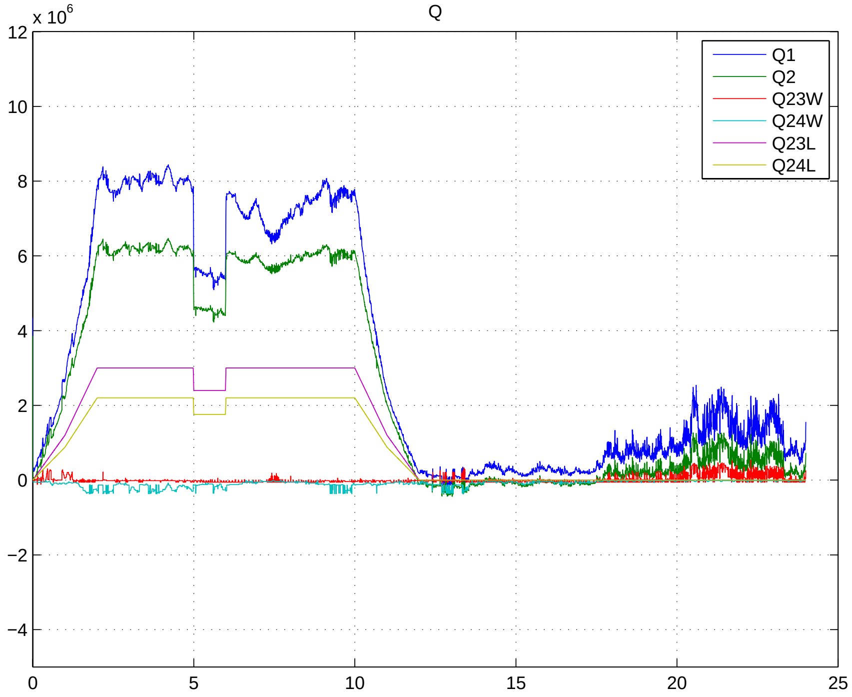

Aparent power
x 10^7
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
S1
S2

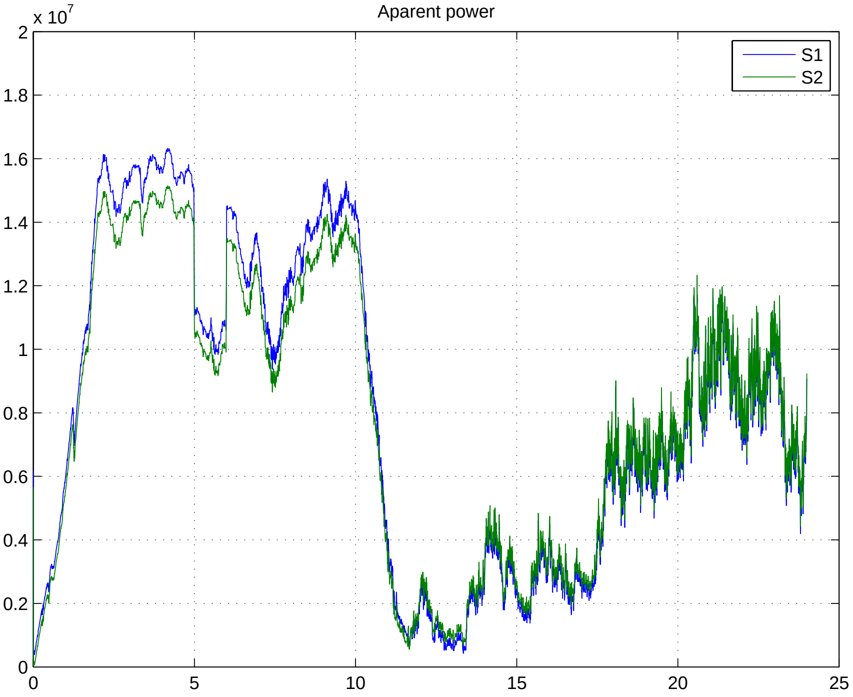
CASE 2: DFIG, Q=0 (any compensation), line



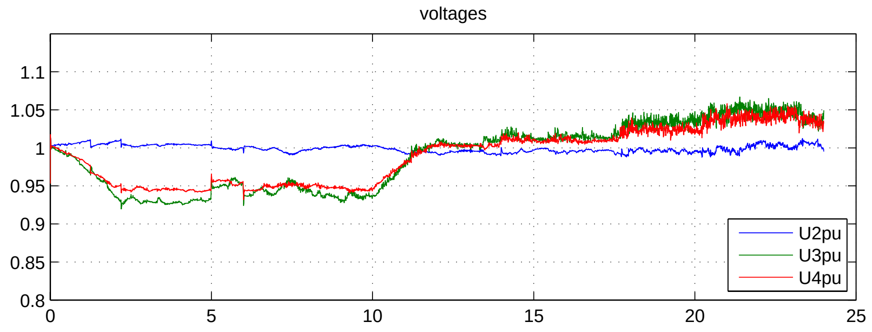


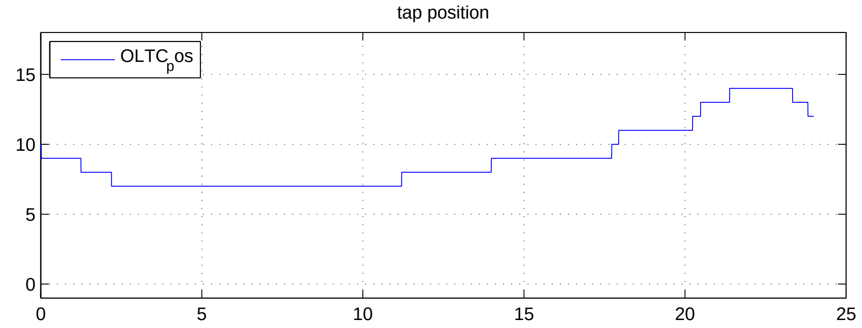


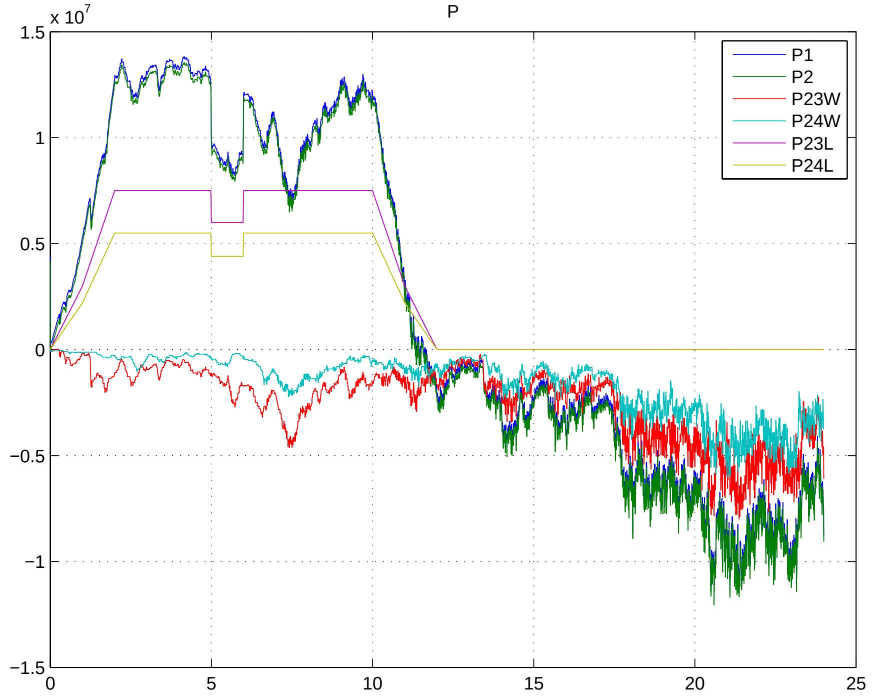

Q
x 10^6
12
10
8
6
4
2
0
−2
−4
0
5
10
15
20
25
Q1
Q2
Q23W
Q24W
Q23L
Q24L

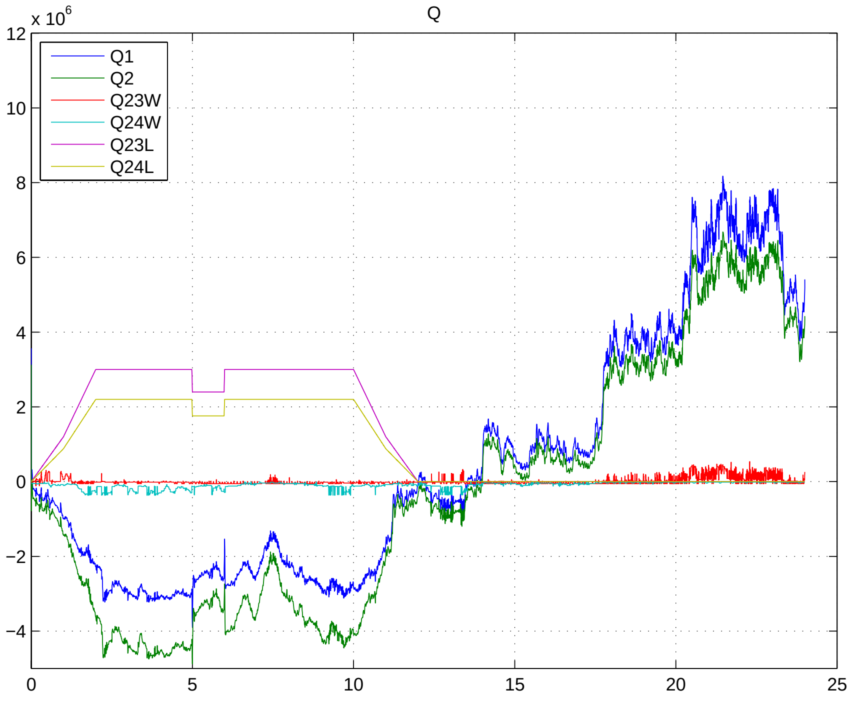

Aparent power
x 10^7
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
S1
S2

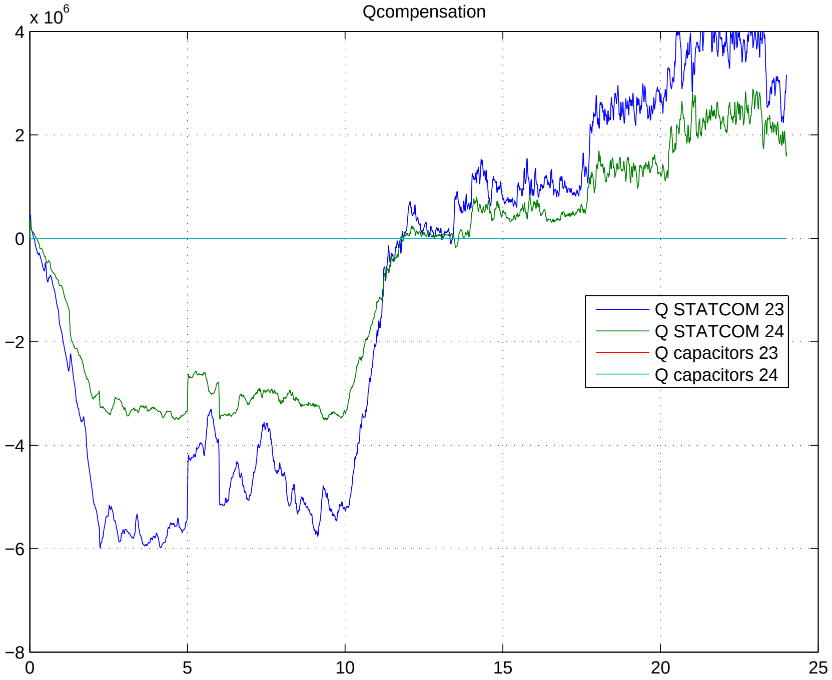
CASE 3: DFIG, STATCOM, cable

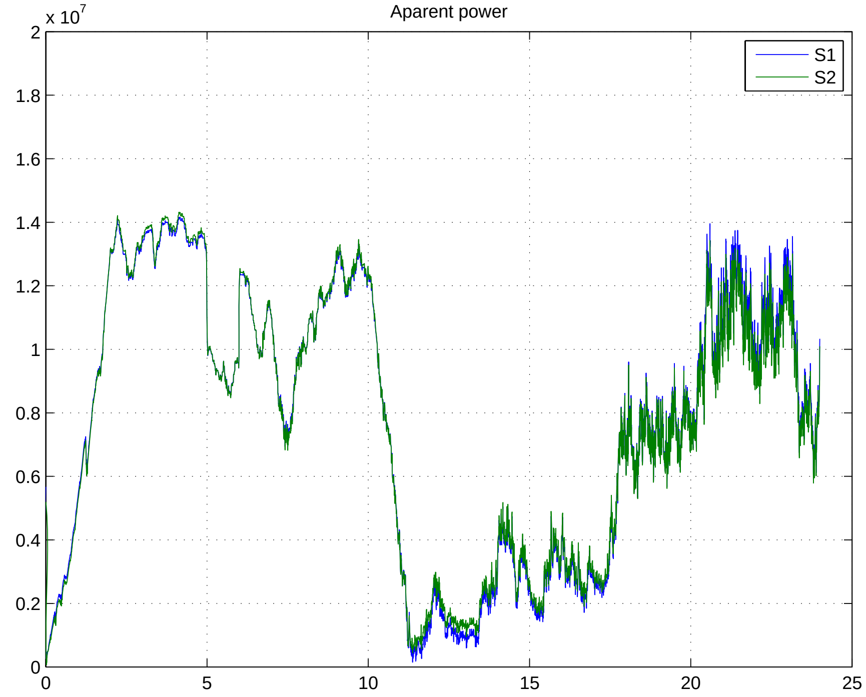




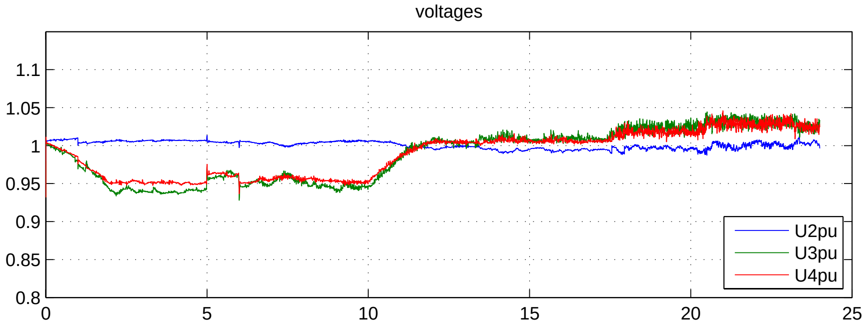


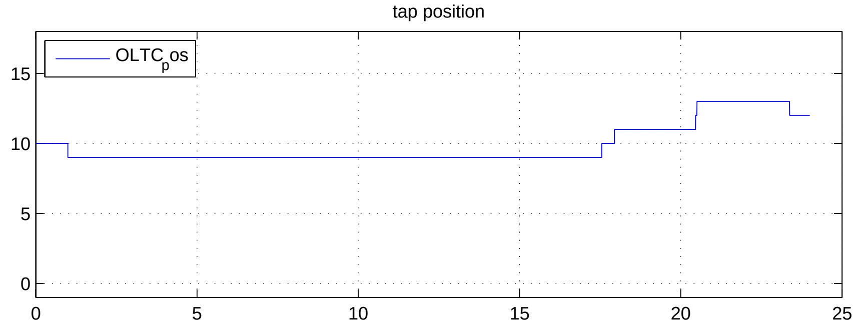

Q
x 10^6
12
10
8
6
4
2
0
−2
−4
0
5
10
15
20
25
Q1
Q2
Q23W
Q24W
Q23L
Q24L

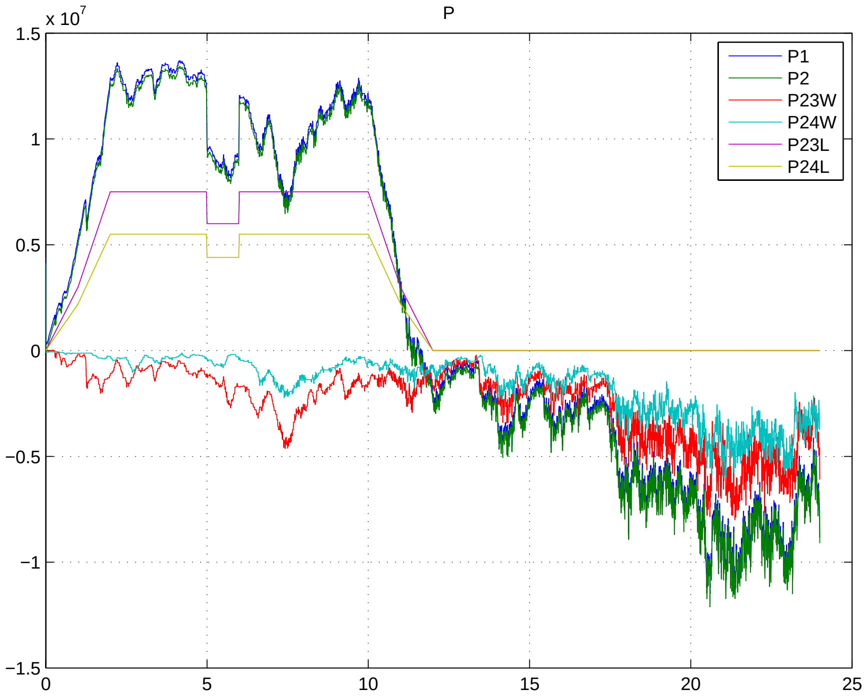

Qcompensation
x 10^6
4
2
0
−2
−4
−6
−8
0
5
10
15
20
25
Q STATCOM 23
Q STATCOM 24
Q capacitors 23
Q capacitors 24

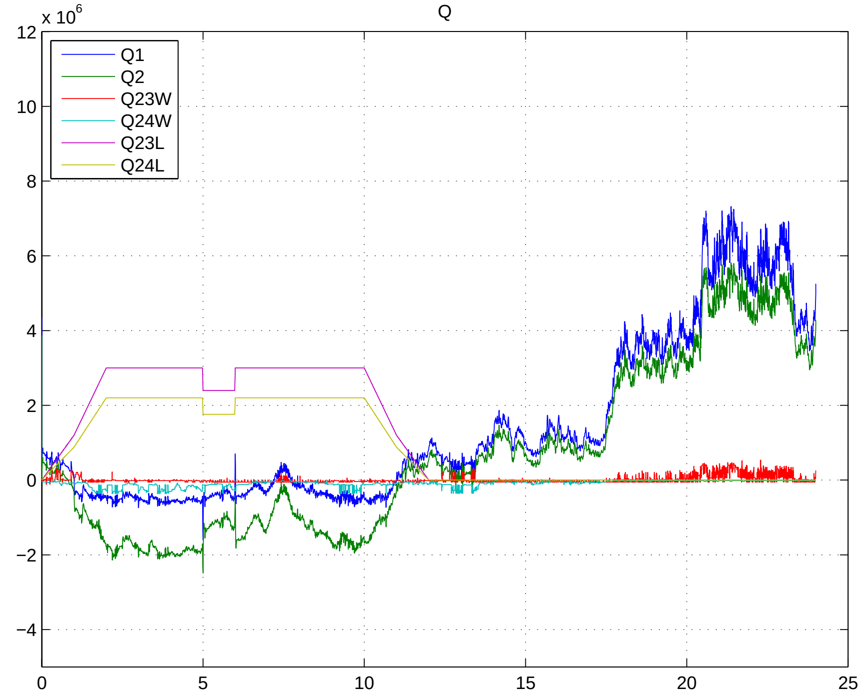


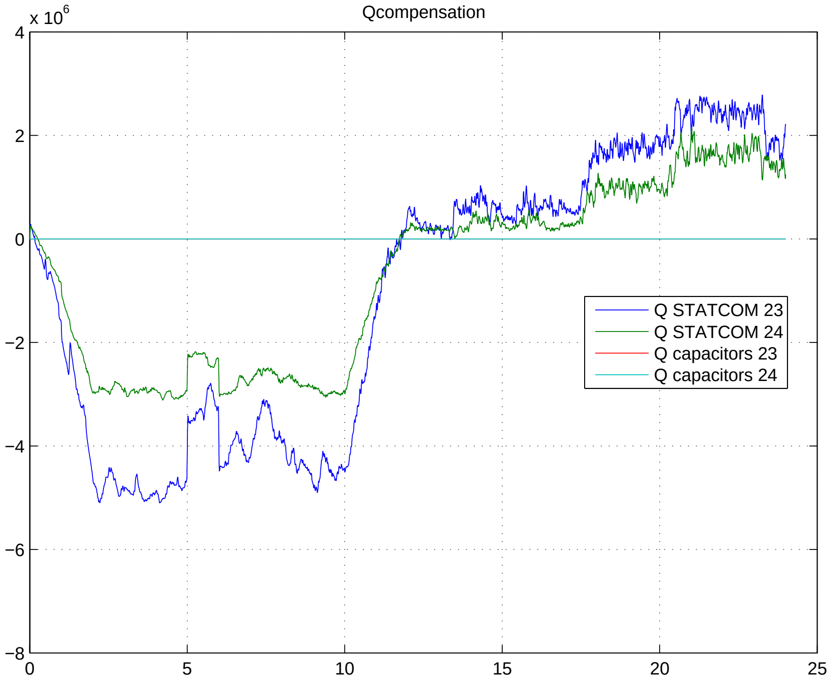
CASE 4: DFIG, STATCOM, line

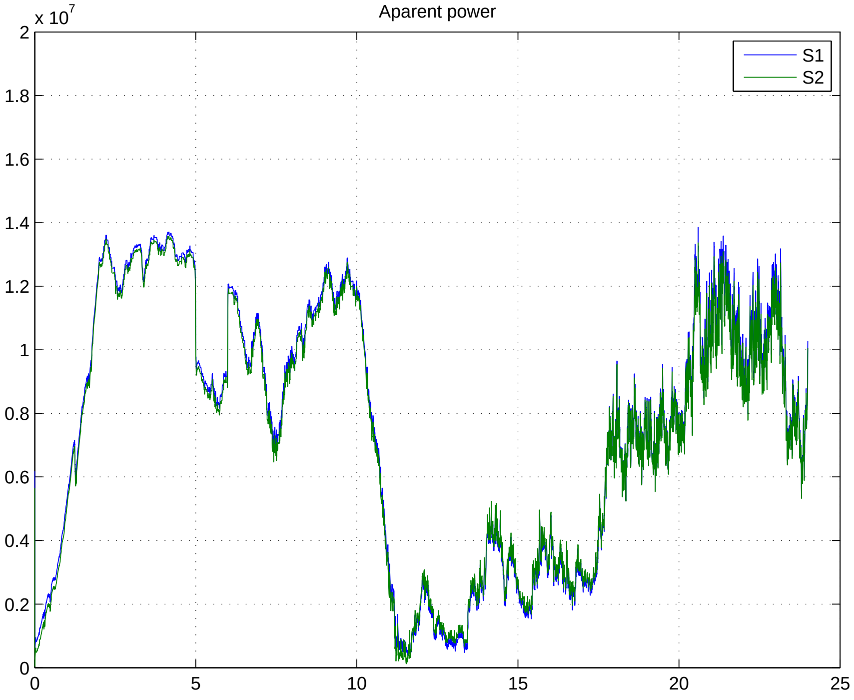




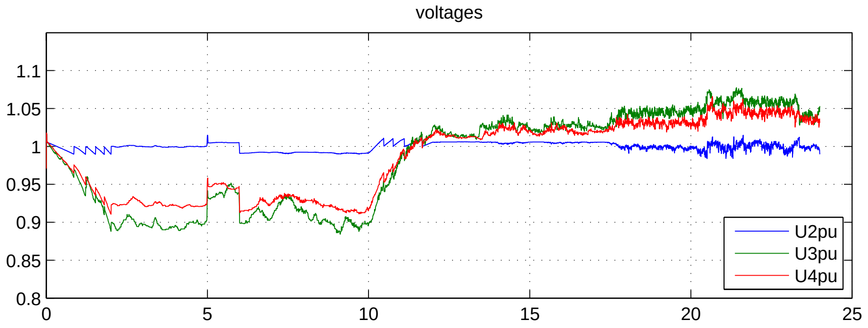

P
x 10^7
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25
P1
P2
P23W
P24W
P23L
P24L

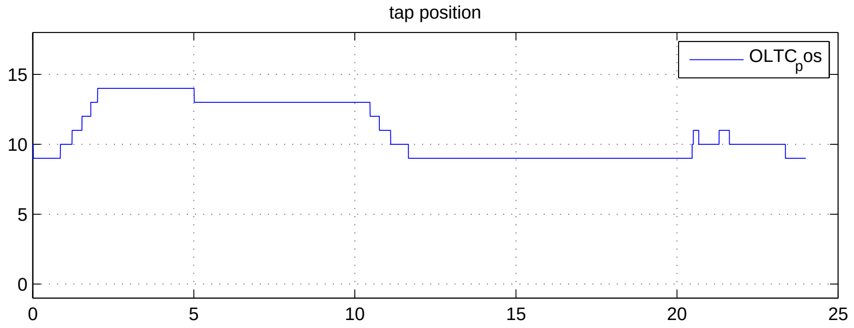

Q
x 10^6
12
10
8
6
4
2
0
−2
−4
0
5
10
15
20
25
Q1
Q2
Q23W
Q24W
Q23L
Q24L

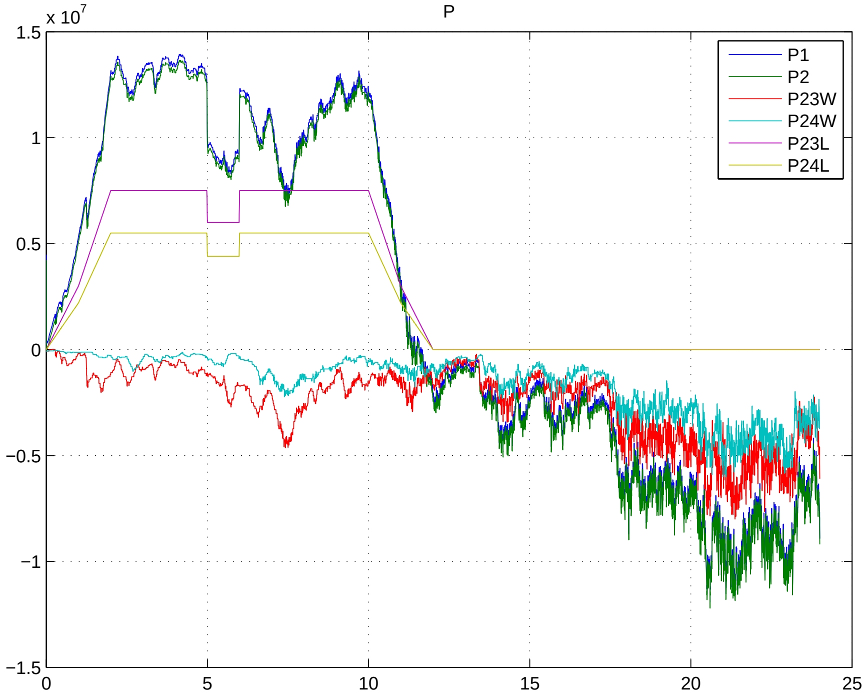

Qcompensation
x 10^6
4
2
0
−2
−4
−6
−8
0
5
10
15
20
25
Q STATCOM 23
Q STATCOM 24
Q capacitors 23
Q capacitors 24

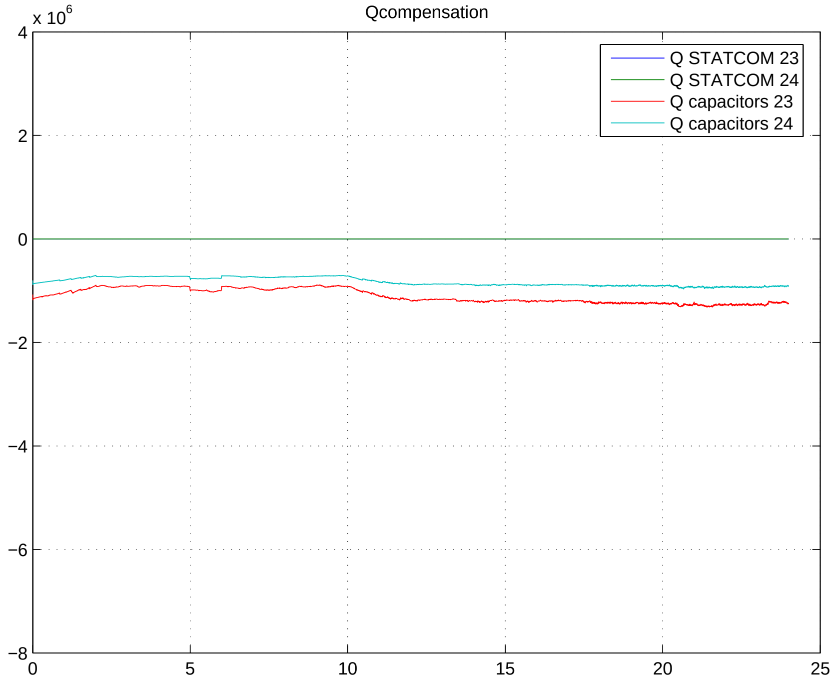

Aparent power
x 10^7
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
S1
S2

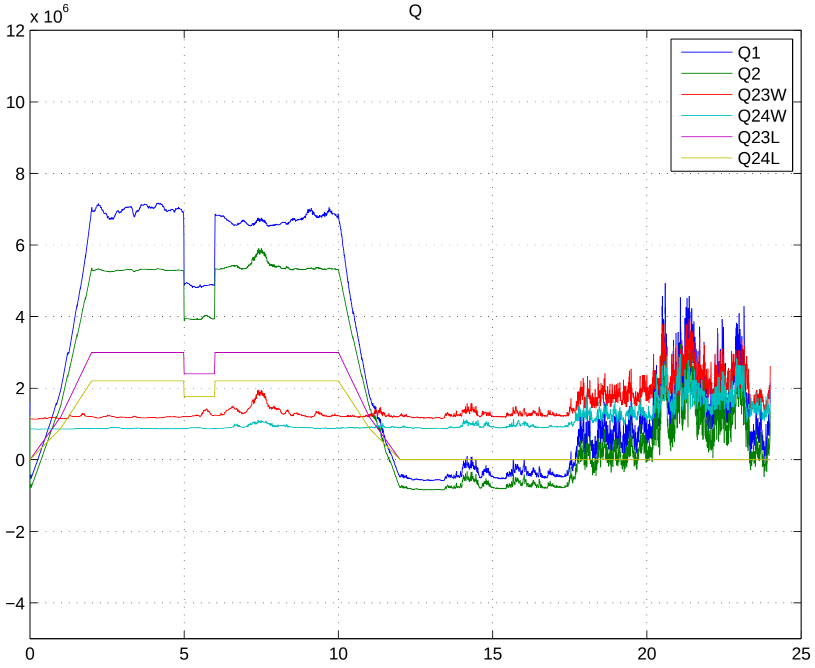
CASE 5: SCIG, fixed C, cable

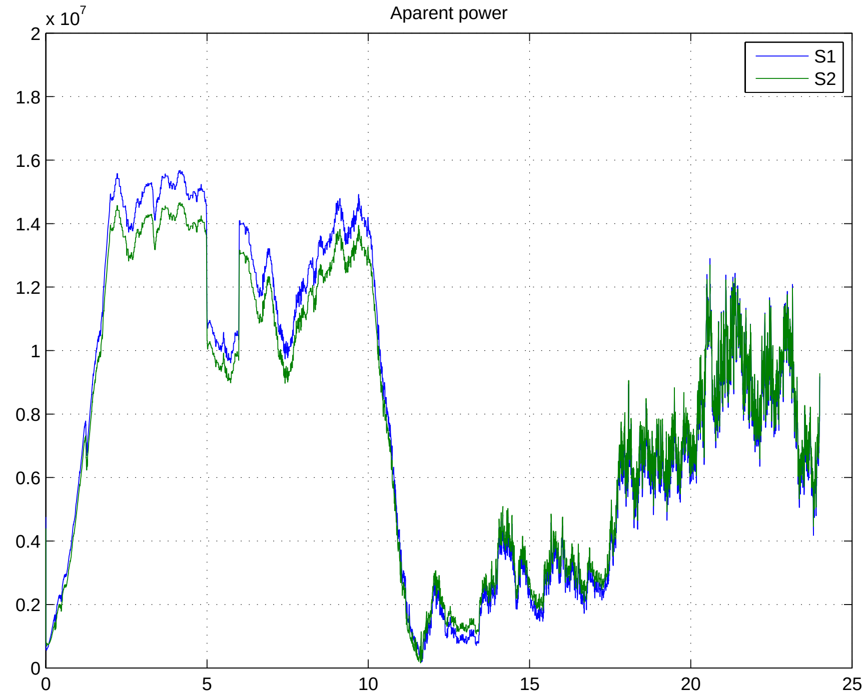




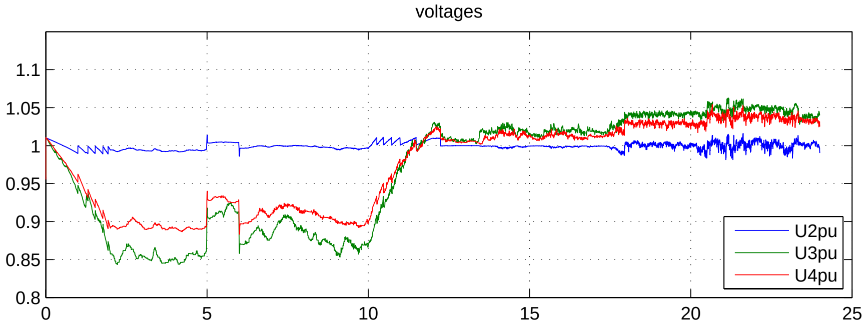


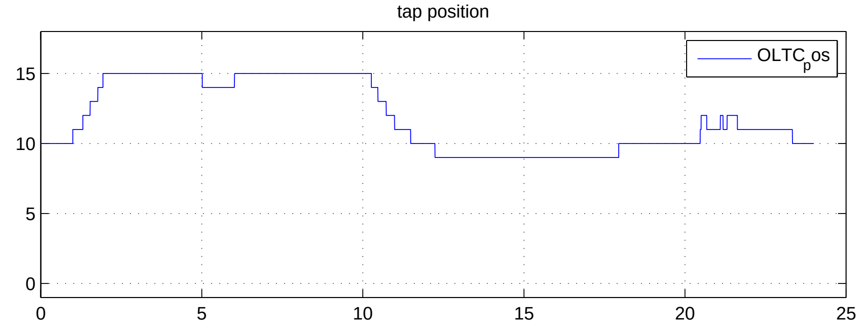

Qcompensation
x 10^6
4
2
0
−2
−4
−6
−8
0
5
10
15
20
25
Q STATCOM 23
Q STATCOM 24
Q capacitors 23
Q capacitors 24

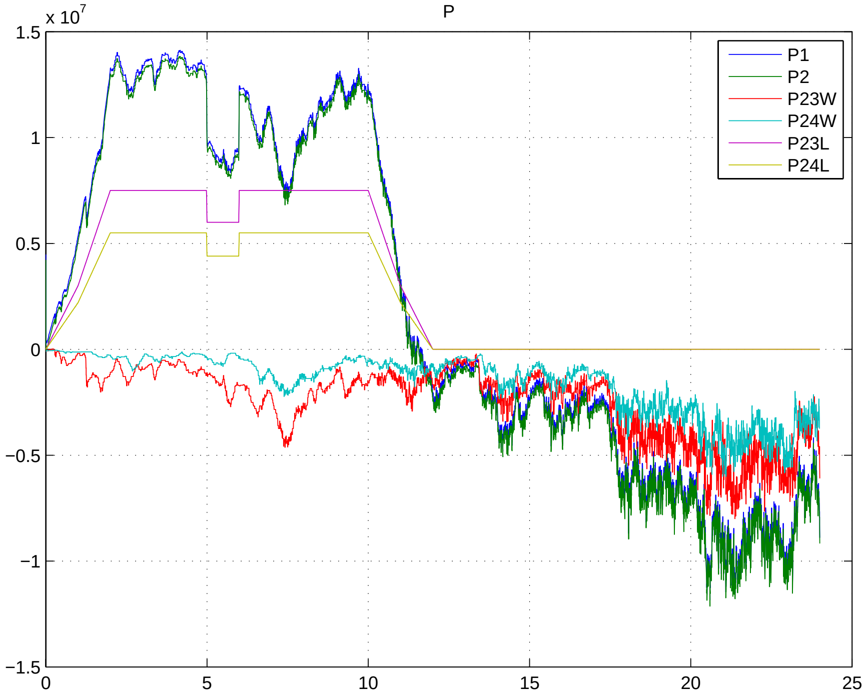

Q
x 10^6
12
10
8
6
4
2
0
−2
−4
0
5
10
15
20
25
Q1
Q2
Q23W
Q24W
Q23L
Q24L

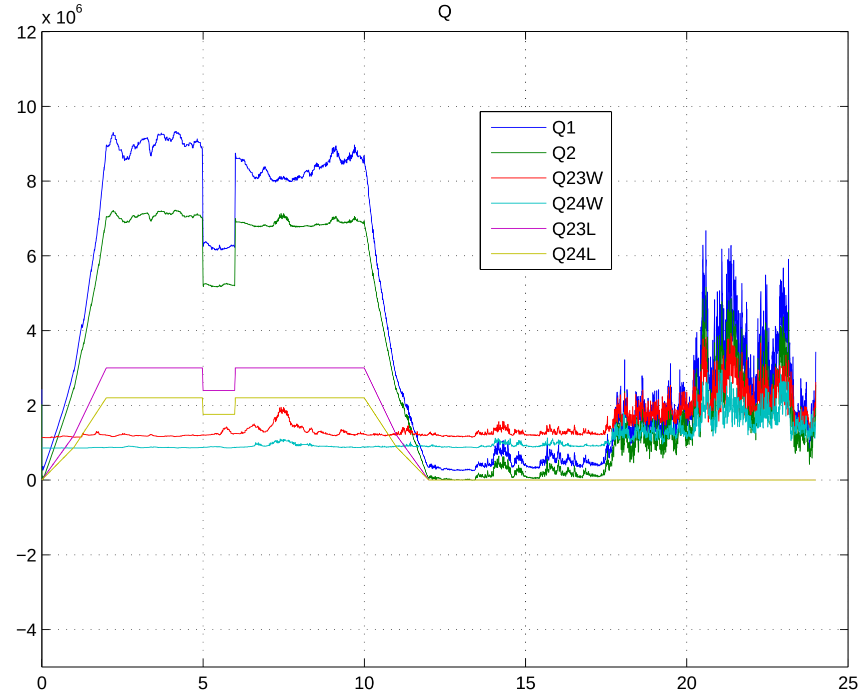


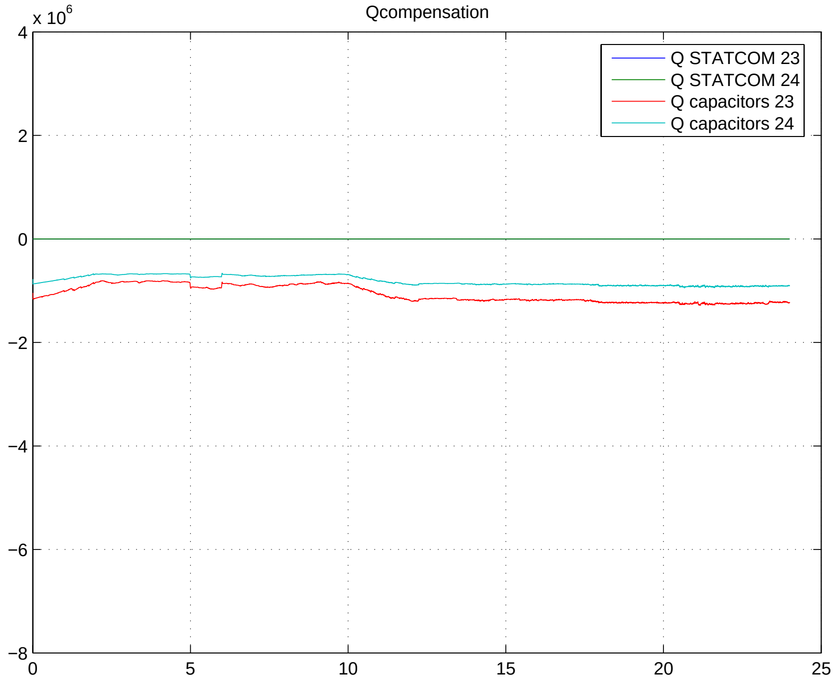
CASE 6: SCIG, fixed C, line

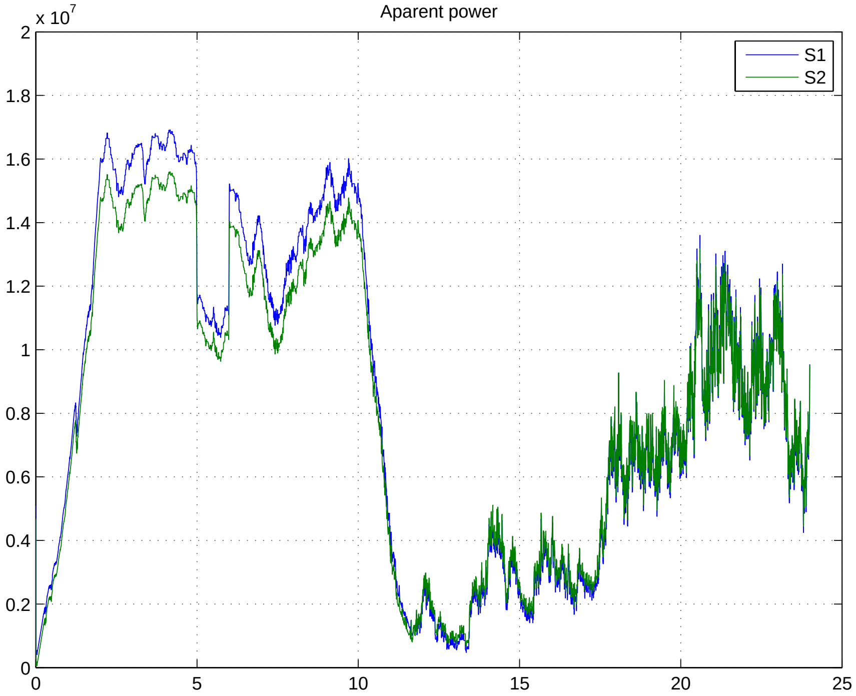




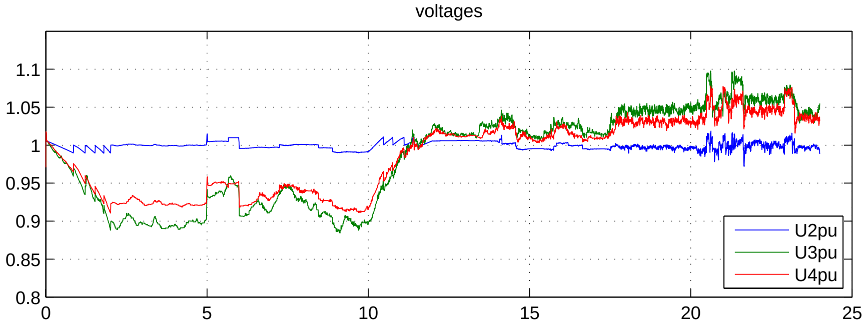

P
x 10^7
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25
P1
P2
P23W
P24W
P23L
P24L

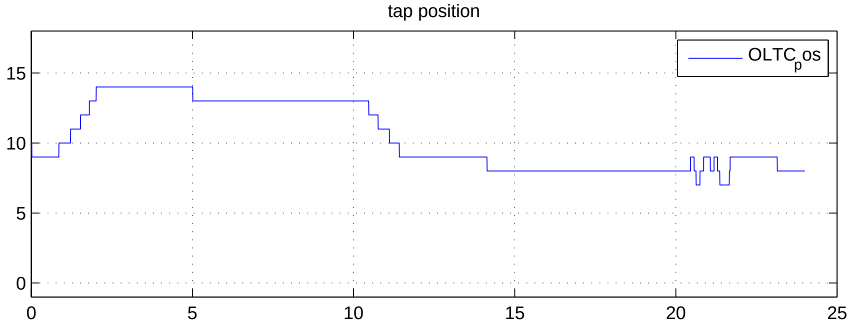

Q
x 10^6
12
10
8
6
4
2
0
−2
−4
0
5
10
15
20
25
Q1
Q2
Q23W
Q24W
Q23L
Q24L

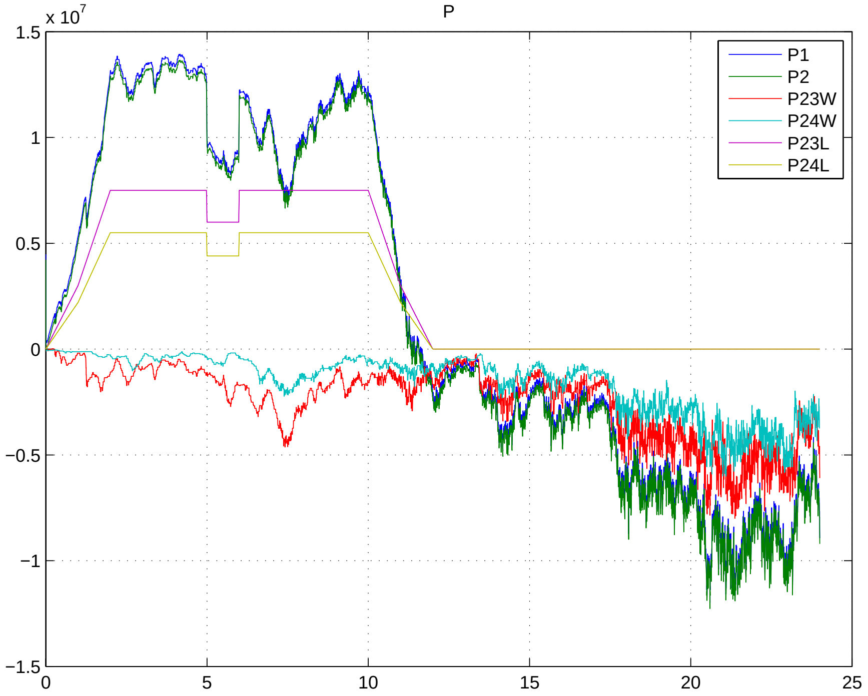

Qcompensation
x 10^6
4
2
0
−2
−4
−6
−8
0
5
10
15
20
25
Q STATCOM 23
Q STATCOM 24
Q capacitors 23
Q capacitors 24

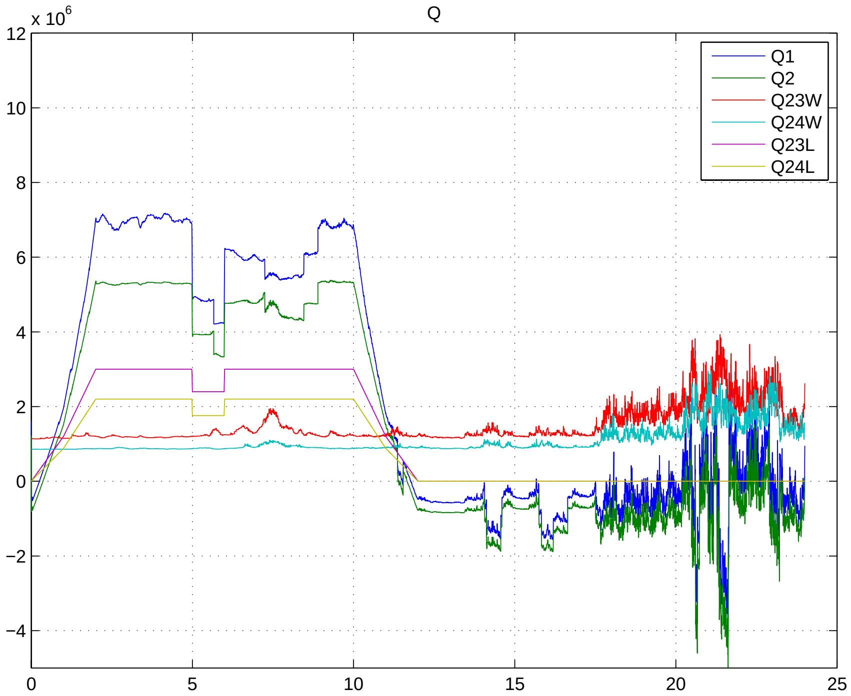

Aparent power
x 10^7
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
S1
S2

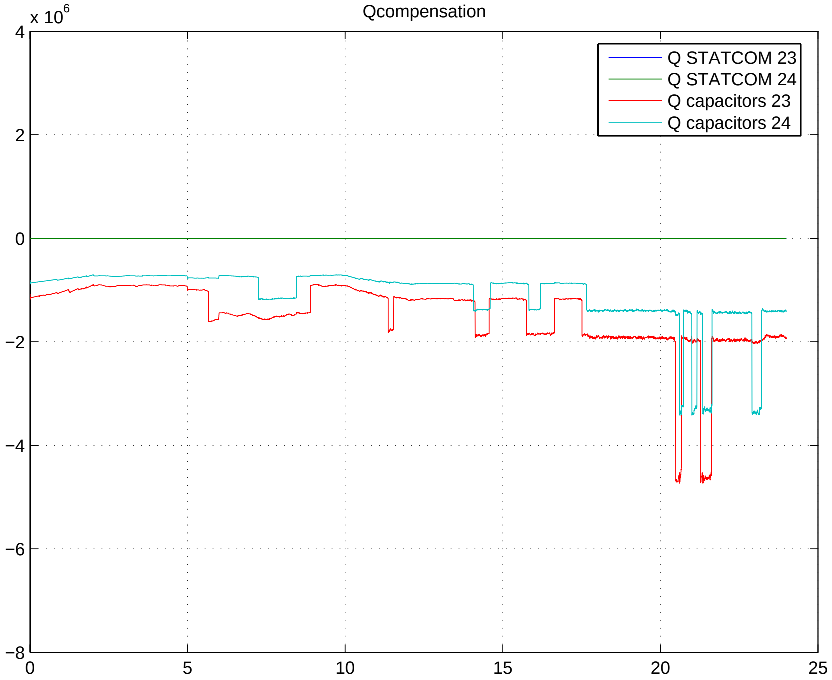
CASE 7: SCIG, switched C, cable

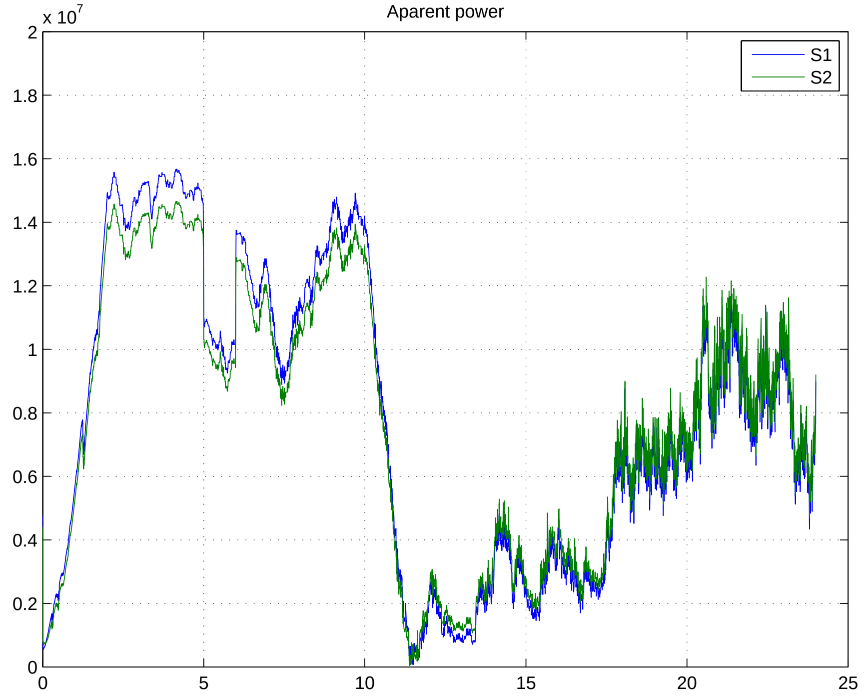




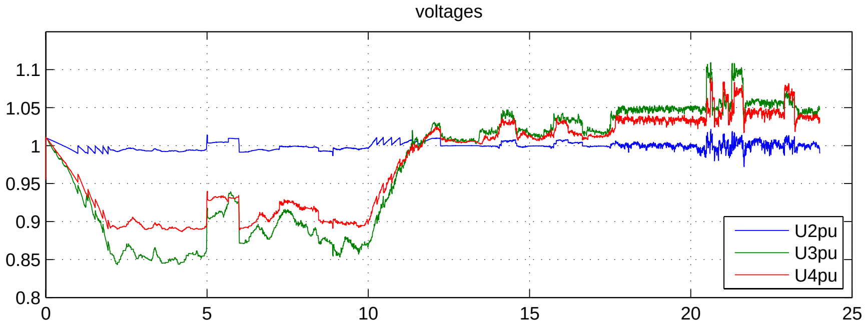


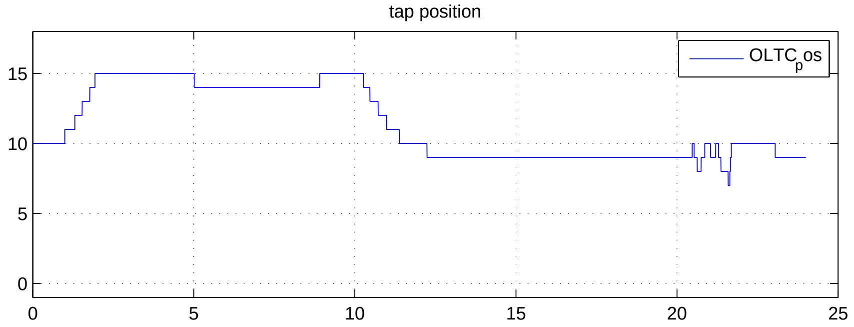

Q
x 10^6
12
10
8
6
4
2
0
−2
−4
0
5
10
15
20
25
Q1
Q2
Q23W
Q24W
Q23L
Q24L

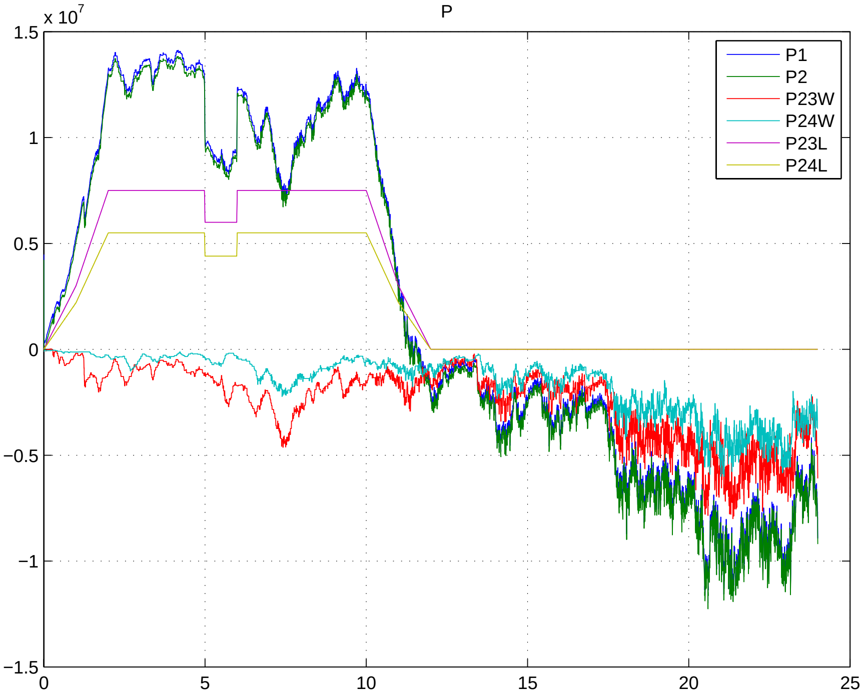

Qcompensation
x 10^6
4
2
0
−2
−4
−6
−8
0
5
10
15
20
25
Q STATCOM 23
Q STATCOM 24
Q capacitors 23
Q capacitors 24

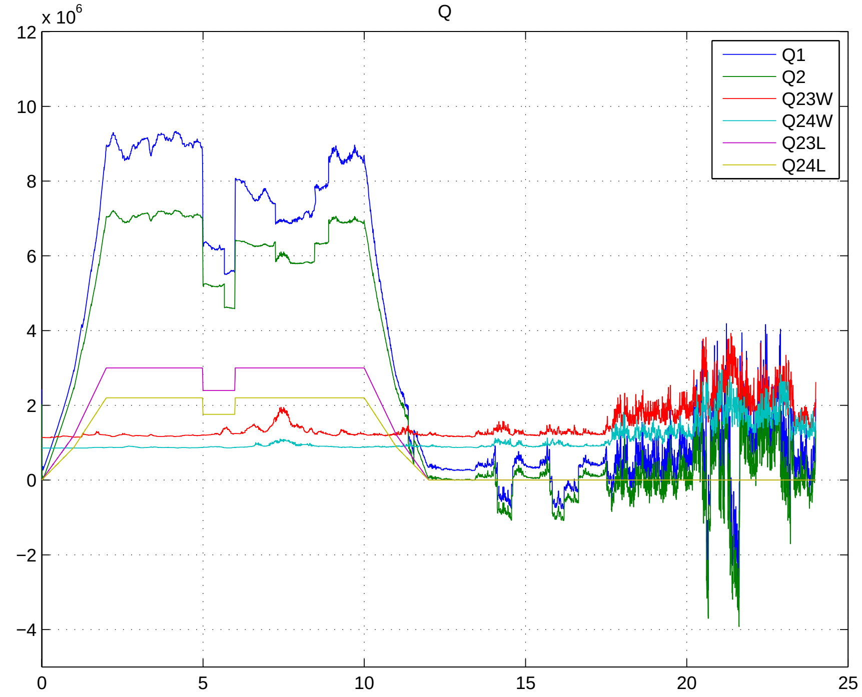


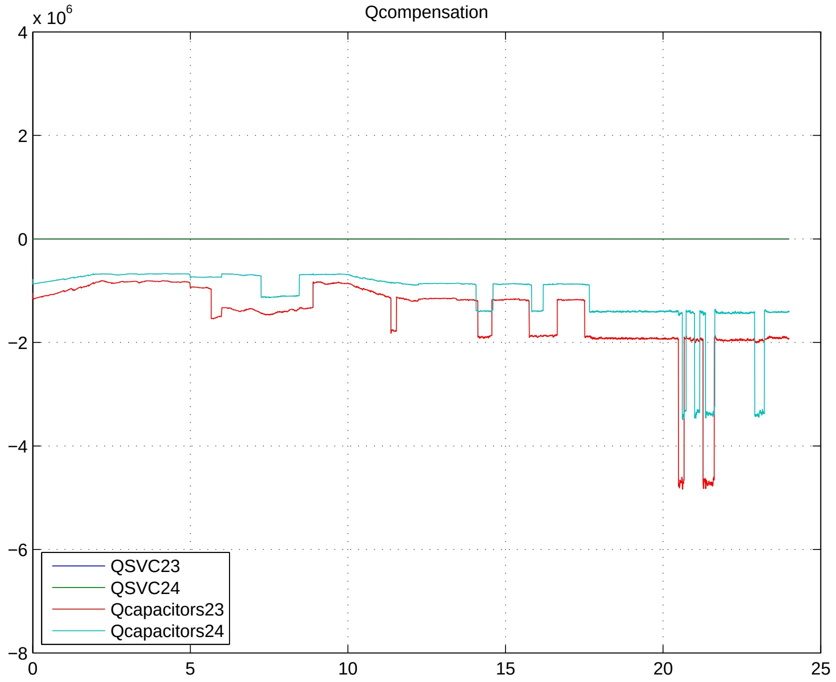
CASE 8: SCIG, switched C, line

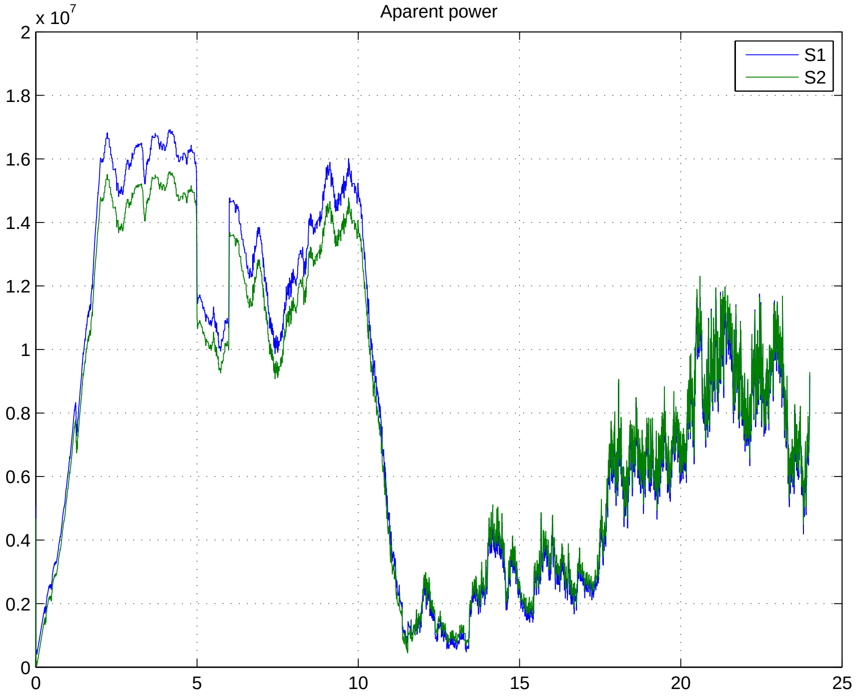




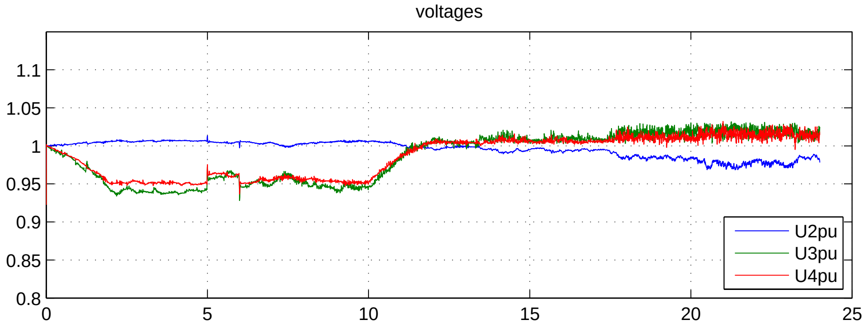

P
x 10^7
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25
P1
P2
P23W
P24W
P23L
P24L

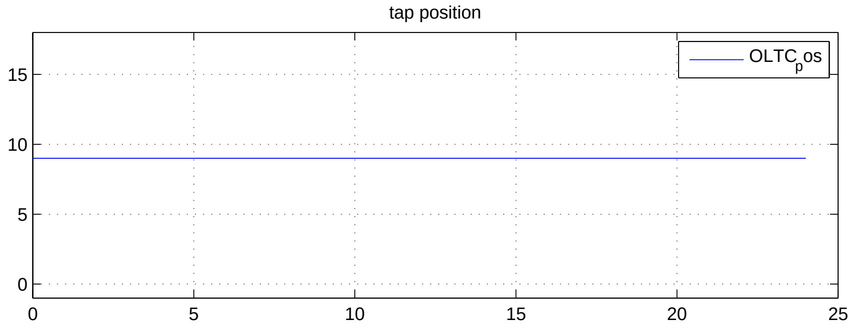

Q
x 10^6
12
10
8
6
4
2
0
−2
−4
0
5
10
15
20
25
Q1
Q2
Q23W
Q24W
Q23L
Q24L

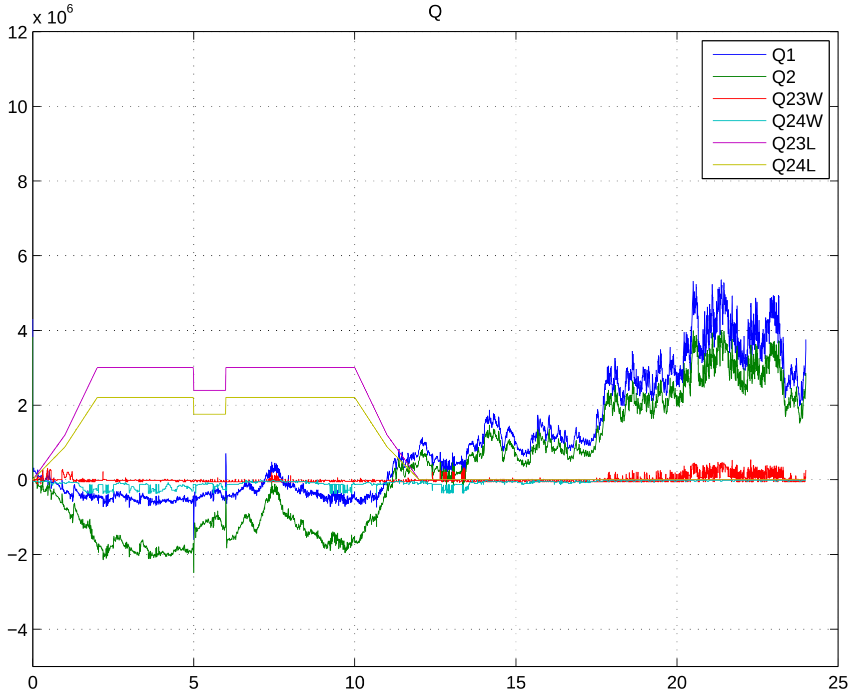

Qcompensation
x 10^6
4
2
0
−2
−4
−6
−8
0
5
10
15
20
25
QSVC23
QSVC24
Qcapacitors23
Qcapacitors24

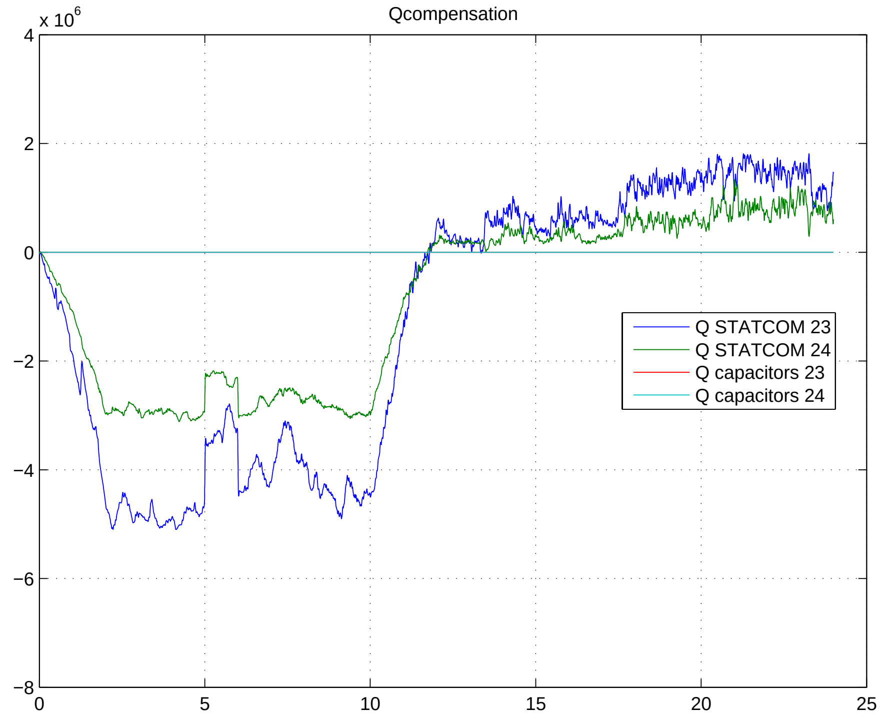

Aparent power
x 10^7
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
S1
S2

CASE 9: no OLTC, line, DFIG, STATCOM

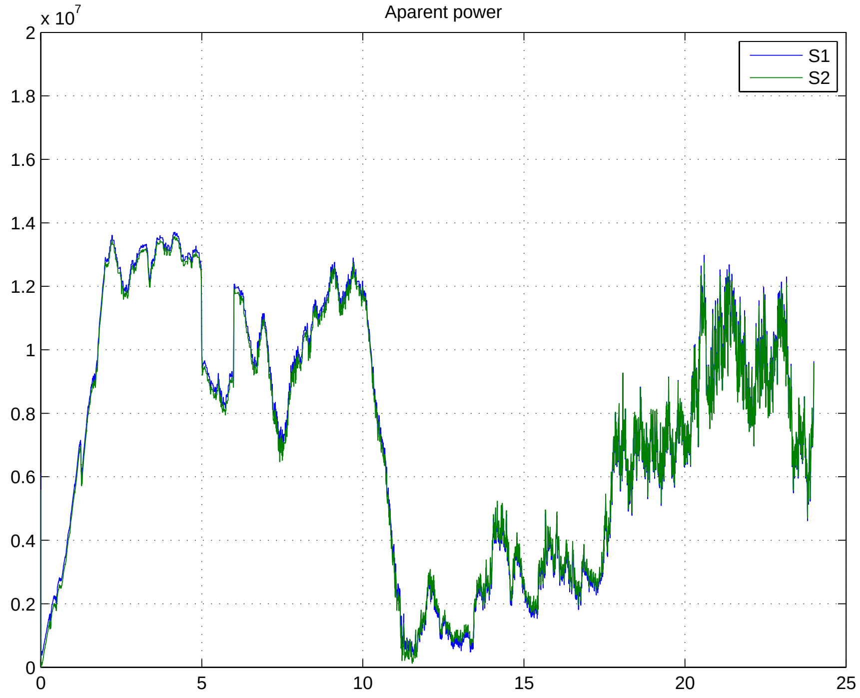








Qcompensation
x 10^6
4
2
0
−2
−4
−6
−8
0
5
10
15
20
25
Q STATCOM 23
Q STATCOM 24
Q capacitors 23
Q capacitors 24



Aparent power
x 10^7
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
S1
S2

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