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Integration of Wind Energy Converters into an Existing Distribution Grid

Maximum of Wind Energy Converters for a 40 kV Substation

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Abstract

In this thesis investigations are done to find how much wind power that can be integrated into an existing distribution grid. Steady state voltage changes, flicker emission and thermal limits of lines and transformers are considered as the limiting factors during these investigations. For these investigations, the distribution grid is modelled in the power system simulation software PSS/E®. The modelling is done on the basis of information provided by the relevant distribution company. These investigations are done for different combinations of wind speed and load conditions.

In this thesis it is found that steady state voltage changes is generally the factor which restricts the amount of wind power that can be connected at a certain point in the grid provided no bottleneck in the transfer capacity. Reactive power control strategy can be used to integrate more wind power in the grid if the voltage limits are the deciding factor. In the case of thermal limits of lines or transformer being the deciding factor, it doesn't work. Fault level and consideration of the number of turbines for a given amount of wind power affects the flicker emission value. The flicker emission level doesn't seem to be a limiting factor when modern variable speed turbines are installed into an existing grid.

The results given in this master's thesis can be used to determine the ratings of the wind turbines which can be connected at a certain point while maintaining the voltage limits and the power quality in the grid.

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Contents

Introduction

Wind energy is one of the renewable energy resources which have the potential to contribute significantly towards electric power generation in the coming years. The conversion of wind energy into electrical energy is not a simple process and to make this conversion successful, information ranging from aerodynamic design of turbine blades to different electrical aspects is required. Wind turbines must be connected to the grid so that the generated power can be supplied to load. In today's power systems, the power companies are bound to deliver power to the consumers within acceptable voltage limits and good power quality. The issues like steady state voltage changes and power quality have to be addressed before a connection of wind turbines is allowed so that it can be assured that connection of a certain amount of wind power to the grid is not going to deteriorate the network conditions.

[6] shows that the X/R ratio has more influence on the steady state voltage changes by the fixed speed turbines as compared to the variable speed turbines due to the presence of power electronic converters. [9] shows that the flicker emission increases with the increase in wind speed for both fixed and variable speed wind turbines however [6] shows that the power electronic converters can reduce the flicker emission from variable speed wind turbines.

The purpose of this master thesis is to point out the factors which limit the amount of wind power at a certain place in the grid, understanding the methods of calculation of relative parameters and analysis to find how much wind power can be integrated into an existing grid through a case study.

There are two sites under consideration. Both sites are different in terms of power collection scheme from wind turbines. PSS/E® is used to do the load flow calculations using models for components of power systems.

This thesis is divided into four main parts. The first part contains basic theory including different types of wind turbine generators, power systems and factors affecting wind power integration. The second part also contains some theory regarding modelling of different power system components. The third and fourth part contains individual analysis of load flow and flicker calculations for both sites.

The contribution of new wind energy converters in case of faults has been investigated for both sites in another master thesis titled 'Fault Analysis and Investigation of Voltage Dips for Wind Energy Integration into an Existing Distribution Network'.

Chapter 1

Wind Energy and Power System

1.1 Wind Generating Systems

There are different types of generators, which are in use by the wind turbines to generate electricity. These generators can be classified by different aspects such as with respect to speed i.e. constant speed or variable speed, with respect to working principle i.e. with or without a power electronic converter. Figure 1.1 includes all these aspects while classifying different generators used by the wind turbines.

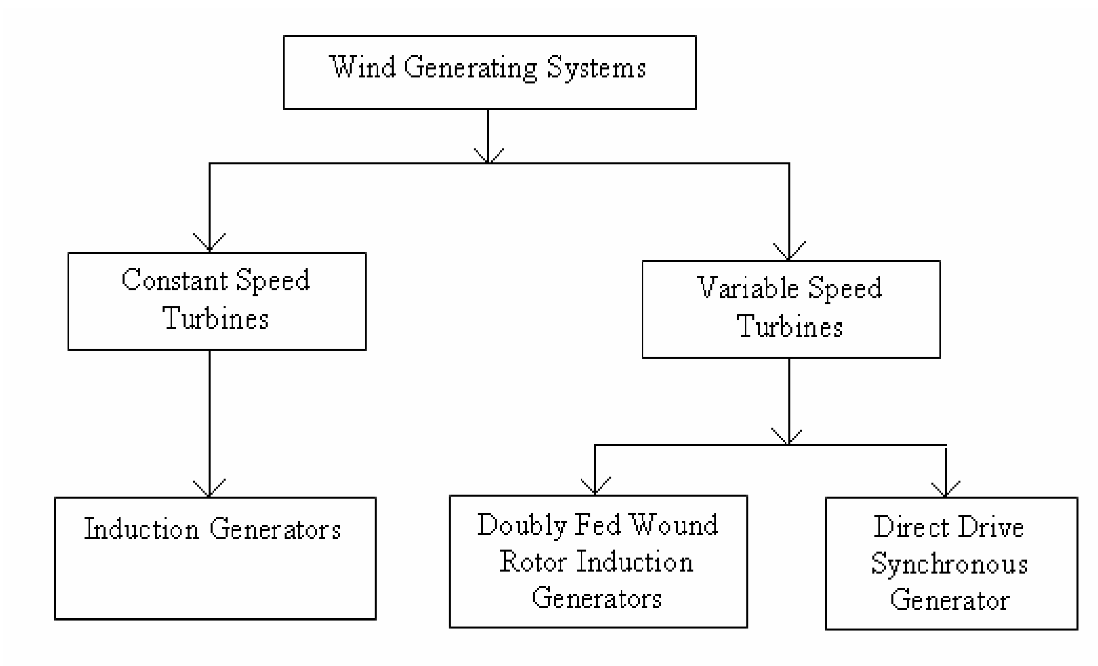

Figure 1.1-Classification of generators used in wind generating systems

1.1.1 Constant Speed Turbines

Constant speed wind turbines are generally stall regulated. In stall regulation, the blades of the turbine are designed in such a manner that at low wind speeds, the blades operate at a high aerodynamic efficiency. As the wind speed increases, the angle between the cross section of wind blade and the air flow increases. This reduces the rotor efficiency and limits the output power [1].

1.1.1.1 Generator for Constant Speed Wind Turbine

Constant speed turbines use induction machines as generators. These induction generators are directly connected to the grid. The excitation to induction generators is provided to the stator windings and the grid frequency decides the synchronous speed of rotation. From the fundamentals of electric machinery, it is known that the speed of the rotating magnetic field in the stator depends on the number of poles and applied frequency and if the rotor of induction machine is rotated with the speed higher than the synchronous speed (the speed of stator rotating magnetic field), then electric power is supplied to the grid by the induction machine.

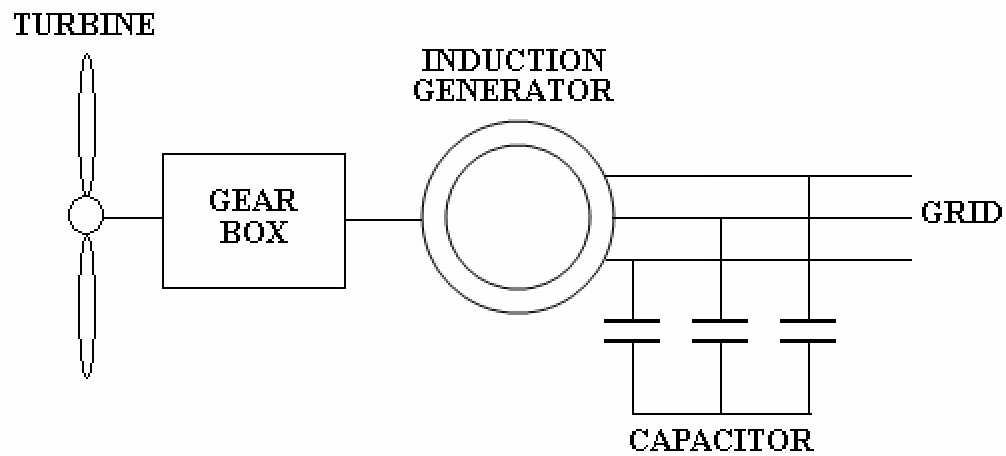

Figure 1.2-Fixed speed induction generator

A gearbox with a high ratio is provided between the wind turbine and the rotor to raise the speed of the rotor in order to make use of the induction machine as generator.

Both active and reactive power of the induction machines are functions of slip. The slip can be defined as the difference between the synchronous speed and rotor speed. Mathematically slip can be expressed as:

$$s = \frac{\omega_s - \omega_r}{\omega_s} x100\,\% \qquad (1.1)$$

Normally the slip is expressed in percentage. When the slip is negative, the induction machine supplies the active power and operates as a generator. When the slip is positive, the induction machine consumes the active power and it operates as a motor. Reactive power is consumed at both positive and negative slip operation.

Constant speed induction generator has two disadvantages:

1. The induction generator is excited by the grid and consumes reactive power; hence the power factor is less than one and cannot be controlled.
2. The speed cannot be controlled either.

The reactive power demand of induction generators is met by installing capacitors at the terminals of induction generators. The rating of the capacitors is chosen in such a way that the self-excitation of induction generators is avoided.

1.1.2 Variable Speed Wind Turbines

Variable speed induction generators can be stall regulated or pitch regulated. Stall regulated variable speed wind turbine's operation is described as follows. At lower wind speeds, the turbine rotates with the variable speed to maintain optimum power coefficient. This is considered as the constant power coefficient operation. As the wind speed reaches the rated wind speed, stall regulation starts as described above. As the wind speed increases, the power increases and this mode of operation is known as the constant speed operation. When the generated power reaches its predetermined value (rated power), then the speed of rotor is regulated to limit the power of rotor and this is called the constant power operation. Two advantages of using variable rotor speed are better power quality and ability to produce or absorb reactive power (regulation of power factor).

During low wind speeds, a pitch regulated variable speed wind turbine rotates with the variable speed and fixed pitch, to have an optimal tip speed ratio. Once the power reaches its rated value, the pitch is controlled in a manner to reduce the aerodynamic efficiency by reducing the rotor speed.

1.1.2.1 Doubly Fed Wound Rotor Induction Motor

The induction machine used for power generation is of a wound type construction. It has two windings, one in the stator and one in the rotor (squirrel cage rotor has copper bars instead of windings on it). The stator windings are connected directly to the network. The rotor windings are also connected to the grid via a frequency converter by means of slip rings. When the stator is excited, a rotating magnetic field is produced. The speed of the rotating magnetic field depends on the system frequency and the number of poles.

The mechanical power captured from the wind is converted into electrical power. This electrical power is fed into the grid by both stator and rotor windings. Since the power in the rotor circuit is at a different frequency, which differs from the network frequency and is a function of generator slip. The output from rotor circuit is first converted into a dc quantity and again converted into an ac quantity with grid frequency.

A gearbox is provided between the rotor and the generator to adopt the speed of the induction generator.

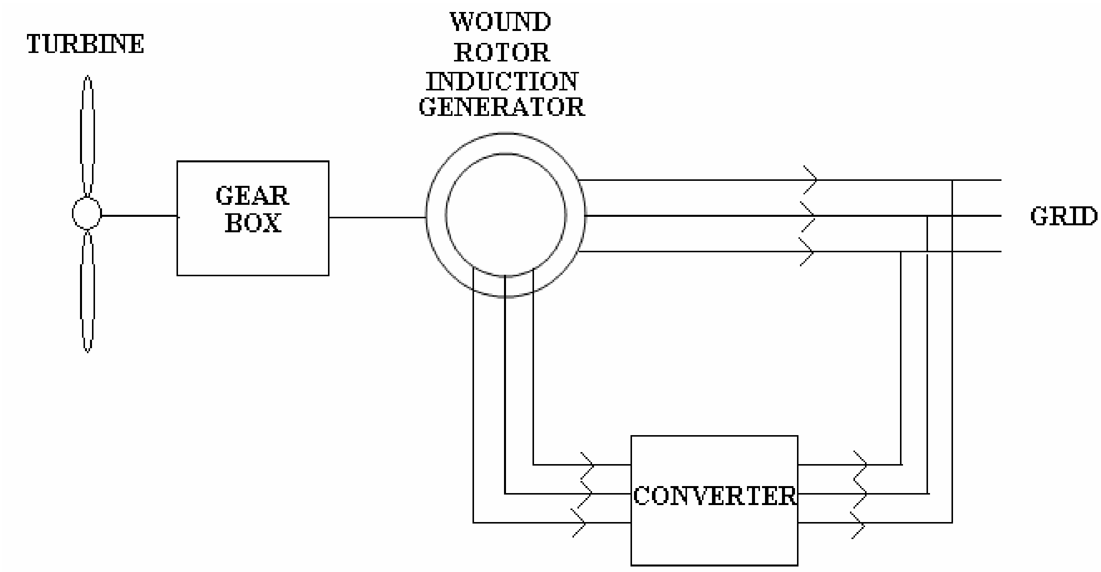

Figure 1.3-Variable speed doubly fed induction generator

Since the converter is placed in between grid and rotor circuit, the power rating of the converter is only around 20-30% of the total power which gives this system a low investment cost and a high efficiency [2].

1.1.2.2 Direct Drive Synchronous Generator

Direct drive generators used in wind turbines are essentially synchronous machines of a special design [1]. The difference between a normal synchronous generator and a synchronous generator used by the wind turbines lay within number of poles. Since synchronous speed is inversely proportional to the number of poles in a machine, the number of poles in these synchronous generators is enough to rotate the generator with the same speed as that of the wind turbine. This design eliminates the need of a gearbox in between the wind turbine and the generator. The stator of the synchronous generator is connected to the power grid through a frequency converter. This frequency converter does the conversion from variable frequency to fixed grid frequency. At wind speed higher than the rated speed, the power is regulated using pitch regulation. One of the disadvantages of these generators is that their size is relatively large due the large number of poles whereas the main advantage of these generators is the flexibility to operate at a power factor which can be lagging, leading or unity.

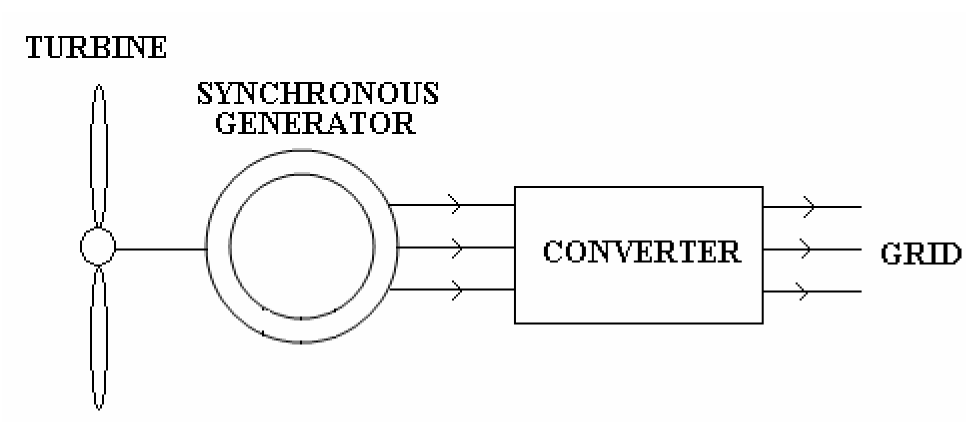

Figure 1.4-Variable speed synchronous generator

1.2 Power System Stability

A power system comprises of generators, transformers, busbars, transmission lines and loads (devices which consume electrical energy). The basic aim of a power system is to deliver the electric power to the customers, fulfilling the power quality demands. It is assured that these demands are met in an economic manner and that the reliability is maintained. Generally a power system is quite large with thousands of buses and transmission lines. The power system is subjected to variety of severe conditions ranging from the faults (may be due to lightning or insulation failures) to the sudden changes in the load conditions.

The ability of a power system or a part of a power system to maintain the voltages under normal conditions as well as during a disturbance is called power system stability.

Power system stability can be further classified as angle stability and voltage stability.
When the active power demand increases in a power system, then these demands are accommodated or met by the variations in the angular momentum of synchronous generators, feeding the grid. These variations in angular momentum are generally taken into account by the difference of the angle between the synchronous field and the rotor field. An increase in the active power demand increases this angle and this increase in the angle tends to reduce the synchronous machine speed. If the active power demand becomes greater than the machine ratings, then the generator can be pulled out of synchronism. The ability of a power system to maintain synchronism during normal conditions as well as after a fault or sudden rise in the active power demand is known as angle stability.

From the knowledge of power systems, it is known that the flow of reactive power between two buses depends on the difference in magnitude of voltages at the buses. When the reactive power demand in a power system increases beyond the capability of generation sources (synchronous machines, capacitor banks), then it becomes difficult to keep the voltage profile within acceptable limits and the power system can become unstable. If after occurrence of a fault, the voltages stay equal to or close to the magnitude of voltages before the fault, then the power system is called voltage stable.

Voltage stability can be defined as ‘‘ability of a power system to maintain steady acceptable voltages at all buses in the system at normal operating conditions and after being subjected to a disturbance’’[3].

Overloading, generators reactive power limits, capacity of reactive power compensation devices (capacitor banks, SVC etc), action of control devices and faults are some factors, which contribute towards the voltage instability in a power system.

It is not only the severity of disturbance, which matters while discussing the voltage or angle stability, but the duration of disturbance is also important. The time scale of stability criteria is divided into short term and long-term time scale.

Angle stability is mainly associated with the synchronous generators and change in the angle between synchronous field and rotor field (due to any disturbance) can be either in

the form of undamped oscillations or may be in the form of gradual acceleration leading towards the loss of synchronisation. The undamped oscillations are often present due to small disturbances and stays for very short duration. This type of stability is referred as steady state or small signal stability, whereas later type of stability occurs mostly due to the large disturbances and referred as transient stability. Both small signal and transient stability fall into short-term time scale and remains on for a few seconds.

Long-term angle stability is also called frequency stability and it follows short-term dynamics after a large disturbance. Frequency stability is mainly about active power balance between the generators and the loads and relative transients last typically for several minutes [7].

Voltage stability is mainly considered as a load driven phenomena since it is the load dynamics, which decide the duration of voltage stability. Short-term voltage stability is mainly concerned with the loads, which are able to restore their consumed power with in time frame, ranging in seconds e.g. induction motors, SVC etc [7].

The need for the analysis of long-term voltage stability arises mainly due to following factors:

- Load recovery due to action of OLTC
- Delayed shunt compensation switching (capacitor banks)
- Load shedding
- Outage of any major generator

Even though the duration of long-term voltage stability and angle stability is more or less same, the important aspect for voltage stability analysis is the need of detailed network representation.

Another important term which often appears when considering system stability is the voltage collapse. It can be defined as a phenomenon, which occurs after voltage instability when system operator actions and automatic system controls fail to prevent the considerable decrease in the voltage profile of the system [8].

A network can be considered more vulnerable or approaching towards the voltage collapse, on the basis of following indications:

- Low voltage profiles
- Heavy reactive power flows
- Inadequate reactive power support
- Heavily loaded systems

Voltage collapse may even lead to blackout, which leaves a number of customers without electric power supply and it may take quite a while before the system can be restored.

Even though the magnitude of voltages in a network is generally attributed towards flow of reactive power, it is not the only factor affecting voltage stability but the active power affects this phenomenon equally.

1.3 Factors Affecting the Capacity of Wind Generation

Wind generation is only possible in those areas, which are rich in wind resources. These areas can be situated either offshore or onshore. Such locations are often remote and open spaces, away from the load centres. The electric network in these areas is designed to supply to the loads and may or may not accommodate generation. This results in that the network may be weak sometimes and imposes some restrictions on the capacity of generation that can be integrated through wind energy converters. These constraints are given as follows:

- Steady state voltage variations
- Reactive power and power factor
- Flicker
- Thermal capacity of lines and other components

1.3.1 Steady State Voltage Variation

Wind turbines are sources of fluctuating power and it is essential to ensure that the grid is capable of staying within the operational limits of frequency and voltage for all conditions of power production and load power consumption [4].

How does this fluctuating production of power affect the voltage in the network? This can be understood from an example given as follows:

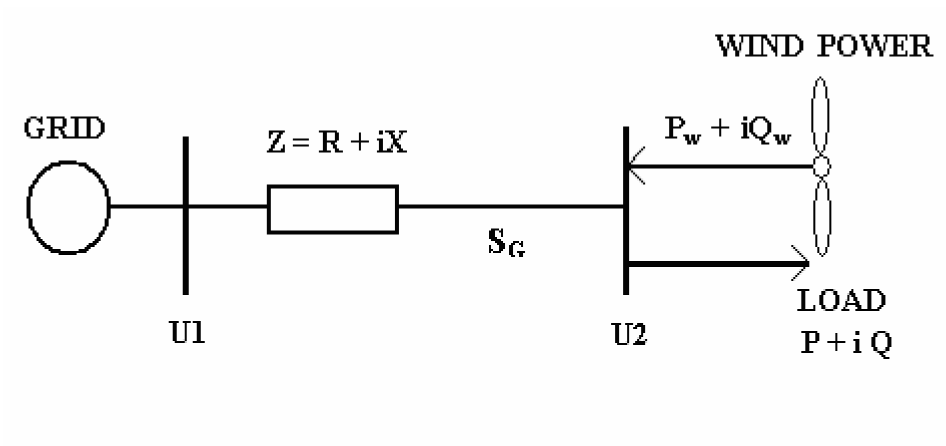

Figure 1.5-Simple arrangement with a wind turbine on grid describing the effect of fluctuating power on voltage.

Figure 1.5 shows a simple arrangement with a wind turbine connected to a bus, which is connected to the grid through an impedance Z. The load which is attached at bus 2 is P + iQ and the wind turbine is injecting both the active and the reactive power, $P_w + iQ_w$ to bus 2. The voltage at bus 1 is denoted by U1 and the voltage at bus 2 is denoted by U2. Bus 1 is an infinite bus and thus voltage U1 is constant.

Applying KVL on circuit shown in Figure 1, we get:

$$U_1 = U_2 + \sqrt{3} I \ Z \tag{1.2}$$

When the power production from a wind turbine is enough to met the load demand, there will be no current drawn from the grid i.e. I = 0. Applying current I equal to zero in Equation (1.2), we get:

$$U_1 = U_2 \tag{1.3}$$

When the power production from the wind turbine is more than what is demanded by the load or the load has decreased due to any reason then the voltage at bus 2 will be greater then the voltage at bus1.

$$U_1 < U_2 \tag{1.4}$$

When the power production from the wind turbine is low, then the difference between the power generated by the wind turbine and the load will be supplied by the grid. The current drawn from the grid, will pass through the impedance Z and the resulting voltage at bus 2 i.e. U_2 will be less than the voltage $U_{1.}$

$$U_1 > U_2 \tag{1.5}$$

In the literature regarding integration of wind turbines in the power system, the existing grid is often classified as weak or strong. Before looking at the effect of this 'weakness' or 'strongness' of grid on the installation of wind power, lets try to find the criteria, which makes a certain point of grid, fall into the specific categories of strong or weak.

There is not a clear and accurate method for distinguishing between a strong and a weak grid, these terms are relative, and that relativity has to do with the point of the grid that we are analyzing and the purpose of the grid assessment in that point [5]. Generally strength of the grid at a certain point is assessed by the available short circuit power or fault level, or being more precise by the short circuit ratio. In case of wind power integration, short circuit ratio is calculated by dividing available fault level at the point where the wind turbine is connected, by the power rating of the wind turbine. The point of connection of wind turbine with existing system is called 'Point of Common Coupling' (PCC). Generally if the value of the short circuit ratio is equal to or above 20, then the system is considered as strong whereas the value of short circuit ratio below 20 represents a weak grid (the value of this parameter is subjected to change depending upon the different standards in different systems) [5].

To see how the strength of grid at 'PCC' affects the wind power installed capacity, let's consider Figure 1.1 again. Let's say S_G is power or fault level available at bus 2. This power can be calculated as:

$$S_G = \frac{U_1^2}{Z} \tag{1.6}$$

As it is described earlier that the short circuit ratio is directly proportional to the fault level and relation given in (1.5) shows that fault level is inversely proportional to the impedance between source and load. If the impedance is larger, than fault level will be less, so will be the short circuit ratio and the grid will be considered weaker. This will restrict the possible installation of the wind turbines because wind turbines are source of fluctuating power and a sudden change in the power output from the wind turbine will cause the flow of current through impedance Z. Voltage fluctuation will take place and it will be severe in case of larger size of wind turbine. The appropriate size of the wind turbine will be such that the value of the short circuit ratio must be around 20.

1.3.2 Reactive Power and Power Factor

In a power system the load is mostly inductive and it leads to the consumption of reactive power. These loads are connected to the generation sources by the transmission and distribution lines and the transformers. These components possess considerable inductive reactance and some resistance. It is often undesirable to transport all reactive power demand through these components mainly due to two reasons:

- Due to increased power losses
- Due to high voltage regulation

The most common way to meet with this reactive power demand is to use the shunt capacitors. These capacitors are connected (in the form of capacitor banks) at the buses where the load is connected and their values is chosen so that they can provide the most of the reactive power demand by the load and keep the power factor near to unity. The power factor is defined as the ratio between active power and apparent power.

$$p.f = \frac{P}{S} \tag{1.7}$$

It is a unit less quantity and it describes how much apparent power that is converted into active power. The values range between 0 and 1.

The effect of load power factor and the presence of inductive reactance in the lines and transformer is different for different types of wind power generators.

It is known that a directly connected induction generator draws reactive power from the grid and the consumption of reactive power increases with the active power production. The voltage at the bus is inversely proportional to the reactive power demand. To keep the voltage within the specified limits and to minimize the power losses, generally the capacitors are installed at the terminals of induction generator. The value of capacitors is selected in such a manner that it can provide the no load reactive power to the induction generator. The installation of capacitors reduces the impact of X/R ratio of line on the voltage. It should be noted that if the wind turbines are connected to the grid by the cables then these cables must be considered as producers of reactive power (due to presence of stray capacitance).

Synchronous generators are mostly connected to the network by means of a frequency converter. The converter enables the synchronous generator to operate with a power factor which is either lagging, leading or one and these generators can keep the voltage within limits either by providing the reactive power (in case of change in the load power factor) or by absorbing the reactive power (in case of lightly loaded line) at the expense of power losses. This type of generator is better as compared to the induction generator with switched capacitor banks in the sense that the control of reactive power is smooth [6].

1.3.3 Flicker

One aim of the power system is to provide the power according to customer demand when it is needed but also in a form (i.e. waveform and frequency), which is either equal or close to the specified standard. This requirement is often referred as ‘Power Quality’.

Flicker can be described as a power quality concern regarding the unsteadiness in RMS value of voltage. It can be defined as a physiological perception of modulation in the intensity of light. A dimensionless parameter called ‘short time severity index, P_{st}’ is normally used to assess the annoyance to voltage fluctuation. Its value is found to be most sensitive around 9 Hz (i.e. 8.8 Hz, being precise) where a voltage fluctuation of 0.25% will give a P_{st} value of 1 [6].

The problem of flicker is associated with both fixed and variable speed turbines. It increases with the increase in wind speed. However, [9] shows that for fixed speed turbines flicker increases at increasing wind speeds whereas for variable speed turbines, the flicker level decreases at rated wind speed.

1.3.4 Thermal Capacity of Lines and Other Components

The thermal capacity of lines and transformers is a limiting factor for all power generation installations. Normally the generating voltages of wind turbines are below 1000V and in European countries the typical voltage level is 690 V. The voltage is stepped up to distribution level voltage by a transformer and the power rating of this transformer along with the rating of line decides the rating of wind turbines. This factor varies from place to place since the power flow varies according to local conditions.

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Chapter 2

Power System Components

2.1 Introduction

Whenever we need to find the voltage stability in a power system or a part of a power system, we have to calculate the power flows and see the effect of changing loads and faults by performing the dynamic simulations and fault analysis respectively. Normally, it is done by modelling the power system in software (e.g. SimPow, Digisilent, PSS/E etc). This is because a power system generally consists of many components (generators, transformers, buses, transmission lines, capacitor banks, loads and sometimes wind turbines like in this case) and the calculation of the voltages while taking the effect of all these components is an iterative process and is almost impossible to do manually. While modelling these components, it is necessary to make assumptions, which can illustrate the effect of these components on system variables as true as possible. In the following section, some theory regarding the power system components is given which we have used to model the power system under study.

2.2 Load

The term load can have different meanings in the power system engineering as defined by the IEEE Task Force on Load Representation for Dynamic Performance [1]:

a. A device, connected to a power system that consumes power (the term 'load device' can be used to be more clear).
b. The total power (active and/or reactive) consumed by all the devices connected to a power system (the term 'system load' can be used to be more clear).
c. A portion of the system that is not explicitly represented in a system model, but is rather treated as if it were a single power-consuming device connected to a bus in the system model (the term 'bus load' can be used to be clearer).
d. The power output of a generator or a generating plant (the term 'generator or plant load can be used to be more clear).

Other commonly used terms in relation to the loads are given below.

2.2.1 Load Component

A load component is the aggregate equivalent of all the devices of a specific or similar type e.g. water heater, room air conditioner, fluorescent lighting.

2.2.2 Load Class

A load class is a category of load such as residential, commercial or industrial. For load modelling purposes it is useful to the group loads into several classes where each class has similar load composition and load characteristics.

2.2.3 Load Composition

The fractional composition of the load by the load components. This term may be applied to the bus load or to a specific load class.

2.2.4 Load Class Mix

The fractional composition of the bus load by the load classes.

2.2.5 Load Characteristic

A set of parameters such as the power factor, variation of power with respect to voltage etc. that characterize the behaviour of a specified load. This term may be applied to a specific load device, a load component, a load class or the total bus load.

2.2.6 Load Model

A load model is a mathematical representation of the relationship between a bus voltage (magnitude and frequency) and the power (active and reactive) or current flowing into the bus load.

2.2.7 Types of Load Model

A load model may be time independent (static) or time dependent (dynamic) or a combination having a static and a dynamic part. Depending on the type and depth of study being conducted, an appropriate model is to be chosen.

2.2.7.1 Static Load Model

It gives the active and reactive power at an instant in terms of the voltage and frequency at the same instant. Static load models are sometimes used as an approximation for dynamic studies also. The different static load models are presented next.

a) Exponential model

It is a frequency independent model. The exponential model is of the form given below

$$P = P_0\left(\frac{V}{V_0}\right)^{\alpha} \tag{2.1}$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{\beta} \tag{2.2}$$

Where,

P_0 and Q_0 are the active and reactive power respectively at rated voltage V_0
P and Q are the active and reactive power respectively at voltage V
α and β are the sensitivity to voltage of active and reactive power

By assigning a value of 0, 1 and 2 to the sensitivity a constant power, a constant current or a constant impedance load is obtained. These special cases of the exponential load model are described below

A load for which the power (active or reactive) is independent of the voltage magnitude is a constant power load.
A load for which the power (active or reactive) varies directly with the voltage magnitude is a constant current load.

A load for which the power (active or reactive) varies as the square of the voltage magnitude is a constant impedance load.

It is to be noted that a load may have different behaviour in the active and reactive power variation depending on the sensitivity to the voltage magnitude variations.

b) Polynomial model

It is also a frequency independent model. The form is

$$P = P_0\left(a_1\left(\frac{V}{V_0}\right)^2 + a_2\left(\frac{V}{V_0}\right) + a_3\right) \tag{2.3}$$

$$Q = Q_0\left(b_1\left(\frac{V}{V_0}\right)^2 + b_2\left(\frac{V}{V_0}\right) + b_3\right) \tag{2.4}$$

Where,
P_0 and Q_0 are the active and reactive power respectively at rated voltage V_0
P and Q are the active and reactive power respectively at voltage V
a_1, a_2, a_3, b_1, b_2, b_3 are contribution factors.

This is also called the ZIP model. The contribution to the overall load behaviour of each part constant impedance Z, constant current I, constant power P is determined by a_1, a_2, a_3 such that a_1+ a_2+ a_3 =1 (similarly for b_1, b_2, b_3 in reactive power Q).

In a constrained model a's and b's are fractions i.e. they have a value from 0 to 1 while in the exact model they can have values greater than 1 and even a negative value, but in both cases the sum should be 1.

c) Frequency dependent model

In order to express the frequency dependence of the load often a frequency factor of the form given as $\left[1 + a_f\left(f - f_0\right)\right]$ is multiplied to the exponential or polynomial model. Here, f is the frequency of the bus voltage, f_0 is the rated frequency and a_f is the frequency sensitivity parameter.

d) Other static load models

Other static load models given in [1] are EPRI LOADSYN and EPRI Extended Transient Mid-term Stability Program (ETMSP), which include the effect of frequency.

2.2.7.2 Dynamic Load Model

It is already stated that the power consumed by the loads, depends on their voltage characteristics. This dependence may be permanent, when the load is purely static, or it may change with time, when the load is dynamic. Since induction motors constitute a considerable part of the load, the dynamic model is often explained by using the induction motor model. Other models have been given by Karlsson [2], by Hill [3], by Pal [4] and Xu and Mansour [5].

The dynamics of various load components (thermostatically controlled radiators) and control mechanisms (on-load tap changers) tend to restore load power, at least to some extent. Karlsson has derived a dynamic load model after a study of measurements done in southern part of Sweden at a voltage level of 10/20 kV [2]. The variations included ramps, steps, sinusoidal variations and pseudo random binary sequence variations (PRBS). In this model the effect of load recovery after a voltage variation is considered. Starting with the often used expression of the load-voltage characteristic $P = P_0 (V/V_0)^{\alpha}$, then deriving α_t and α_s for the transient and steady state characteristics respectively and finally estimating the time constant combining the two extreme characteristics for the load under study, provides a very accurate model for the load power consumption after a voltage reduction.

It is mostly acceptable in the voltage stability studies to exclude the influence of frequency [1]. It is often appropriate in the voltage stability studies to represent the active and reactive power as a function of each other. Active and reactive powers can be related by a given power factor with the power factor angle ϕ if they have the same voltage sensitivity as

$$Q = P.\tan\phi \tag{2.5}$$

For different voltage sensitivity, they can be related using the exponential model as

$$Q = Q_0\left(\frac{P}{P_0}\right)^{\frac{\beta}{\alpha}} \tag{2.6}$$

provided V_0 is same for both P_0 and Q_0.

2.3 Wind Turbine

The generation from the wind turbines depends on the availability and speed of wind, which varies from area to area. Most of the time the locations which are found suitable for generation from the wind turbines are such that the system, responsible for supplying electrical energy is either operating in isolation or relatively weak in that area.

As it is already stated in chapter 1, the wind turbines can carry both synchronous and asynchronous machines as the generators, which can be connected to the grid directly or through a converter.

The factors, which prevent the modelling of wind turbine generators like conventional electrical power generators (e.g. thermal, hydropower or diesel), are given as follows.

- The sources of mechanical energy for conventional generators are such that these quantities can be stored and controlled by applying appropriate methods. The ability to regulate the input makes it easier to control the output of these generators to fulfil the fluctuating demand (with in certain limits). Whereas the driving torque for the wind turbine generators is dependent on the available wind energy.

- The excitation of conventional generators is normally independent of grid supply whereas the excitation of wind turbine generators depends on the construction of generating system. Normally the asynchronous generators draw reactive power from the grid for excitation and the synchronous generators can be excited from permanent magnets or grid supply.

To deal with the fluctuating nature of electrical power output from the wind turbine and ever-changing load demand, the power electronic converters are the most common solution. Power converters are used to modify output voltage and frequency of wind turbine, such that it becomes equal to that of the grid, especially in the variable speed turbines.

Power electronic converters are mainly made up of power semiconductor devices, which can conduct the electricity in only one direction and works primarily as switches. These devices can be controlled or uncontrolled like thyristors and diodes respectively.

The frequency converters used in the wind turbine connection generally employ controlled semi conductive devices. The triggering and commutation devices along with energy storage circuit elements and filters are the other parts of frequency converters, which help to achieve the satisfactory operation.

Frequency converters can be classified as:

- Direct frequency converters
- Indirect frequency converters

As compared to direct frequency converters, the indirect frequency converters have been used predominantly to connect the variable speed wind turbines to the network. Therefore discussion about only the indirect frequency converters is going to follow. Indirect frequency converters can be divided into four parts as shown Figure 2.1.

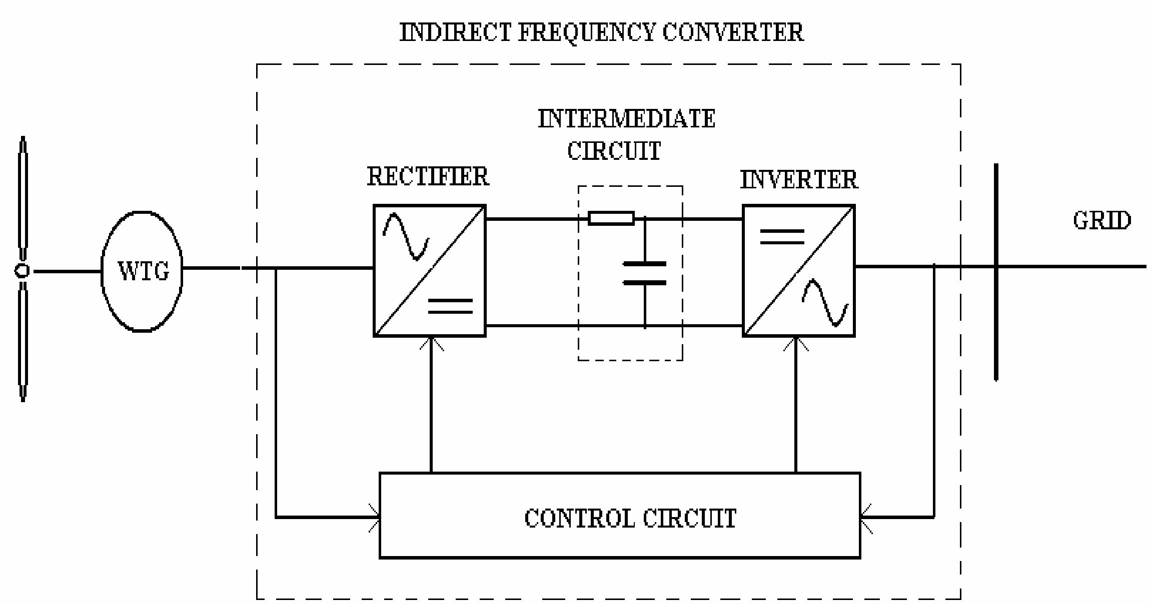

Figure 2.1-Indirect frequency converter

Variable speed wind turbines generate power with different frequencies instead of system frequency. A rectifier converts the generator output voltage and current into dc quantities. This rectifier can again be controlled or uncontrolled. Normally a controlled rectifier with disconnect able valves is used due to its ability to meet the demands regarding wind energy converter control and operation [6].

Intermediate circuit carries the energy storage devices i.e. capacitor or inductor. The presence of the capacitor in the intermediate circuit smoothens the input voltage for inverter, whereas the presence of an inductor maintains the current constant during the commutation process. This part of the frequency converter separates the grid frequency from the WTG frequency.

Inverters are used to convert the dc quantities into ac quantities with waveform and frequency of the output voltage close to the grid voltage. The output of inverter is determined by the supply gird. Self-commutated pulse inverters can regulate the magnitude and the phase angle of the output current within certain limits. The control on the phase angle of the output current allows its leading and lagging relation with the voltage thus making the supply and consumption of reactive power possible.

Control circuit can be considered as the brain of frequency converter and its main function is to issue signals to electronic valves to turn off and turn on. This controller is normally synchronized with the grid voltage.

2.4 Transformer

Transformers are static devices which are used to transfer power from one voltage level to another voltage level by electromagnetic induction. Normally the transformers are provided with the data like the maximum power it can transfer, the voltage levels at both sides of transformer, the active and reactive power losses, off nominal turn ratio, the total number of tap positions, the change in voltage with each change in tap position, magnetising losses and short circuit impedance etc.

Load flow calculations are usually carried in per unit system. In per unit system, a transformer is generally presented by the short circuit impedance. Short circuit impedance of transformer is normally expressed in percentage or per unit values based on its own rating. To express transformer’s short circuit impedance on system base values, these parameters are changed to the actual values and this conversion is done by using transformer’s voltage and MVA rating.

Tap changer is an important part of a transformer. Tap changer is basically a group of contacts, aligned in series. These contacts are connected to some taps on the winding. The function of tap changer is to change the turn ratio of the transformer. Tap changer performs this job either with or without interrupting the power flow, depending on its construction and thus can be classified as Under Load Tap Changer (ULTC) or On Load Tap Changer (OLTC) respectively. Tap changers are mostly situated at the high voltage side of the transformer.

Besides transferring the electrical power from one circuit to another circuit, the transformers are also able to maintain the voltage in certain limits at its secondary winding due to the tap changer action. To model this ability of transformer, information regarding the tap changer is required. This information includes total number of taps available, the regulation in voltage accompanied with change in one tap position and the time taken during one step change. Normally this information is given in the nameplate data of the transformer. The utility companies generally decide the secondary voltage limits beyond which the tap changer must work.

2.5 Cables and Overhead Lines

Power cables and overhead lines are an important part of the electrical power distribution network. These lines connect the load with the distribution grid and substation transformers. The key requirement for these transmission mediums is the power carrying capacity. The capacity must be enough to meet the system demands. The other aspect of concern is the length of the line. The parameters like resistance, inductive reactance and charging of the line is often expressed in per unit length. While planning for a line or feeder, the length is kept such that while carrying rated power, the voltage at the load end shouldn't lie outside the permissible limits. It should be kept in mind that the charging susceptance is only considered when the distribution medium is cable. For the overhead lines, the charging is not significant enough to consider.

The details of power systems component modelling in PSS/E is given in Appendix C.

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[2] D. Karlsson,' *Voltage Stability Simulations Using Detailed Models Based on Field Measurements*', Technical Report No. 230, ISBN 91-7032-725-4 Dept. of Electrical Power Systems, Chalmers University of Technology, 1992.

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[4] M. K. Pal,' *Voltage Stability Conditions Considering Load Characteristics*', IEEE Transactions on Power System, Vol.7, No.1, February 1992.

[5] W. Xu, Y. Mansour,' *Voltage Stability Analysis Using Generic Dynamic Load Models*', IEEE Transaction on Power Systems, Vol.9, No.1, February 1994.

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Chapter 3

Investigation for Hällekis Substation

3.1 Brief Description of the Network

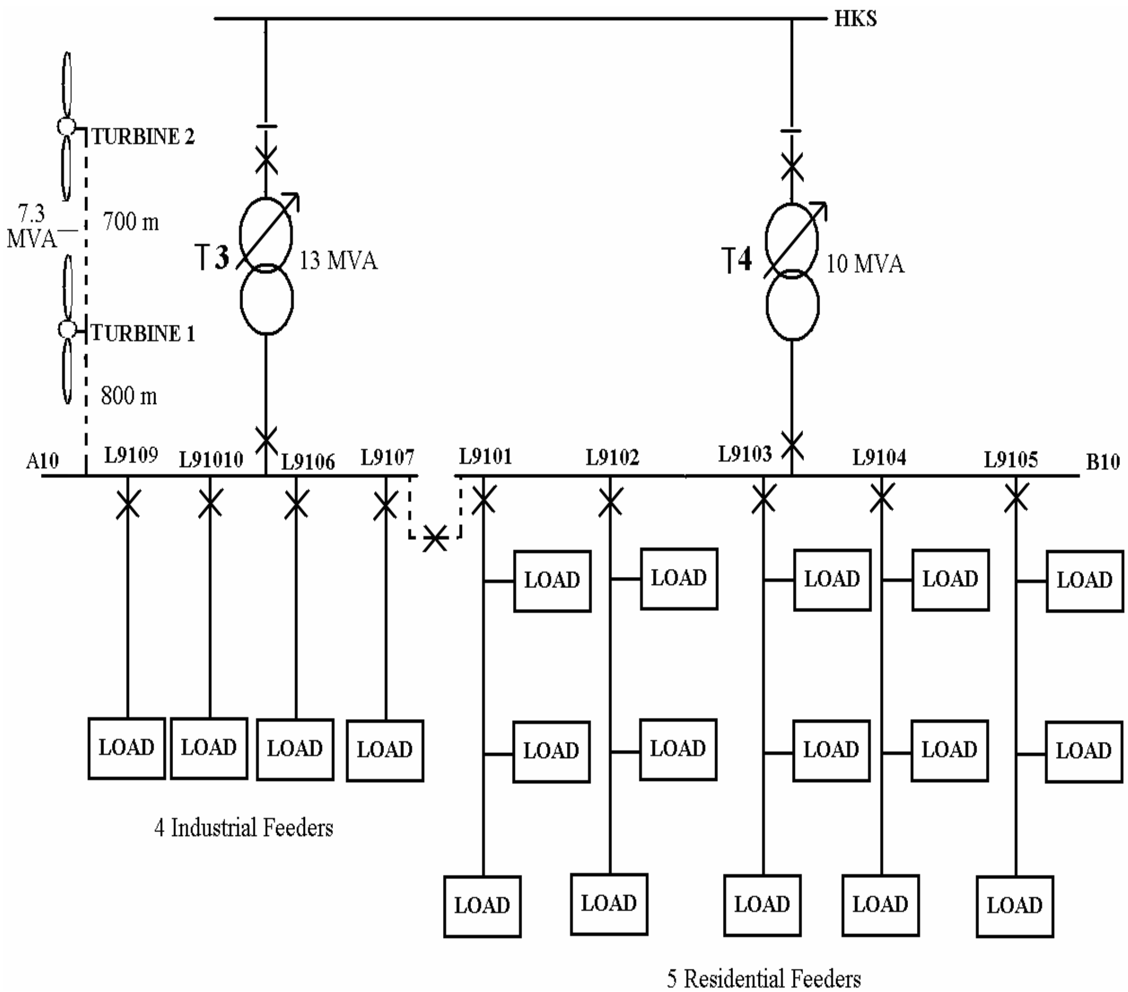

Figure 3.1-Single line diagram of Hällekis

The Single line diagram of the network at Hällekis is shown in Figure 3.1. The distribution network at Hällekis comprises of two transformers which are labelled as ‘T3’ and ‘T4’. Transformer ‘T3’ is rated for 13 MVA whereas the transformer ‘T4’ is rated for 10 MVA. Both transformers are supplied from a single 42 kV bus called ‘HKS’. The fault level available at the 42 kV bus is 279 MVA with the system impedance is R = 0.5 ohms and X = 6.3 ohms.

Both transformers are in operation and feed the separate buses. Transformer ‘T3’ feeds the bus ‘A 10’ and transformer ‘T4’ feeds the bus ‘B 10’. Both buses can be connected by a circuit breaker. This circuit breaker is normally open and only closes when any transformer is required to be taken out for the maintenance or any other purpose.

There are four feeders which emanate from the bus ‘A 10’. These feeders are marked as L9109, L91010, L9106 and L9107. The BUS ‘B 10’ feeds five feeders which are marked as L9101, L9102, L9103, L9104 and L9105. All these feeders are radial in nature and are combinations of the cables and overhead lines with varying diameters. The feeders emanating from the bus B10 feed residential loads while the feeders emanating from the bus A-10 feed industrial loads.

The load is calculated from the currents measured at the start of the feeders. The residential loads at lines L9101, L9102, L9103, L9104 and L9105 are then split up in three equal parts and placed at three equal distances along the feeder. Whereas the loads at lines L9109, L91010, L9106 and L9107 are lumped at the end of feeders since these lines supply the power to the industrial loads. There are no wind turbines installed at the moment at Hällekis network and the bus ‘A10’ is the point under investigation for the wind power integration.

There are no capacitor banks or any other sources of reactive power, installed in the grid.

3.2 Objectives

The main objectives of this study are to study the connection of the maximum amount of wind energy that can be connected to bus A10 while considering all the limiting factors. These limiting factors are given as follows.

- The voltage profile at all the load buses must stay within the permissible limits of +2% to -4% of reference voltage.
- The loading of the existing feeders up to the thermal rating at full wind power production.
- The loading of transformer T3 up to the thermal rating at full wind power production
- To keep the flicker severity index at the network below 0.35.

3.3 Modelling of the Network

The following assumptions are taken while modelling the distribution network at Hällekis.

- The wind turbines are modelled as negative constant power loads with the power factor equal to one. The incoming wind turbines at Hällekis are considered as variable speed turbines. These turbines are equipped with a converter at the interface between the generator and the grid. The presence of a converter justifies the selection of power factor and the variable speed ensures constant power operation. The negative sign shows the injection of active power by the wind turbine.

- The power rating of both turbines is assumed same when considered together.
- The transformers connecting the wind turbines with the grid are neglected during these calculations.

- Loads are modelled as constant power loads.

- Power factor is considered as 0.9 (lagging) for the residential loads and 0.85 (lagging) for the industrial loads.

3.4 Analysis Procedure

In the calculations, two load conditions are taken into consideration, 100% and 10% of the full load. Since there are no wind turbines installed at present in Hällekis, the wind speed situations are not taken into consideration. Steady state analysis is used to observe the effect of increasing wind power on the voltages and the power flow of the distribution grid.

A model is built in PSS/E® for the analysis and the related information like system impedance and short circuit level, short circuit impedance of transformers, the OLTCs settings, resistance, inductive reactance and charging of lines is provided by the company *Götene Elförening,* which is running this distribution system at Hällekis.

Following cases are considered to take into account the possible combinations of load and wind power.

Case A-1: Wind turbine 1 injects power and load is 100 %
Case A-2: Wind turbine 2 injects power and load is 100 %
Case A-3: Both wind turbines inject power and load is 100 %
Case B-1: Wind turbine 1 injects power and load is 10 %
Case B-2: Wind turbine 2 injects power and load is 10 %
Case B-3: Both wind turbines inject power and load is 10 %

In these cases initially the capacity of the cable joining the wind turbines with bus A10 is not considered. The injection of active power from the wind turbines is increased up to 25 MW. Since a wind turbine with such power rating doesn't exist, the capacity of wind turbine above 5 MW can be considered as a group of wind turbine units. The voltage and the power flowing through feeders L9101, L9102, L9103, L9104 and L9105 and the transformer T-4 were also observed while increasing the power injection from the wind turbines but the preliminary analysis showed no change in the above mentioned parameters under all conditions and the thermal loading of the lines and the transformer T4 was considerably below their thermal limits. Thus, during further analysis, the parameters related with only transformer T3 and the associated feeders are considered.

3.4.1 Case A-1: Wind Turbine 1 Injects Power and Load is 100 %

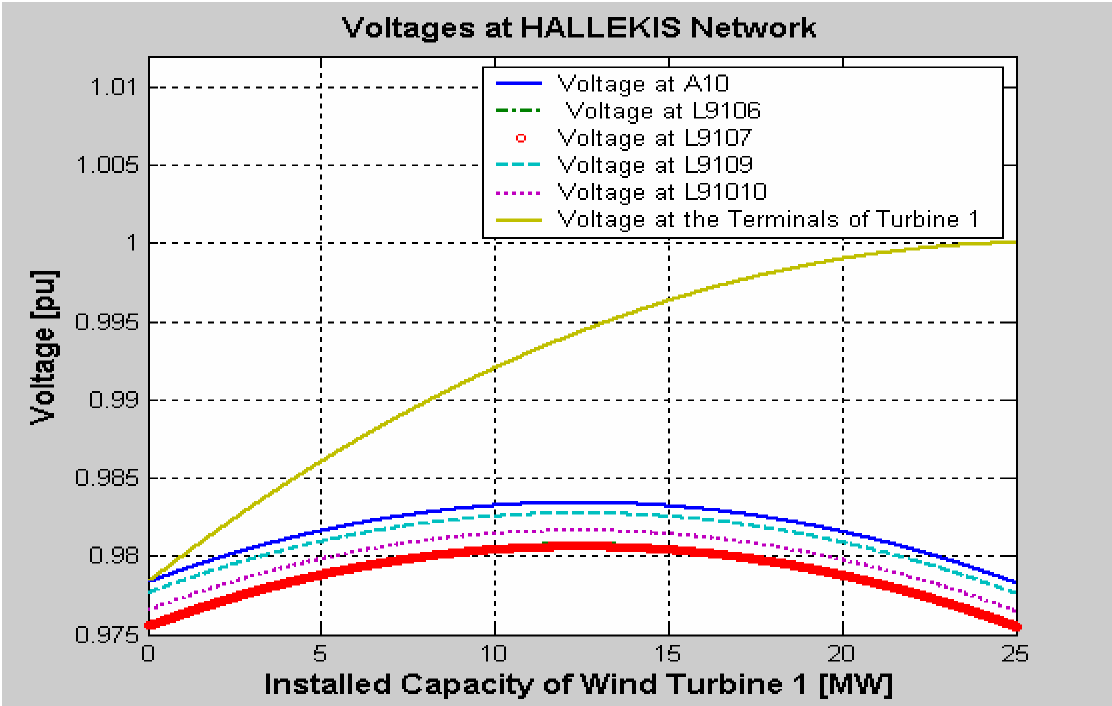

Figure 3.2-Voltages at the terminals of turbine 1, at the secondary of transformer T3 and associated buses against the installed capacity of wind turbine 1

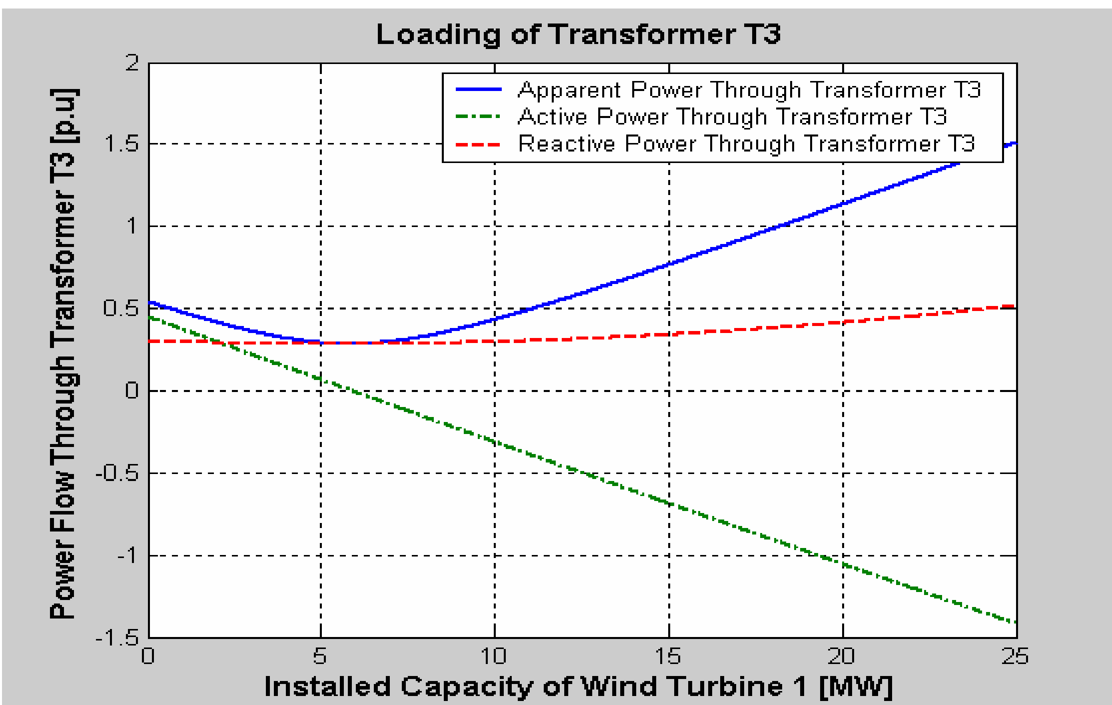

Figure3.3-Loading of transformer T3 against the installed capacity of wind turbine 1.

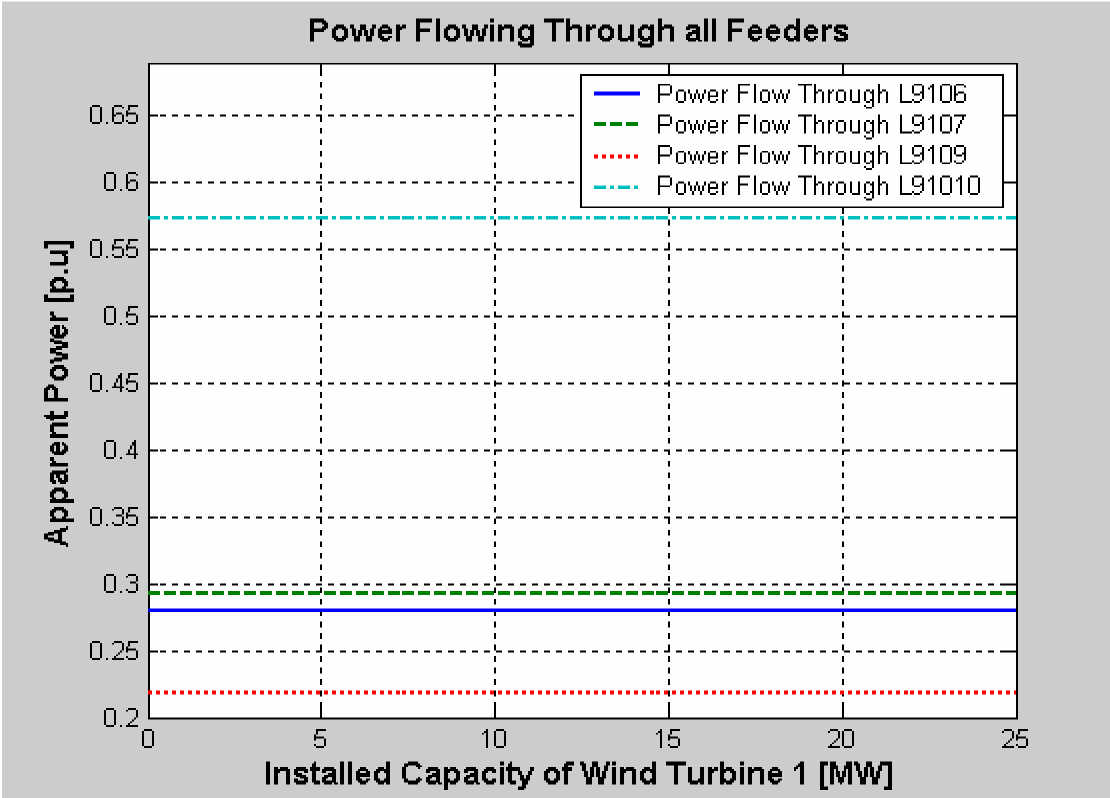

Figure 3.4-Loading of line segments of minimum short circuit capacity in each industrial feeder against the installed capacity of wind turbine 1

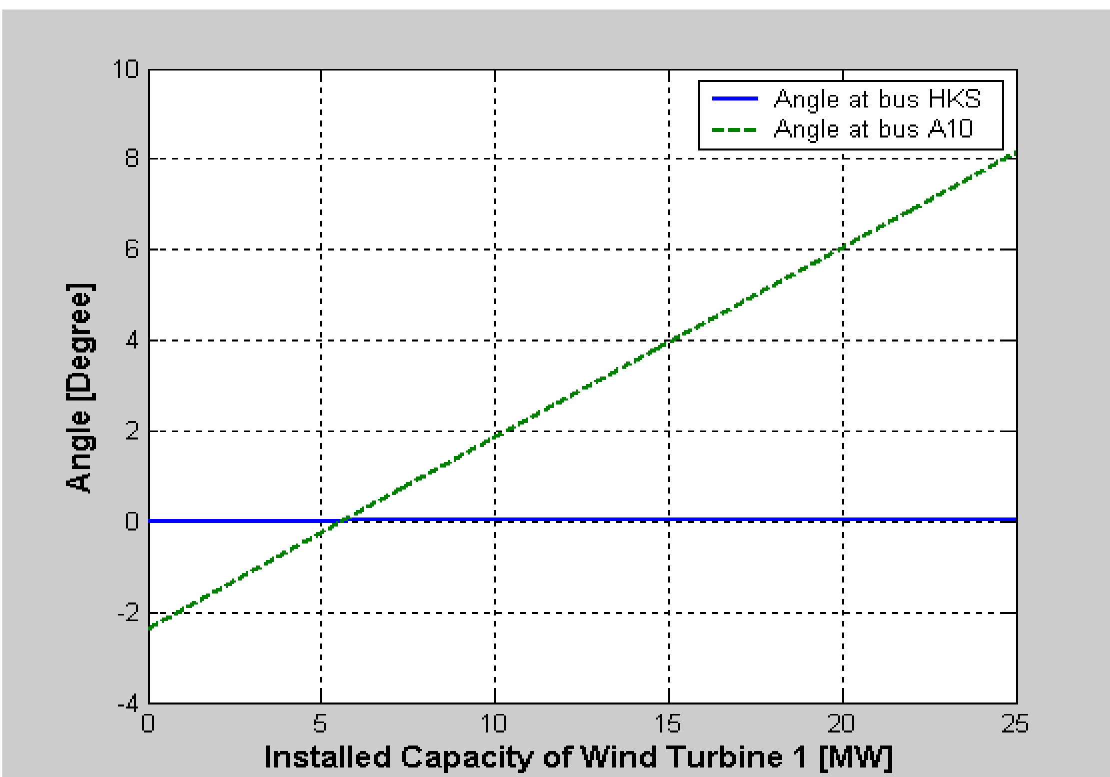

Figure 3.5-Voltage angles at primary and secondary side of transformer T3 against the installed capacity of wind turbine 1

Figure 3.2 shows the voltages at bus A10, at the terminals of turbine 1 and all the load buses fed by transformer T3. Wind turbine 1 is connected to the bus A10 by an 800 m long, 240 mm^2 cable. As the power production from wind turbine 1 increases, initially the voltage increases at the terminals of turbine as well as on the bus A10 and load buses until the power production reaches 12 MW. The reason for the increase in voltage at the load buses can be found out from Figure 3.3. This Figure shows that as the power production from the wind turbine increases, the active power flow through transformer T3 starts to decrease and reaches a point when the apparent power flow through transformer T3 becomes equal to the reactive power flow i.e. $P_{T3} = 0$. At this point, the power converted from the wind turbine is 6 MW (5.87 MW being precise).

The combined active power demand on the lines L9109, L91010, L9106 and L9107 is 5.82 MW. The remaining 0.05 MW is lost in the feeders' impedances and line impedance between wind turbine 1 and bus A10.

As the power injection from the wind turbine further increases up to 12 MW, the apparent power through transformer T3 starts increasing again since the active power now flows back towards the grid through transformer T3.

Up till this point, the reactive power through transformer T3 decreases from 0.302 p.u. to 0.283 p.u. and increases back to 0.302 p.u. This change in the reactive power also allows the voltages to increase up to this point. As the power injection further increases from 12 MW, now the reactive power flow increases from the grid to the load thus causing an increase in the apparent power of transformer T3. Active power keeps flowing towards the grid. This increase in the reactive power import reduces the magnitude of the voltage at the bus A10 and the voltages on the load buses follow this reduction in voltage at the bus 'A10'.

Figure 3.4 shows that the apparent power flow through all the feeders remains the same and well below the thermal ratings of the lines. The maximum loading is attained by the line L91010 that is 0.5728 p.u.

The changes in the reactive power can be explained with respect to the voltage angles at the bus 'HKS' and 'A10', as shown in Figure 3.5. These angles are plotted against the installed capacity of wind turbine 1. From the fundamentals of power systems, it is well known that the reactive power flow between two buses joined by impedance can be expressed as:

$$Q_1 = \frac{U_1^2}{Z}\cos\delta - \frac{U_1 U_2}{Z}\cos(\psi - \delta) \tag{3.1}$$

Where,

U_1, U_2	Magnitude of the voltages at two buses
Z	Impedance between two buses
ψ	Difference between the voltage angles at two buses
δ	Loss angle ($\delta = \tan^{-1}\frac{R}{X}$)

It can be seen from the Figure 3.5 that initially the difference between angle 'a1' (voltage angle at bus HKS) and angle 'a2' (voltage angle at bus A10) was positive at $P_T = 0$ (where P_T stands for installed capacity of wind turbine). As the power injection increases to 6 MW, the difference between the angle vanishes (a1-a2 = 0), which leads to a decrease in the reactive power flow. With further increase in the power injection, the difference in the voltage angles becomes negative. This angle difference being negative, adds up with the loss angle. The increase in angle decreases the value of the cosine trigonometric function. The negative sign doesn't affect the outcome. The reduction in the term $\cos(\psi - \delta)$ increases the reactive power flow and it keeps on increasing as the power injection from the wind turbine increases.

The transformer T3 hits the thermal limit when the generation from wind turbine 1 reaches 18.2 MW where as the voltages on the load buses never go on to hit the upper limit of +2% due to the reactive power import from the grid and remains in the tolerable limits of 0.978 p.u. and 0.985 p.u. No change in the tap positions of transformer T3 is observed as the power injection of up to 25 MW from wind turbine 1 doesn't cause the voltage at bus 'A 10' to decrease below 0.978 p.u. which is the lower limit of voltage, below which the tap changer must operate in order to bring back the voltage in the given limit at the transformer's secondary.

An analysis for this working condition suggests that it is the thermal limit of the cable joining the wind turbine with the grid, which restricts the amount of wind power that can be connected at the PCC. The thermal limit of this cable is 7.3 MVA.

3.4.2 Case A-2: Wind Turbine-2 Injects Power and Load is 100 %

Figure 3.6 shows the voltages at bus A10, at the terminals of turbine 2 and all the load buses fed via transformer T3 against the power injection from wind turbine 2. Wind turbine 2 is connected with the wind turbine 1 by a 700 m long, 240 mm^2 cable. During this condition no generation from wind turbine 1 is considered.

As the power injection from the wind turbine 2 increases up to approximately 6 MW, voltages at the terminals of turbine 2 as well as on the bus A10 and load buses, increase. This increase in the voltages can be better understood from Figure 3.7.

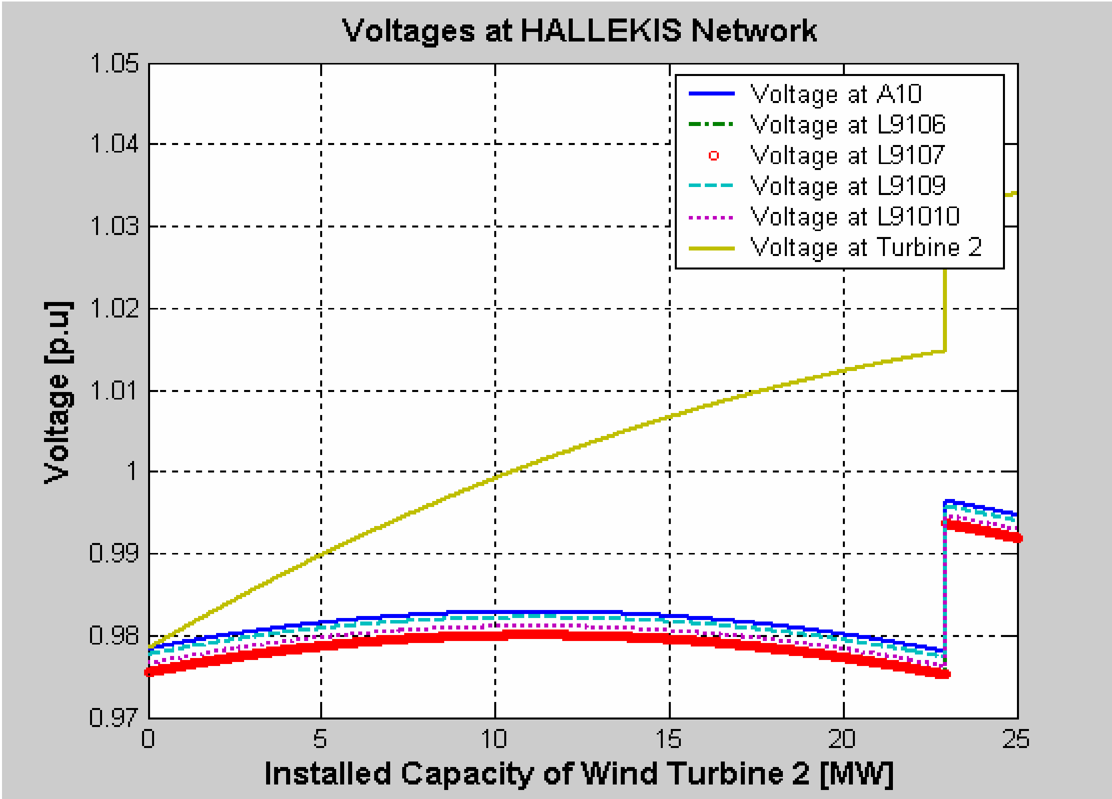

Figure 3.6-Voltages at the terminals of turbine 2, at the secondary of transformer T3 and associated buses against the installed capacity of wind turbine 2.

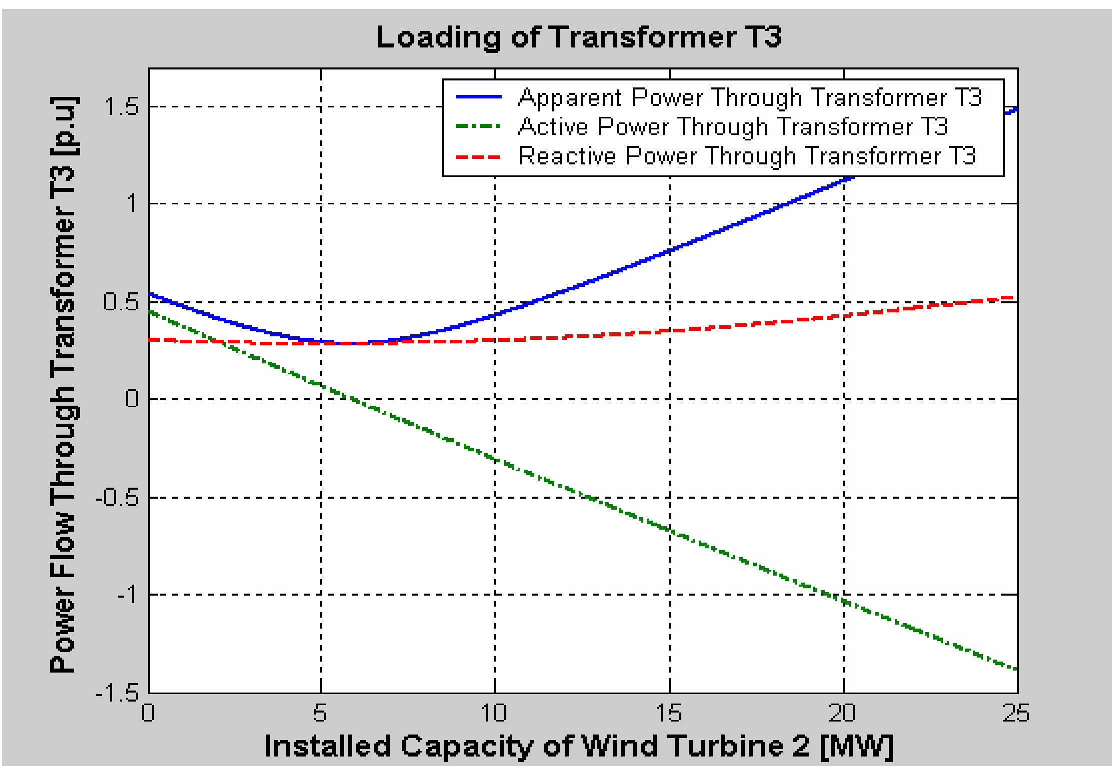

Figure 3.7-Loading of transformer T3 against the installed capacity of wind turbine 2.

Figure 3.7 shows the apparent, active and reactive power flow through transformer T3 against the power injection from wind turbine 2. As the power production from wind turbine 2 reaches 5.88 MW, the active power through the transformer T3 becomes zero which shows that now all the active power demand and losses for lines L9109, L91010, L9106 and L9107 are supplied by the wind power units. The combined active power demand on lines L9109, L91010, L9106 and L9107 is 5.82 MW. It shows that now the power losses are 0.06 MW. These loses are a bit more i.e. 0.01 MW, as compared to when the wind turbine 1 was generating. The reason for the increase in power losses is the presence of impedance between wind turbine 1 and wind turbine 2. The apparent power flow through transformer T3 decreases up to this point and becomes equal to the reactive power of transformer T3.

As the power production from wind turbine 2 increases further up to 11 MW, the active power through transformer T3 goes negative, which means that the additional active power flows towards the grid now and the apparent power again increases in turn. Voltages at the load buses keeps rising at this moment as can be seen in Figure 3.6.

With the increase in power production from wind turbine 2 beyond 11 MW, the voltages at the load buses start going down. The decrease in the voltages is due to increase in the reactive power from the grid to the load as can be seen in Figure 3.6.

It is found that the change in the voltage angle at bus A10 with respect to the voltage angle at bus HKS is almost similar as in the case A-1. The changes in the reactive power can be explained again with the help of Figure 3.5 and Equation (3.1). It can be seen that initially the voltage angle at bus A10 is negative and the voltage angle at bus HKS is set to zero (bus HKS is considered as slack bus). The difference between the voltage angles at 'HKS' and 'A10' is positive. The increase in active power production from the wind turbine reduces this difference in angles, to zero thus causing the reactive power through transformer T3 to decrease a bit. Further increase in the voltage angle 'a2' (angle of voltage at bus A10) makes the difference of angles positive, causing the reactive power to increase again. This increase in the reactive power is responsible for the decrease in the voltages at the load buses when the power production from wind turbine 2 increases beyond 11 MW.

The apparent power through all the feeders remains constant as it was shown in Figure 3.4 and well below the thermal limits. The highest thermal loading is attained by L91010 (Svenska foder 2) i.e. 0.57 p.u.

Transformer T3 hits its thermal limits at 18.35 MW generation from wind turbine 2, which is 0.15 MW more as compared to when wind turbine 1 was in operation alone. The voltage at the bus A10 hits the lower limit of 0.9786 p.u. due to increase in the reactive power import from the grid when wind turbine 2 generates 22.97 MW. One tap position change is observed at this point.

The analysis for this working condition suggests that it is the thermal limit of the cable joining the wind turbine with the grid that restricts the amount of wind power to be integrated at this point. The thermal limit of this cable is 7.3 MVA. The connection of this amount of wind power at this point will increase the voltage at bus A10 from 0.978 p.u. to 0.982 p.u. and the voltage at the turbine terminal will be around 0.994 p.u.

3.4.3 Case A-3: Both Turbines Inject Power and Load is 100 %

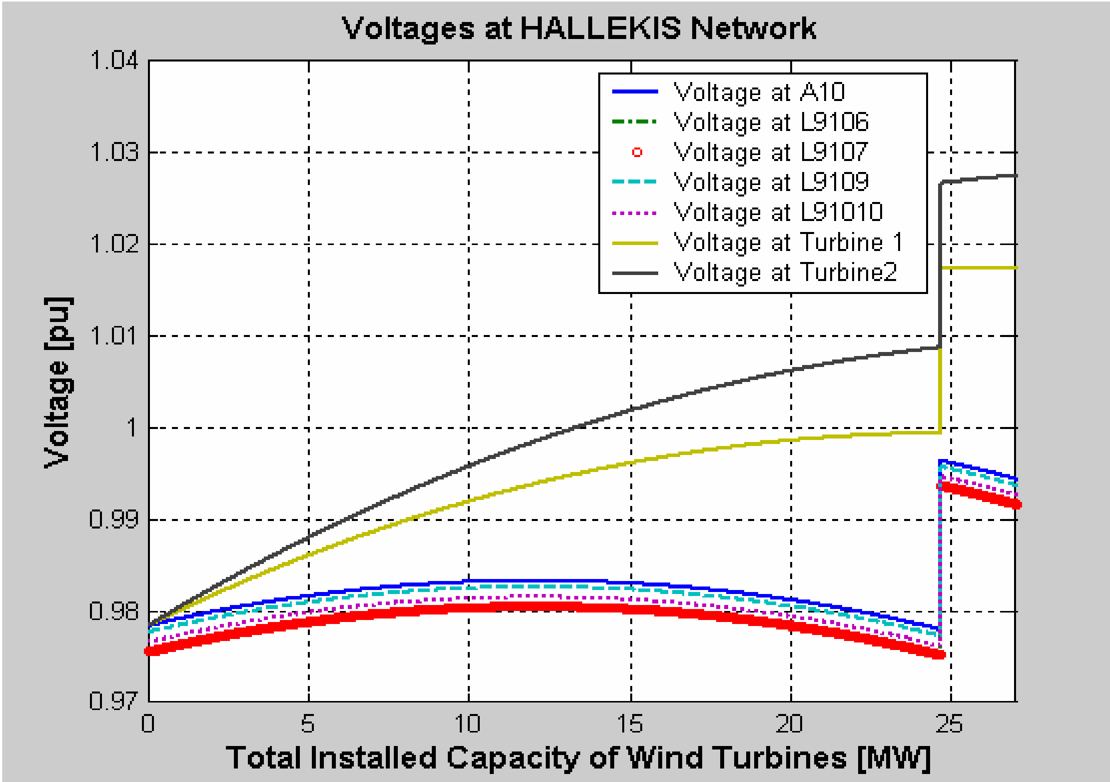

Figure 3.8-Voltages at the terminals of both turbines, at the secondary of transformer T3 and associated buses against total installed capacity of wind turbines

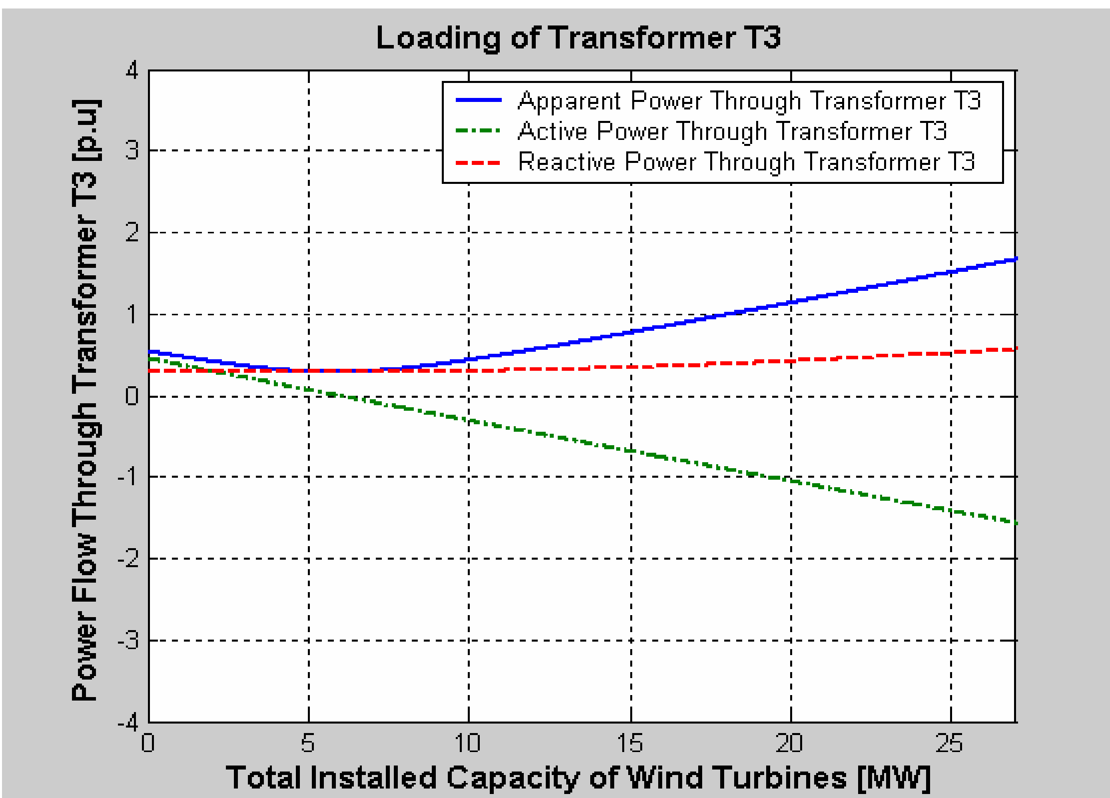

Figure 3.9-Loading of transformer T3 against the total installed capacity of wind turbines.

In this working condition, generation from both the wind turbines is considered under the assumption that the installed capacity of both wind turbines is the same.

Figure 3.8 shows the voltages at the terminals of both turbines as well as on the load buses, fed by transformer T3 against the installed capacity of both wind turbines. As the power production from both turbines increase up to 3 MW each, the voltages at bus A10 increases from 0.978 p.u. to 0.982 p.u. and the voltages at load buses also increase. This increase in voltages can be justified by observing the active power flow through transformer T3, which is shown in Figure 3.9. This Figure shows the apparent, active and reactive power flow through transformer T3 against the installed capacity of both wind turbines. The combined active power demand on the lines L9109, L91010, L9106 and L9107 is 5.82 MW whereas the active power through transformer T3 becomes zero when the combined power production from both turbines reach 5.88 MW. The losses in this working case up to this generation from wind turbines, are the same i.e. 0.06 MW as compared to when turbine 2 was generating alone.

As the power production from each wind turbine increases up to 6 MW, the voltage at the bus A10 only increases up to 0.983 p.u. The active power through transformer T3 at this point is 6 MW (flowing towards grid) and the losses are 0.178 MW.

With more increase in the power production, the voltage at bus A10 starts to decrease and so do the voltages at the load buses supplied by transformer T3. The decrease in the voltages is due to the increase in the reactive power flow through transformer T3. The increase in the reactive power flow can be justified due to change in the sign of difference between the voltage angles at bus ‘HKS’ and bus ‘A10’ as shown in Figure 3.5.

The thermal loading of the lines is the same as noted during previous working cases.

Transformer T3 hits the thermal limits when the individual production from the wind turbines is 9.13 MW and the active power flow through transformer T3 is 0.925 p.u. i.e. 12.02 MW. The losses at this point are 0.454 MW at 18.2 MW combined power production from both turbines. As the power production further increases to 24.7 MW, the voltage at the bus A10 decreases until it hits the lower limit of 0.978 p.u. (following subsequent change in load voltages) thus causing first tap change. This step change causes the voltage at the terminals of turbine 2 to increase above 1.02 p.u. At this point the individual production from each turbine is found to be 12.3 MW.

Like the earlier two working cases, again it was the rating of cable, joining the wind turbines with the grid, which limits the amount of wind power to be integrated in the grid. The capacity of this cable is 7.3 MVA. The individual power production from each turbine, which can be connected, is 3.6 MW. The voltages at the load buses will be between 0.979 p.u. to 0.982 p.u. whereas the voltages at turbine terminals will be 0.989 p.u. and 0.991 p.u. for turbine 1 and turbine 2 respectively.

3.4.4 Case B-1: Wind Turbine-1 Injects Power and Load is 10 %

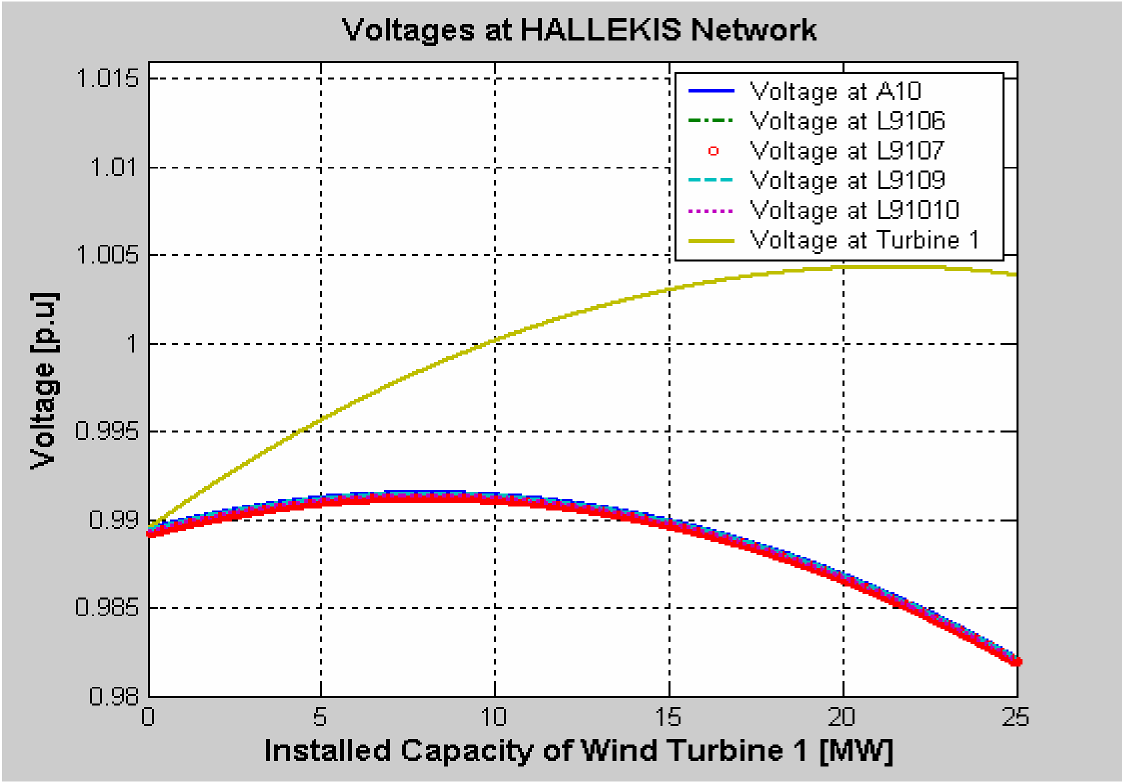

Figure 3.10-Voltages at the terminals of turbine 1, at the secondary of transformer T3 and at associated buses against the installed capacity of wind turbine1.

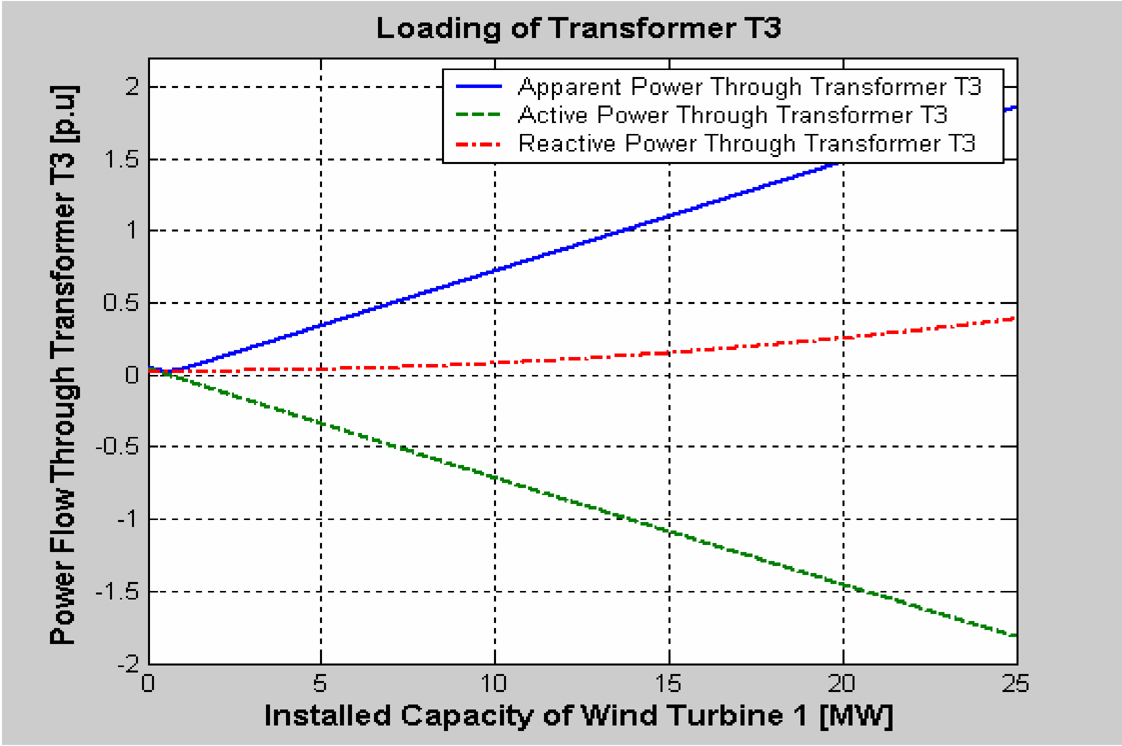

Figure 3.11-Loading of transformer T3 against the installed capacity of wind turbine 1.

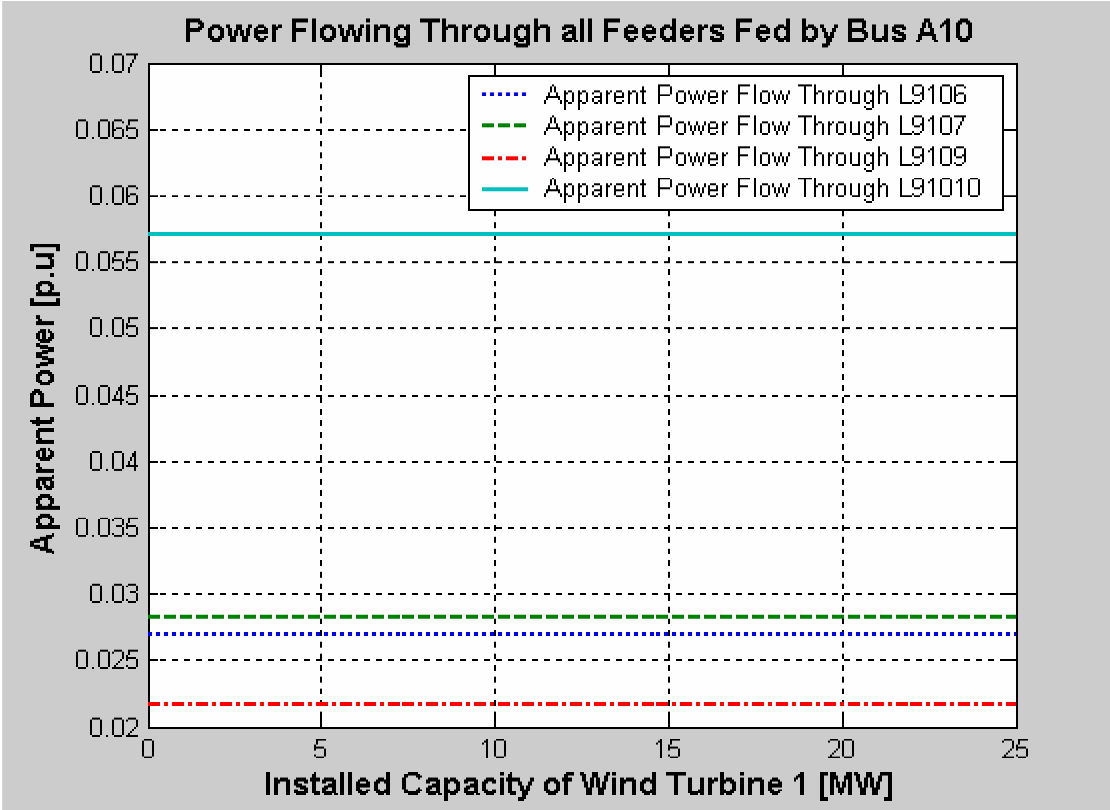

Figure 3.12-Loading of line segments of minimum rating in each industrial feeder against the installed capacity of wind turbine 1.

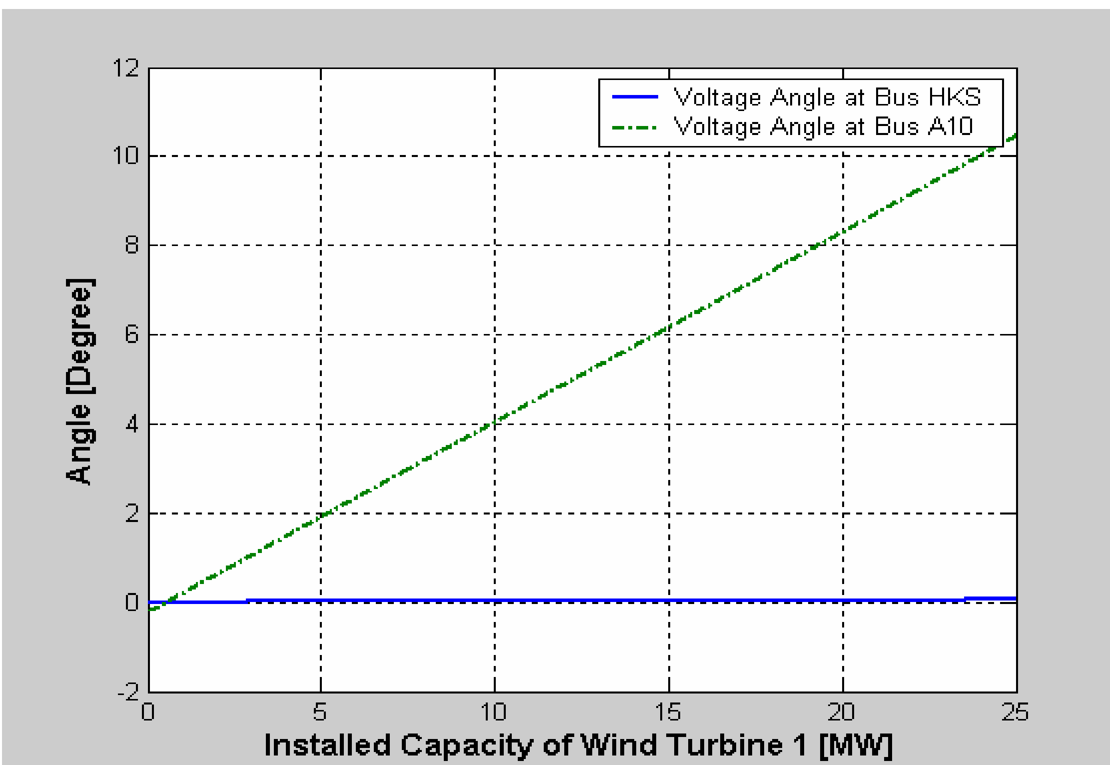

Figure 3.13-Voltage angles at primary and secondary side of transformer T3 against the installed capacity of wind turbine 1.

Figure 3.10 shows the voltages at the terminals of wind turbine 1 and at load buses fed by transformer T3. Under this working condition, the load is reduced by 90% and only wind turbine 1 is generating. It can be seen in Figure 3.10 that reduction in the load raises the voltage at bus A10 to 0.99 p.u. As the power production from wind turbine 1 increases up to 0.583 MW, the voltage at bus A10 increases and the voltages at the load buses increase in response. The active power flow through transformer T3 goes to zero as shown in Figure 3.11. The combined active power demand on the transformer T3 is 0.582 MW. At this point all the active power demand and losses are supplied by wind turbine 1 and the apparent power through transformer T3 becomes equal to the reactive power.

As the power production from wind turbine 1 further increases up to 8 MW, the increase in the load voltages continues. The voltage at bus A10 reaches 0.991 p.u. The active power through the transformer T3 now starts flowing towards the grid and reaches 7.3 MW, thus causing the apparent power through transformer T3 to increase again up to 7.37 MVA.

With a further increase in power production up to 13.72 MW, the load voltages start to decrease. The voltage at bus A10 decreases up to 0.99 p.u. The decrease in the voltages occurs due to increase in the reactive power flow. The active power through transformer T3 increases, which in turn increases the apparent power through transformer T3 up to 1 p.u.

The increase in the power production up to 25 MW from wind turbine 1 neither causes the voltage at bus A10 to decrease down to 0.978 p.u.(the lower limit for the tap changer to operate) nor does it cause the increase in the voltage at the terminals of wind energy installations up to 1.02 p.u.

Figure 3.12 shows the apparent power flowing through different lines against the installed capacity of wind turbine 1. The apparent power flowing through the different lines is constant throughout the increase in power injection from wind turbine 1 and way below the maximum rating of 1 p.u.

The increase in the reactive power can be explained with the help of Figure 3.13 and Equation (3.1). Figure 3.13 shows the voltage angles at Bus 'HKS' and bus 'A10' against the power injection from wind turbine 1. Initially the difference between the voltage angle at bus 'HKS' and at bus 'A10' is positive, which shows that the active power is flowing from the grid to the load. With the increase in the power injection from wind turbine 1, the difference between these angles starts to decrease, eventually leading to zero which shows that there is no active power flow between the grid and load. Further increase in power injection from wind turbine 1 turns this difference between angles negative, thus causing an increase in the reactive power flow as described by Equation (3.1).

The analysis shows that it is the power carrying capacity of the cable joining the wind turbine 1 with the grid, which limits the amount of wind power that can be integrated at this point. The rating of this cable is 7.3 MVA. The connection of this amount of power will increase the voltage at bus A10 from 0.989 p.u. to 0.991 p.u. and the voltages at the load buses will lie around 0.99 p.u. The voltage at the terminals of turbine 1 will be 0.997 p.u. Transformer T3 will be 51.4% loaded, transferring 6.64 MW to the grid. No change in the tap position is observed.

3.4.5 Case B-2: Wind Turbine 2 Injects Power and Load is 10 %

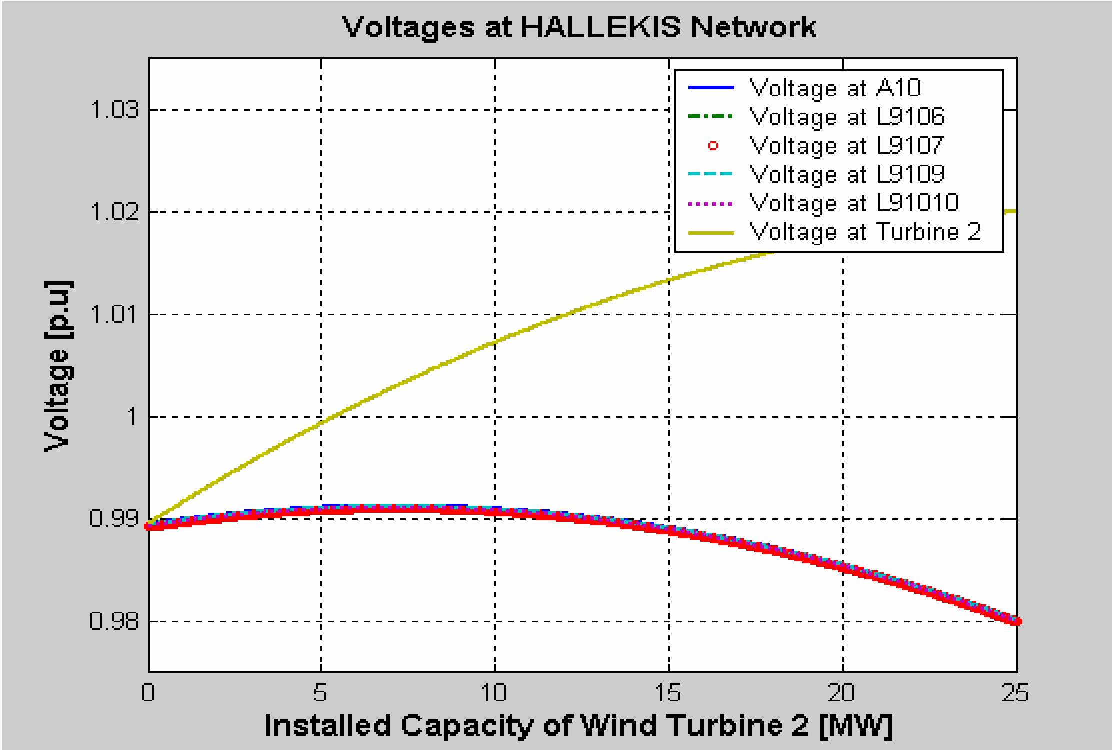

Figure 3.14-Voltages at the terminals of turbine 2, at the secondary of transformer T3 and associated buses against the installed capacity of wind turbine 2.

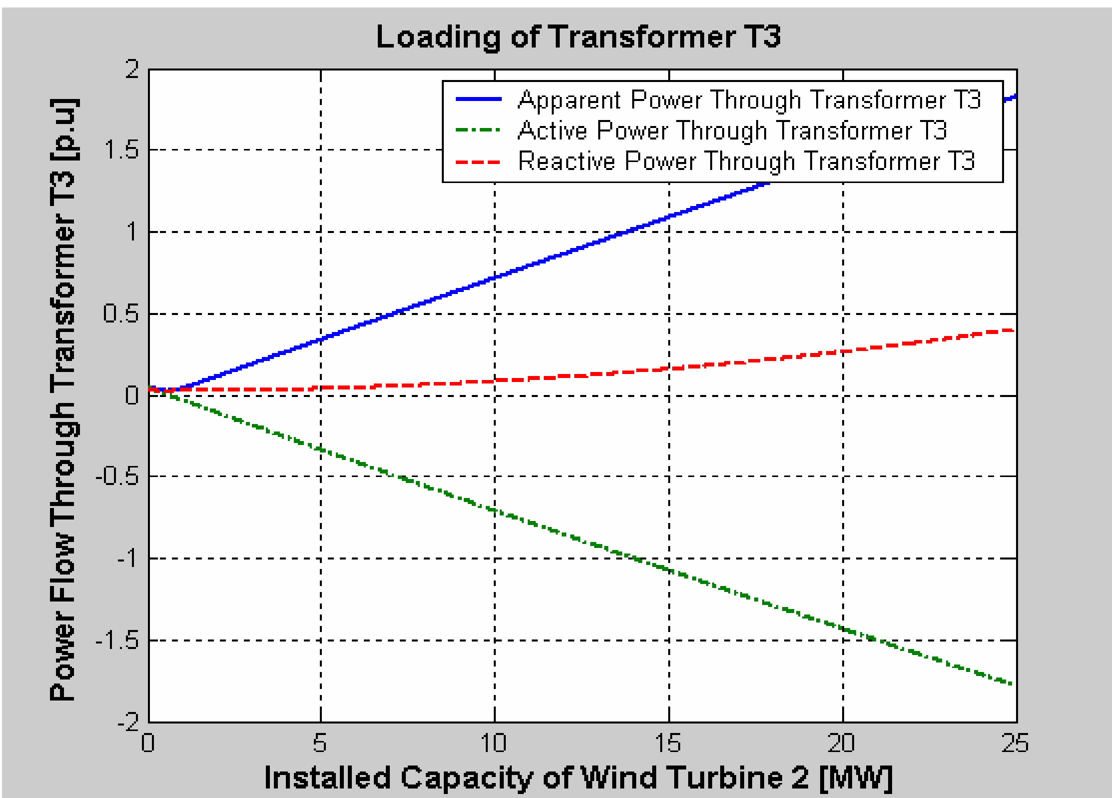

Figure 3.15-Loading of transformer T3 against the installed capacity of wind turbine 2.

Figure 3.14 shows the voltages at bus A10, at the terminals of wind turbine 2 and all the load buses fed via transformer T3 against the installed capacity of wind turbine 2 only. The load is reduced up to 10% of the actual load. With the increase in the power injection from wind turbine 2 up to 0.583 MW, the voltage at bus A10 increases and the active power production through transformer T3 becomes zero as shown in Figure 3.15. At this point, all the demand for the active power is provided by wind turbine 2. The voltages at the load buses also increase.

A further increase in the power production from wind turbine 2 up to 7.2 MW increases the voltage at bus A10 to 0.991 p.u. and the voltages at load buses increase as well. The active power through transformer T3 starts flowing towards the grid and becomes 6.51 MW, increasing in negative direction as shown in Figure 3.15. The increase in the active power also increases the apparent power flow through transformer T3 up to 6.53 MVA.

A further increase in the power production from wind turbine 2 up to 13.85 MW accompanies a decrease in the voltage at bus A10 and the voltages at the load buses follow this decrease. This decrease in the voltages is attributed to an increase in the reactive power flow through transformer T3. The active power flow towards the grid increases up to 12.87 MW, causing the apparent power of transformer T3 to reach the value of 1 p.u. i.e. 13 MVA.

An increase in the power injection from wind turbine 2 up to 25 MW doesn't cause the voltages at the load buses to fall below 0.978 p.u. but the voltage at the terminals of wind turbine 2 can increase up to 1.02 p.u. No change in the tap position is observed.
The apparent power flowing through the lines stays constant and its magnitude for each line is the same as observed in the case B-1.

It is found that a change in the voltage angle at bus A10 with respect to the voltage angle at bus HKS is almost similar as it was in case B-1. The change in the reactive power of transformer T3 can be best explained with respect to Figure 3.13, keeping Equation (3.1) in review. The increase in the active power flow from wind turbine 2 to the grid causes a change in the sign of the voltage angle at bus A10. This change in the sign of angle with respect to the voltage angle at bus HKS causes a minor decrease in the reactive power initially and then increases it again.

The analysis shows that the MVA rating of the cable joining wind turbine 2 with the grid is the main factor in deciding the rating of wind turbine 2. The rating of this cable is 7.3 MVA. The connection of this amount of power will increase the voltage at bus A10 from 0.989 p.u. to 0.991 p.u. and the voltages at the load buses will be around 0.99 p.u. The voltage at the terminals of turbine 2 will be approximately 1 p.u. Transformer T3 is 51.1% loaded, transferring 6.6 MW to the grid. No change in the tap position is observed.

3.4.6 Case B-3: Both Wind Turbines Inject Power and the Load is 10 %

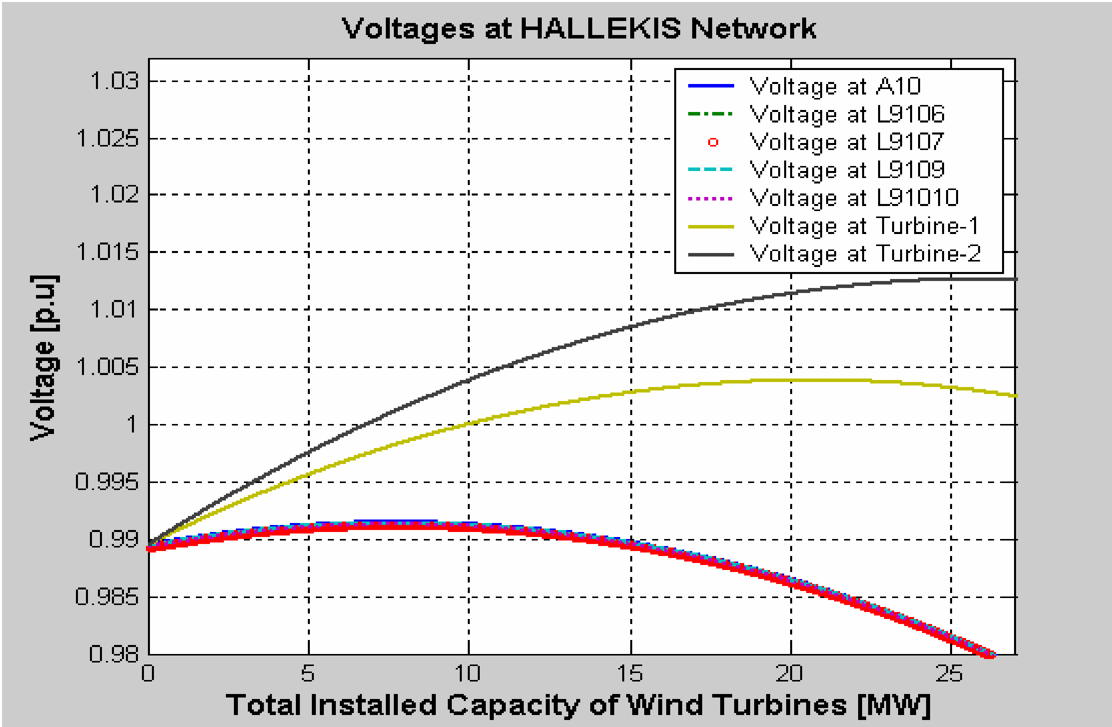

Figure 3.16-Voltages at the terminals of both turbines, at the secondary of transformer T3 and associated buses against the total installed capacity of wind turbines

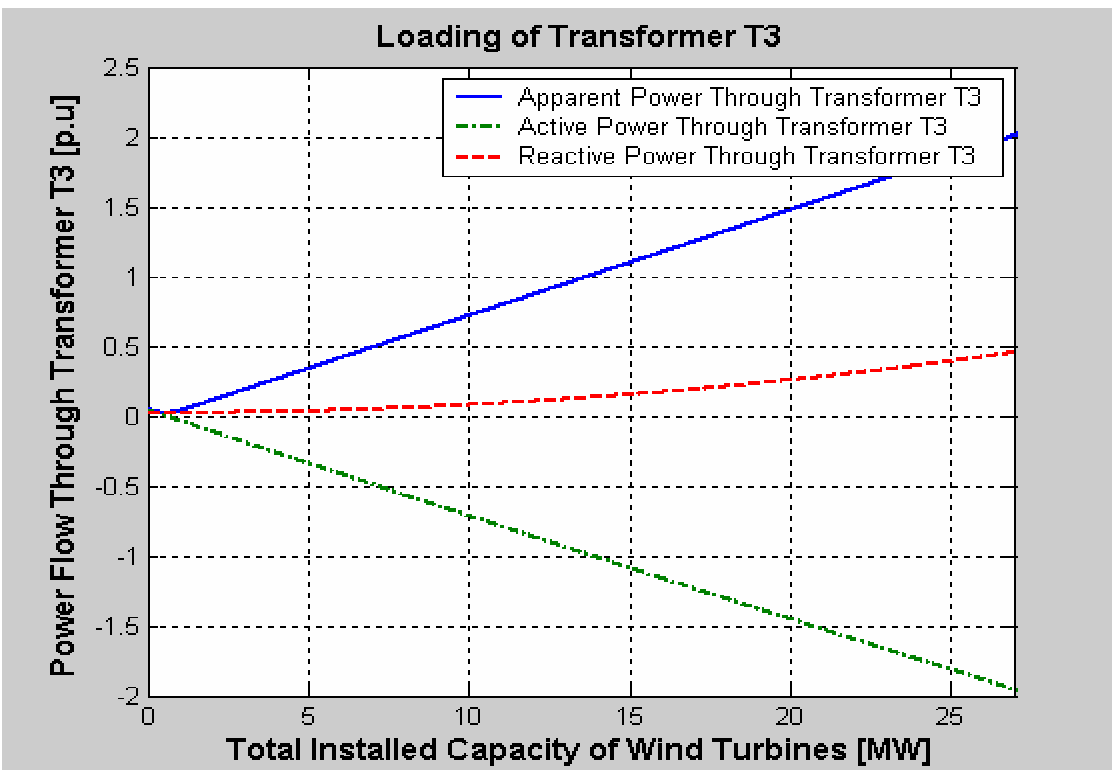

Figure 3.17-Loading of transformer T3 against the total installed capacity of both wind turbines.

In this case, the generation from both wind turbines is considered under the assumption that the installed capacity of both wind turbines is same. The load at transformer T3 is reduced up to 10% of estimated load to represent the light load conditions.

Figure 3.16 shows the voltages at the terminals of both turbines, at all load buses fed by the transformer T3 and at bus A10 (transformer T3 secondary side) against the installed capacity of both wind turbines. As the power injection from both turbines reach 0.583 MW, the voltage at bus A10 increases slightly, followed by an increase in the load voltages. The active power flow from the grid to the load falls to zero and the apparent power through the transformer T3 decreases to the reactive power of transformer T3 as shown in Figure 3.17. The voltages at the terminals of wind turbine 1 and wind turbine 2 increase to approximately 0.99 p.u.

As the combined power production from both turbines increases up to 8 MW, the voltage at bus A10 increases to 0.991 p.u. and the voltages at load buses follow this increase. The voltages at the terminals of wind turbine 1 and wind turbine 2 increase to 0.988 p.u. and 1.001 p.u. respectively. Active power through the transformer T3 now flows towards the grid as the active power demand and losses are already catered by both wind turbines and its value is 7.33 MW at this point. The apparent power of transformer T3 also increases up to 7.37 MVA.

Further increase in the power production up to 13.7 MW causes the voltage at bus A10 to decrease to 0.99 p.u. and the load voltages also decrease. This decrease in the voltages occurs due to the increase in the reactive power import from the grid to the load. The active power flowing towards the grid is 12.88 MW. This increase in the active power feed into the grid and the reactive power import from the grid causes the apparent power of transformer T3 to attain the value of 1 p.u. The voltages at the terminals of wind turbine 1 and wind turbine 2 increase to 1.002 p.u. and 1.007 p.u. respectively.

An increase in the combined power production from both turbines up to 25 MW keeps the voltages at the terminals of both turbines below 1.01 p.u. where as the voltages on the load buses do not fall below 0.98 p.u. No change in the tap position of transformer T3 is observed.

The magnitude of apparent power flowing through the feeders is the same as it was observed in case B-1 since the load on each line is constant and the difference in voltage magnitudes between the load voltages and the voltage at bus A10 remain the same throughout this power injection in the grid. The values of the power for all feeders are quite below 1 p.u.

The change in the reactive power of transformer T3, despite the constant reactive power demand can be explained again with the help of the voltage angles, shown in Figure 3.13 and Equation (3.1). Continuous injection of active power from both wind turbines increases the voltage angle at the bus A10 from a negative value to a positive one whereas the voltage angle at bus HKS is held constant. The ever changing difference between both voltage angles causes the increase in reactive power of transformer T3 as the production from the wind turbines increases.

It is the MVA rating of the cable which limits the amount of wind power to be integrated, effectively. The rating of the cable is 7.3 MVA. The connection of this amount of power at this point will increase the voltage at bus A10 from 0.989 p.u. to 0.991 p.u. whereas the voltages at the load buses will be around 0.991 p.u. as well. The voltages at the terminals of wind turbine 1 and wind turbine 2 will be 0.997 p.u. and 1 p.u. respectively. Transformer T3 will be 51.4% loaded, transferring 6.643 MW towards the grid.

3.5 Summary of Results

Table 3.1-Rating of wind turbine 1 with respect to different limiting factors for both 100% and 10% load conditions

	Load 100 %	**Load 10 %**
Voltage at Turbine Terminal (Turbine-1)	25 MW	25 MW
Thermal Limit of Lines	7.3 MW	7.3 MW
Thermal Limit of Transformer T3	18.2 MW	13.72 MW

Table 3.2-Rating of wind turbine 2 with respect to different limiting factors for both 100% and 10% load conditions

	Load 100 %	**Load 10 %**
Voltage at Turbine Terminal (Turbine-2)	22.97 MW	25 MW
Thermal Limit of Lines	7.3 MW	7.3 MW
Thermal Limit of Transformer T3	18.35 MW	13.85 MW

Table 3.3-Rating of both wind turbines with respect to different limiting factors for both 100% and 10% load conditions

	Load 100 %	**Load 10 %**
Voltage at Turbine Terminal (Turbine-1)	19.49 MW	19.2 MW
Voltage at Turbine Terminal (Turbine-2)	12.33 MW	13.9 MW
Thermal Limit of Lines	3.6 MW	3.6 MW
Thermal Limit of Transformer T3	9.13 MW	6.8 MW

3.6 Voltage Control using Reactive Power

Wind resources are often distributed in terms of geographical locations. Electric power generated as a result of these resources, is often collected by the distribution grids. It is obligatory for the distribution companies to provide power to the customers with the voltages in tight limits and acceptable power quality.

Reactive power has a major effect on the magnitudes of voltages in the system. It is a basic understanding of power systems that injection of the reactive power in a bus can increase the bus voltage whereas a load drawing reactive power causes a decrease in the voltage at the respective bus.

At Hällekis, the proposed use of reactive power is to limit the voltage at the terminals of the wind turbines up to 1.02 p.u. by drawing some reactive power from the grid while injecting active power.

But the summary of results suggests that transformer T3 hits its thermal rating way before the voltage at the terminals of turbines, reaches the upper voltage limit of 1.02 p.u. and in order to employ the reactive power control strategy at Hällekis, the transformer T3 is needed to be replaced with another transformer of higher rating.

3.7 Flicker Calculation

IEC 61400-21 is used as a reference document for the calculation of flicker emission at Hällekis substation. This document describes a procedure to assure the accuracy in the measurements and a method to asses the effects of wind power generation on the power quality of the grid. The quantities which are necessary to state for the characterization of power quality of a wind turbine are maximum permitted power, maximum measured power, reactive power, voltage fluctuations (flicker and voltage changes) for both continuous and switching operations and harmonics. In this report only flicker calculation for the continuous operation is done.

The effect of flicker is normally expressed in terms of a quantity called flicker severity index, denoted as 'P_{st}'. It is a unit less quantity which describes the amount of annoyance over 10 minutes period. It can be calculated by applying the following formula.

$$P_{st}(\psi_k) = c(\psi_k) \times \frac{S_n}{S_k} \tag{3.2}$$

Where S_n is the rated apparent power of the wind turbine, S_k is the fault level at PCC, ψ is the grid angle at PCC and 'c' is called flicker coefficient. The method for the calculation of flicker coefficient is also described in the same document. Normally its value is provided by the wind turbine manufacturers.

Equation (3.2) is valid to calculate the flicker severity index from only one wind turbine installation. In case more wind turbines are connected at the same point of common coupling, then the combined flicker emission can be calculated by applying the following formula.

$$P_{st\Sigma} = \frac{1}{S_k} . \sqrt{\sum_{i=1}^{N} (c_i(\psi_k).S_{n,i})^2} \tag{3.3}$$

Where N is the total number of turbines connected at same PCC. The description of other parameters is same as given in Equation (3.2).

The maximum P_{st} contribution from a wind turbine installation should not exceed 0.35, as recommended in Sweden [1].

At Hällekis, no wind turbine is installed at the moment and two wind turbines are intended to install at the bus A10. After the load flow analysis, the rating of these wind turbines is already identified. Since the point of common coupling is the same for both turbines, Equation (3.3) is used to calculate the flicker severity index for both turbines. The short circuit power at PCC is found to be 90.14 MVA and the grid angle is 86 degrees at the PCC. The value of the flicker coefficient is varied in the range of 1 to 8 for both turbines to get the relative values of flicker severity index values.

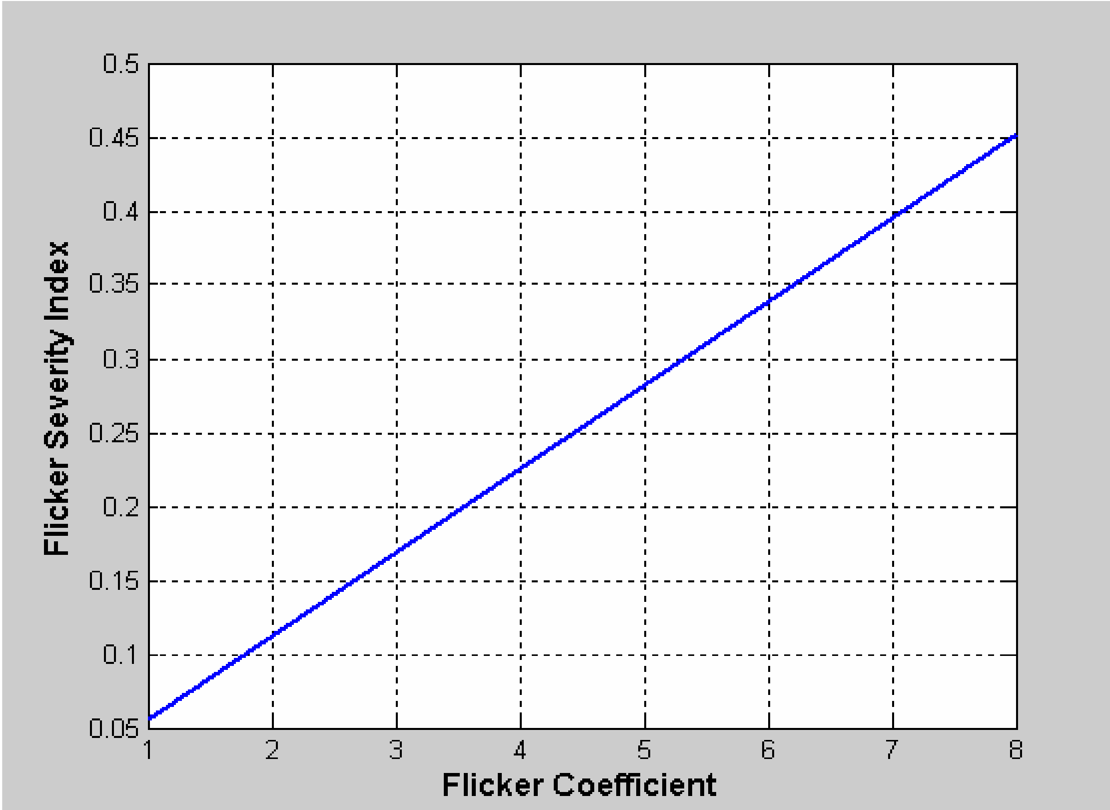

Figure 3.18-Combined flicker severity index of new wind turbines at A10 against the flicker coefficient of new wind turbines.

Figure 3.18 shows the effect of increasing the flicker coefficient on the flicker emission from both turbines. It can be seen that the production of 3.6 MW from each wind turbine with the flicker coefficient of 6 or any value above it, will definitely exceed the value of flicker severity index above 0.35.

3.8 Conclusion

The analysis done in section 3.3 shows that the connection of two wind turbines, with the power rating of 3.6 MW each, doesn't cause the voltages at the load buses to increase beyond permissible limits or makes any component to hit its thermal limits. It should be remembered that the flicker coefficient for both wind turbines must stay below 6 to keep the value of flicker severity index within tolerable limits.

References

[1] *Anslutning av Mindre Produktionsanläggningar till elnätet* (AMP), Sveriges elleverantörer, 1999.

Chapter 4
Investigation for Lundsbrunn Substation

4.1 Brief Description of the Network

The Lundsbrunn site consists mainly of residential loads with some large farms and a small industrial load of 350 kVA. It has individual wind turbines installed on all of its five feeders except one. The already installed wind generation capacity is 5.35 MVA and a maximum load of 3.87 MVA. The rating on most of its 8 installed turbines is 850 kVA while one is 800 kVA and two are 150 kVA each. The distribution medium runs a total of about 42 km and is mainly cables and overhead lines of different thermal limits. The site has two 8 MVA rated transformers of which only one is in operation at a time. The nominal voltage levels at the two sides of the transformer are 42 kV and 10.7 kV. The fault level on at the 42 kV bus is 217 MVA with a grid resistance of 1.9 ohms and reactance of 7.5 ohms.

The feeders are in a radial arrangement with a possibility of interconnection at some points under non-usual conditions. There is an average load of 40 A on each feeder.

The layout of the site is presented in Figure 4.1 below with the turbines at various places indicated.

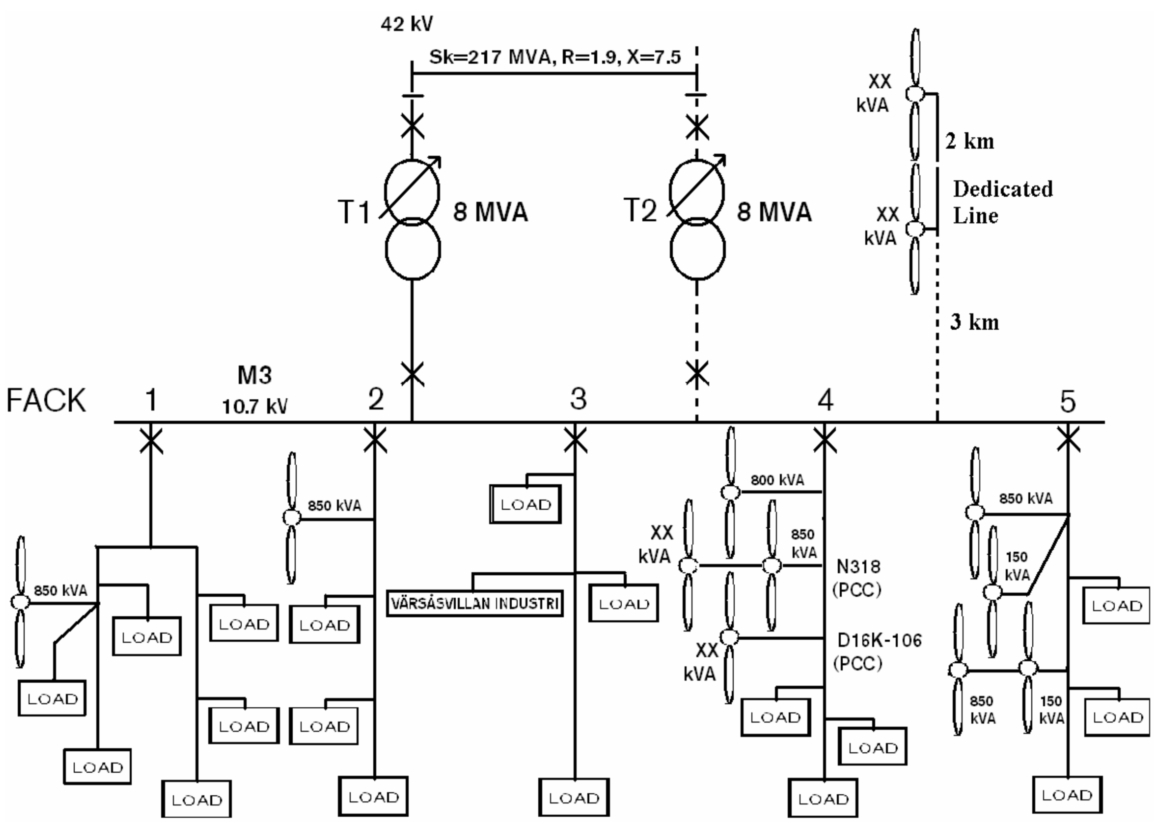

Figure 4.1-Layout of distribution system at Lundsbrunn

4.2 Objectives

It is clear from Section 4.1 that the presently installed wind power capacity is capable of fulfilling the power requirements of the local load while supplying additional power to the grid. The suggested new wind power generators are to be placed at two different locations on feeder 4, which are N318 and D16K-106. The new turbines in Figure 4.1 are shown with a rating of X MVA. These have the option of being 850 kW or 2MW each but the feasible rating and placement location has to be investigated.

Once the feasible rating and location for the new wind turbines on Feeder 4 has been found another interesting possibility has to be studied. A 10 kV line (dedicated to wind power) connected directly to the substation bus M3, assuming an AXCEL 240 cable of a total length of 5 km with a one 2 MW turbine connected at 3 km and two 2 MW turbines connected at 5 km. This is the proposed layout by the client.

For normal operation the questions that have to be answered are

1) Maximum wind power load, mixed with ordinary load, on one transformer? With two transformers operated in parallel?
2) Voltage levels for different load operation conditions (combination of different mixes of load and wind power), including the operation of on-load tap changers.
3) How is the on-load tap changer affected by power fluctuations? Does the number of changes increase?

4.3 Modelling of the Network

In Lundsbrunn the loads are mainly residential and industrial so they are modelled as constant power loads due to the fact that these loads behave as such when their behaviour is studied over a larger time frame.

The residential loads are predominantly heating loads with thermostatic control devices. With a decrease in voltage they behave as constant impedance loads in a shorter time frame but as the on-time of these devices in increased there is a load recovery so that they consume the same amount of power over time [8].

Industrial loads are considered to mostly be dominated by induction motors. In a shorter time frame they also behave as constant impedance loads because their slip cannot be instantaneously changed. But over an extended period of time their behaviour is of constant power nature [9].

Using the constant impedance model for the transient stability studies and constant power model for the voltage stability studies, is relatively accurate for the transient stability studies, and on the safe side for the voltage stability studies [8]. This suggested model is based on studies that have been performed in Sweden.

Since the detailed distribution of loads was not available the total load on a feeder has been divided into three parts and placed at three locations at almost equal distances along the feeder.

The network has variable speed turbines which are normally operated at unity power factor. The wind turbines have been modelled initially as negative power loads at unity power factor. Since the installed wind power generation capacity is not that significant when compared to the fault level available at the point of connection of these turbines, their contribution can be seen as a fluctuating load by the system. They are modelled as generators with a capability to exchange reactive power when voltage control at the point of connection is to be implemented.

4.4 Analysis Procedure

First the operation with one transformer is analyzed and then both transformers are put into operation.

Four possibilities for placement of a turbine are investigated and presented which are,

1) A turbine connected near and supplying power via Västermark (through the same cable) to the point N318 on Feeder 4 as the PCC.
2) A turbine supplying power via D16K-106 as the PCC on Feeder 4.
3) Turbines connected at both the places with some generation.

4) After a feasible rating and placement location is decided from the above possibilities and a turbine of the same rating is assumed to be installed at the location, further integration of wind energy through a separate cable dedicated to wind power supplying directly to the substation.

The analysis is based on the limitations already defined in Section 1.3. Different conditions of load and wind power generation are taken to establish the possible situations in the network. They are

Case A: No Generation, Low Load
Case B: No Generation, Full Load
Case C: Full Generation, Low Load
Case D: Full Generation, Full Load

In the above cases no generation (0%) and full generation (100%) refers to the output from the already installed wind turbines. Low load means a load value on a feeder calculated using 10% of the maximum current recorded on each of the feeders and full load means a load value calculated using maximum current on the feeder.

A series of load flows are calculated to asses the steady state operation of the network, with an increasing amount of power from the new turbine, for any of the above cases defining the condition prevalent in the system.

4.4.1 Steady State Voltage Variation

The new turbine supplies power to the feeder rather than directly to the substation. The voltage at the Point of Common Coupling (PCC) should be within acceptable limits, +2% and -4% provided by the client for a load bus, since a customer can be connected to the PCC.

4.4.2 Thermal Limits

The increased flow of active power also increases the reactive losses [1] in the medium. So the overall loading on the distribution medium is increasing which is also a limiting factor to the integration of wind power.

Although the reactive losses are not the same as resistive losses (which decrease useful energy by conversion to heat) they are used to build-up magnetic field, due to the inherent inductance in the medium, and require the flow of energy from the source. This takes up part of the energy transfer capacity of the medium and thus reduces the space for useful energy with this amount.

Since the system is a low voltage system (11kV) the resistance can be of the same order or more as the series reactance of the medium, per unit length and it cannot be neglected.

The loading on the transformer has to be considered also. The application of load in excess of name plate rating involves a degree of risk and accelerated aging. For short term transformer failure, the main risk is the reduction of dielectric strength due to the release of gas bubbles in regions of high electric stress. The probability of occurrence of these bubbles is closely related to the winding insulation hot spot temperature and moisture content of insulating paper. The main consequence of long duration over-load is the thermal aging of solid insulation [2]. The system has two transformers of 8 MVA rating each. Both the transformers are over 37 years old. So aging might be a significant factor. A transformer can be operated 50% overloaded but that is only for some hours.

In normal operation only one of the transformers is put into operation. The transformer nominal voltage rating is 42 kV/10.7 kV. Each transformer is equipped with a tap changer. The magnetization losses of the transformer have been neglected during the analysis; they are about 39.2 kW at full load given by the manufacturer.

In the system being studied the thermal limit of four components has to be considered. These are the cables and overhead lines (of Feeder 4) of different ratings and the transformer. These are indicated in Table 4.1. The feeder diagram indicating the location of these components is presented in Figure 4.2.

Table 4.1-Thermal rating of components

Component	Type	Rating (MVA)	Links
Transformers	Substation	8.0	42 kV grid to M3
Cable	ACJJ70	3.1	M3 to D17L-101
Over-Head Line	FeAl99	5.2	D17L-101 to N318
Cable	AXCEL95	4.5	N318 to Västermark

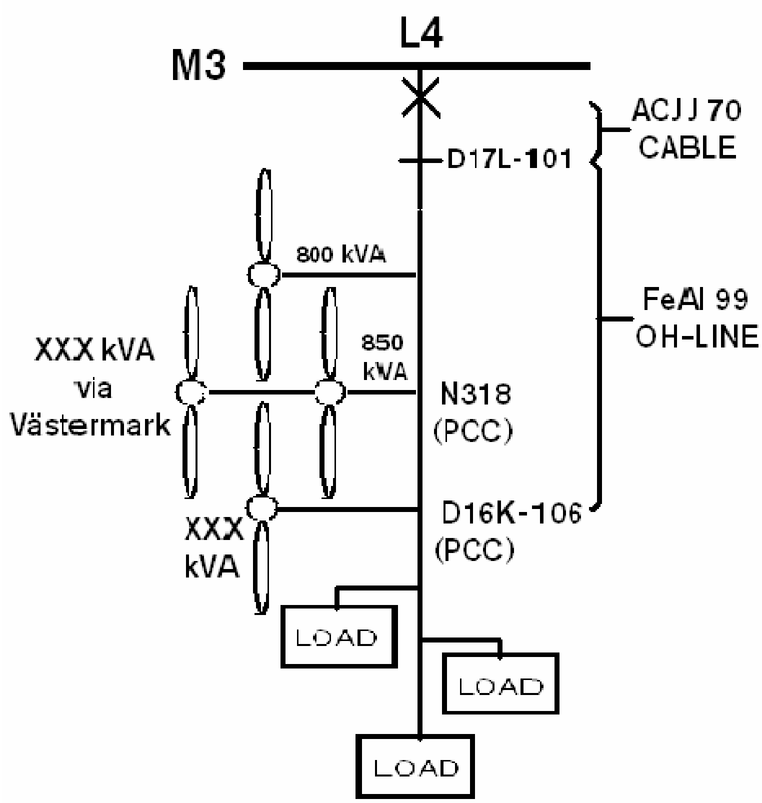

Figure 4.2-The layout of Feeder 4 at Lundsbrunn with the possible connection points of the new turbines

4.4.3 Parallel Operation of Transformers

At Lundsbrunn one transformer out of the two is in operation at any time. The transformers are rated 8 MVA each but have slightly different reactance so it is expected that they will have different loading if put into parallel operation depending on the reactance.

The conditions for parallel operation of two or more transformers are summarized below [3].

1) Same voltage values at both sides of the transformers.
2) Same voltage phase shift, which means identical clock numbers.
3) Same relative short circuit impedance.

The two transformers at the Lundsbrunn substation have different relative short circuit impedance. Transformer T1 has a relative short circuit resistance and reactance of 0.49 % and 7.75 % respectively. Transformer T2 has a relative short circuit resistance and reactance of 0.49 % and 6.35 % respectively. This means that there will be a larger voltage drop over T1 than T2 at full load.

In order to have the required voltage on the secondary of the transformers, the off-nominal voltage on the secondary of T1 is adjusted to 1.0023 p.u. and for T2 it is adjusted to 0.9972 p.u. This means that if the two transformers are operated in parallel there will be a circulating reactive power between the two transformers, from transformer T1 to T2, which will cause unnecessary loading on both transformers. In the analysis with parallel operation of transformers we keep these adjustments. It is found that 0.3 Mvar power circulates between the two transformers. The calculation concerning this is found in Appendix B.

Normally the transformers operated in parallel have one control governing both of them. The dead band setting for both the transformers is the same so that they change their taps at the same time.

The regulating transformers in this system implement voltage control only. This means that using the tap changer, only the magnitude of the voltage is changed at the secondary of the transformer (reactive power control) and not the phase angle (active power control).

4.5 Turbine Connected via Västermark

The new turbine to supply power via Västermark (given the name Västermark 2 for ease of reference) is to be connected with an additional cable length of 500 meters of type AXCEL95. The already installed turbine at Västermark (given the name Västermark 1) has a rating of 850kVA.

4.5.1 Operation with One Transformer

4.5.1.1 Steady State Voltage Variation

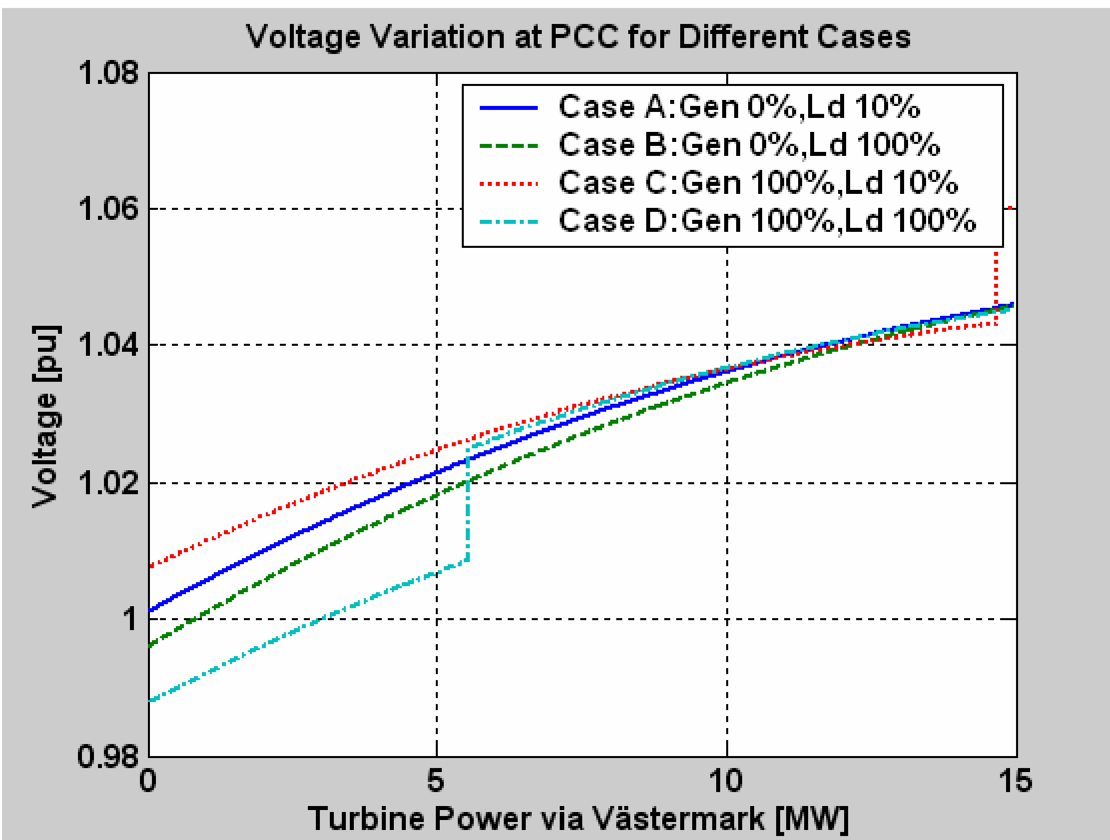

Figure 4.3-Voltage variation at point of common coupling (N318) for different cases

The power output from a wind turbine will vary in a shorter time frame as well as in a longer time frame. This causes voltage variations in the system. The power injection from the wind turbine will cause a voltage rise at its point of connection. In the simulations performed, the turbine output is limited so that the steady state variation in voltage at the PCC is not more than +2% and -4% within its generation range. In Figure 4.3 the voltage at N318 (which is the PCC) for the four generation and load possibilities is shown.

It can be observed in Figure 4.3 that before any power from the new turbine is fed into the network the starting voltage for Case C is the highest, since we have low consumption and high generation of power. This case gives the lowest amount of wind power for the 1.02 p.u. voltage limit at PCC. So it appears that the maximum power input from a turbine if installed at Västermark is 3.5 MW, considering voltage limits.

One more thing that can be observed is that the voltage rise per unit of turbine power is lower for Case C as compared to other cases so that the all the voltage profiles seem to coincide at 1.04 p.u. This may be attributed to reactive power flow difference for different cases as discussed below. It should be kept in mind that the voltage rise rate at a bus, with the injection of active power, can be reduced if more reactive power is absorbed [7].

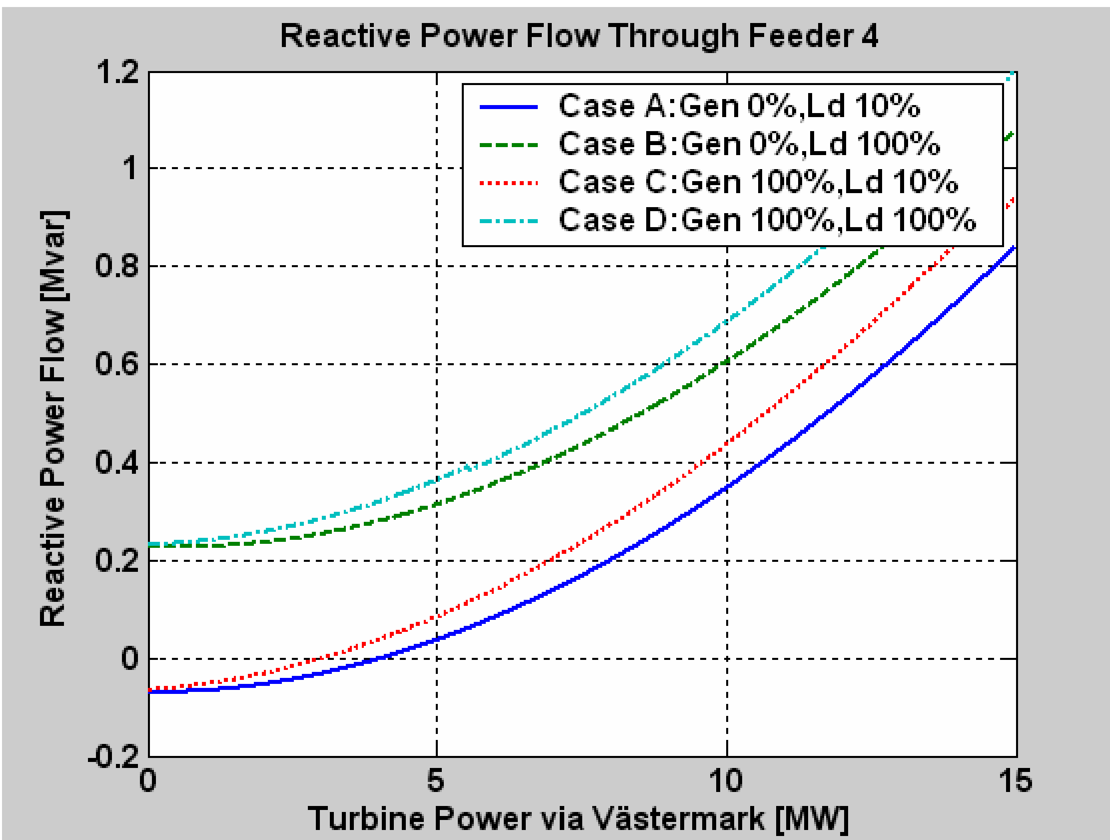

Figure 4.4-Reactive power flow through Feeder 4

The Figure 4.4 shows the reactive power flow along Feeder 4 with increasing turbine active power.

Two things can be observed, one being that the reactive power generated in the system is more than the load requirement for Case A and Case C with 10% load and 0% and 100% generation respectively. It is indicated by a starting negative value of reactive power. This is due to the fact that here the distribution medium is mostly made up of cables which have a greater charging. This capacitance, between phases and phase to ground, is a constant source of reactive power dependent on the operating voltage [3]. This generation of reactive power limits the flow of active power.

The charging in over-head lines is less compared to cables because in cables the inter-phase distance is very small. But there is always capacitance between phases and from phase to ground in an over-head line.

When the reactive power flow along the line becomes zero the reactive power generation and consumption in the line is balanced.

In Case B and Case D with 100% load and 0% and 100% generation respectively the system is consuming reactive power throughout. The load reactive power requirement and the reactive losses in the series reactance of the medium is more than charging alone can provide.

The other observation made for example, for Case A and Case C is that the rise in the reactive power consumption with active power injection from the turbine is more with 100% generation (Case C) than with 0% generation (Case A) from the already installed turbines keeping the same amount of load (10%). This can be explained if one appreciates the fact that the reactive losses in the transmission medium increase in direct proportion and exponentially to the active power transmission [1]. For the same amount of active power added, the increase in reactive losses is more when there is already a greater amount of active power being transmitted than when there is a comparatively smaller amount transmitted. In Case C with 100% generation (from the installed turbines) this means that the two turbines in feeder 4, one at Lunden with 800 kVA and the other at Västermark with 850 kVA, are contributing their full generation capacity of active power and thus the input from the new turbine is being added on top of it. This leads to that the reactive consumption (loss) increases more for Case C than Case A.

This is the reason cited above for the less steep voltage profile for Case C in Figure 4.3. A close up view of the Figure 4.4 is presented in Figure 4.5 where it is seen that the reactive power supplied to the network is less in Case C than in Case A because some of the reactive power generated by the line charging is used to make up for the reactive power consumption as a result of the 100% generation from the installed turbines.

The active power flow along Feeder 4 is shown in Figure 4.6.

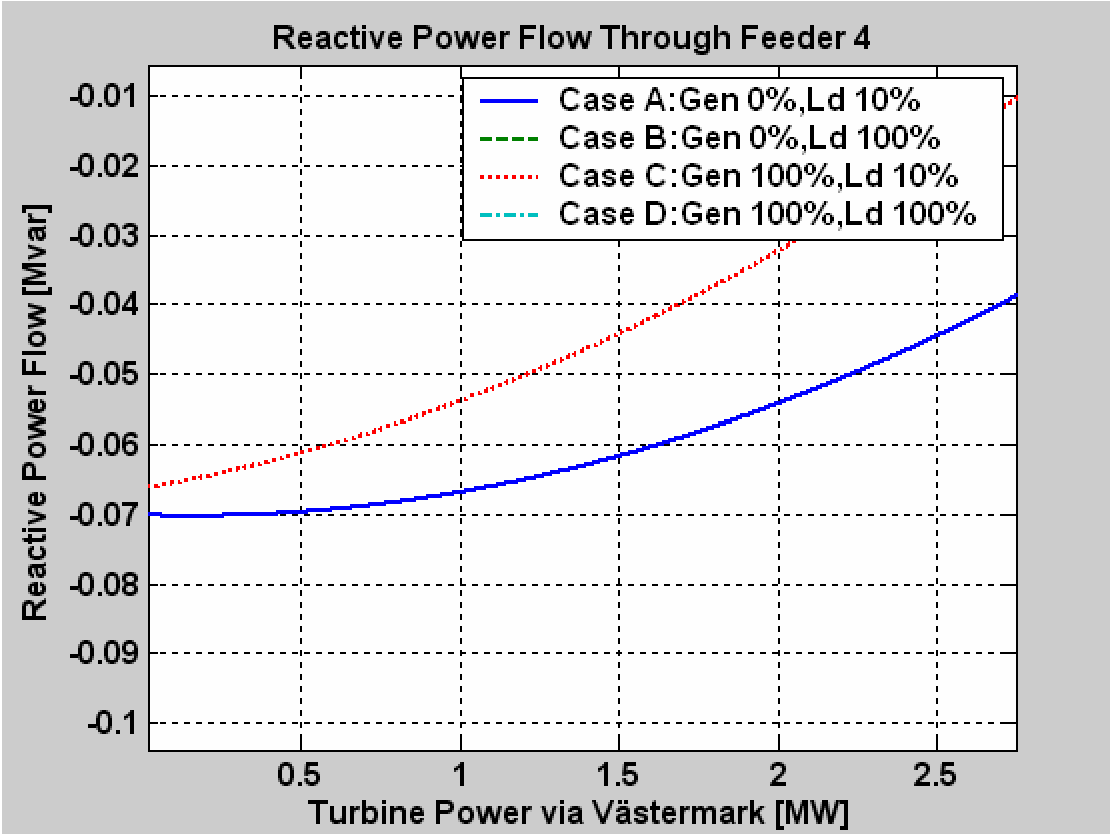

Figure 4.5-Close-up presentation of reactive power flow through Feeder 4

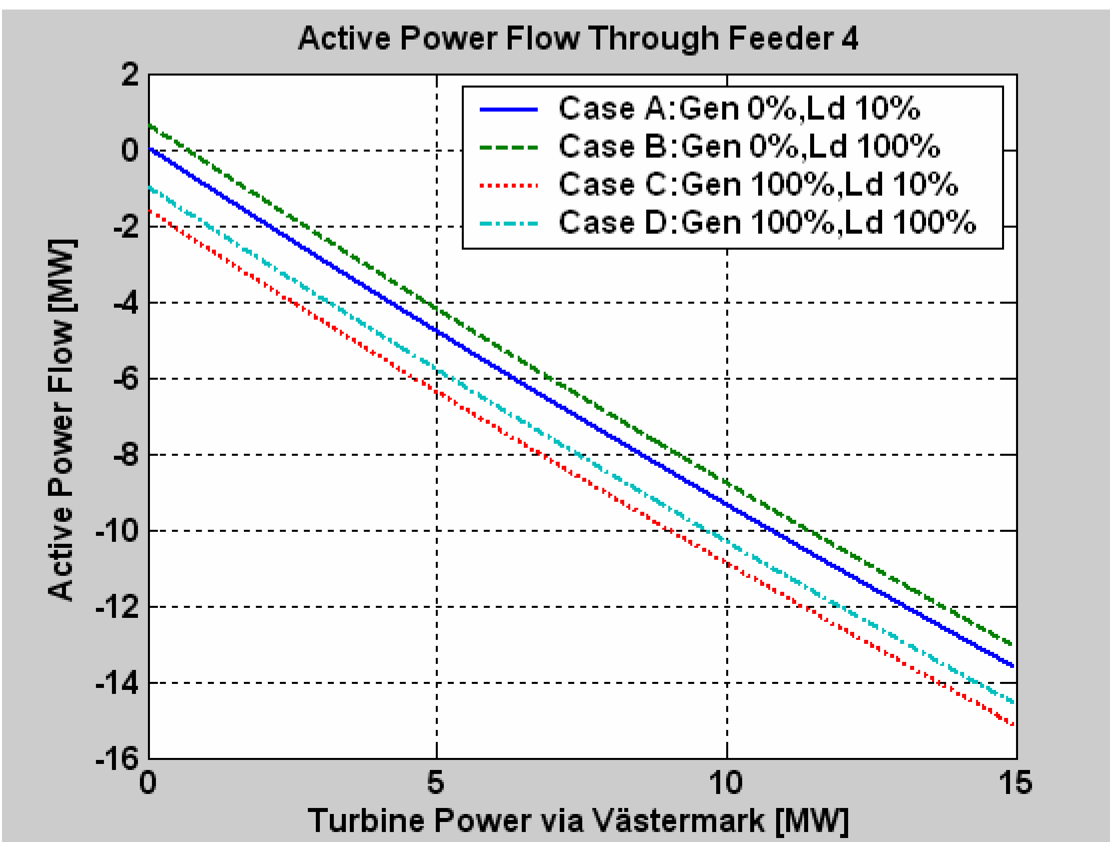

Figure 4.6-Active power flow through Feeder 4

4.5.1.2 Bus Voltages across the Network

The voltage on the feeders depends on the voltage on the secondary of the transformer, already installed wind turbine generation as well as the amount of load. The voltage at various load points on the feeder has to be observed to ensure that it is within limits of +2% and -4% recommended by the client.

The voltage at the secondary of the transformer, designated as M3 depends on the active and reactive power through the transformer. The active power through the transformer is shown in Figure 4.7. Since the loads are modelled as constant active and reactive power loads their consumption does not vary with active power injection from the turbine. This is why the active power through the transformer is varying with the same rate for all cases with the increasing input from the new turbine.

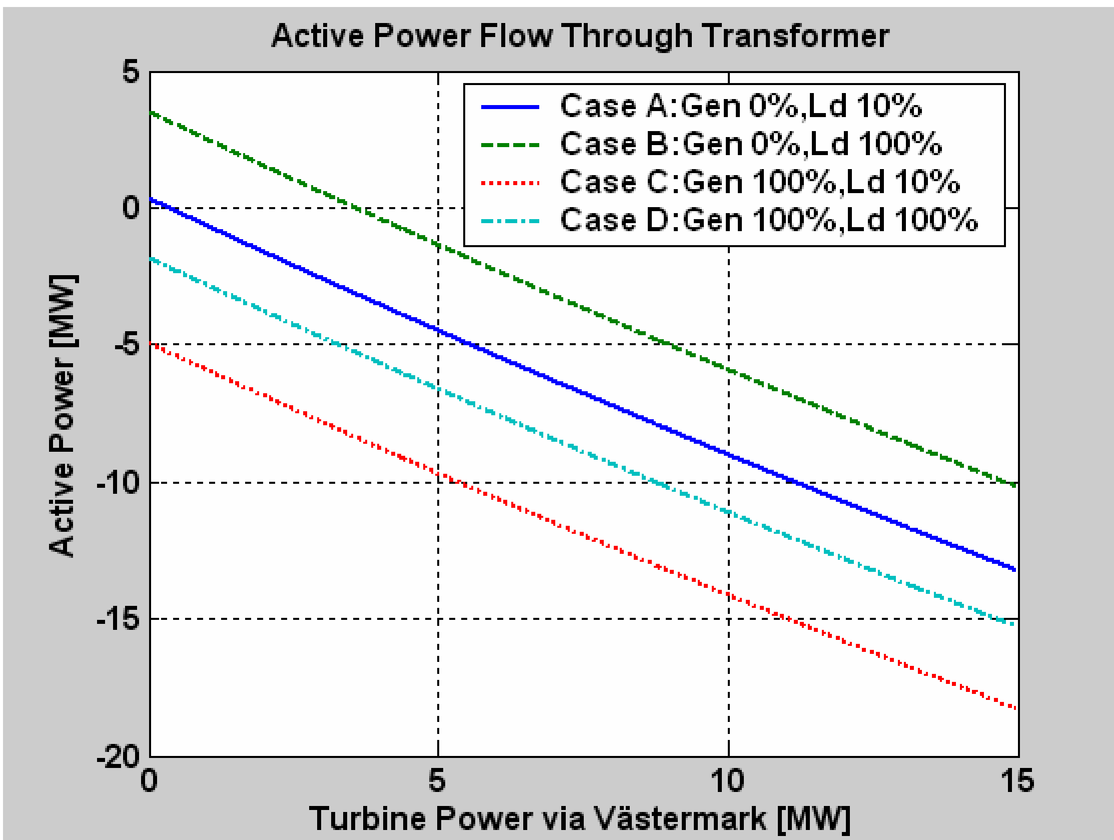

Figure 4.7-Active power flow through transformer

The Figure 4.8 shows the voltage on M3 for different cases. The difference in the voltage profile for different cases is a consequence of the reactive power flow through the transformer. The Figure shows a greater starting voltage for Case B (0% Generation, 100% Load) than Case D (100% Generation, 100% Load) because the transformer has changed its tap to correct the voltage outside its dead band (1.4% above and below the nominal value).

The voltage at M3 for Case A and Case D increases as more active power is injected by the turbine while the reactive power consumption increases by almost the same rate. The reactive power flow through the transformer is shown in Figure 4.9.

If we compare the voltage profile for Case C and Case B it behaves quite the opposite. In Case C the voltage is decreasing while in Case B it is increasing. This is also explained by the reactive power flow through the transformer. The reactive power in Case C increases more rapidly than in Case B.

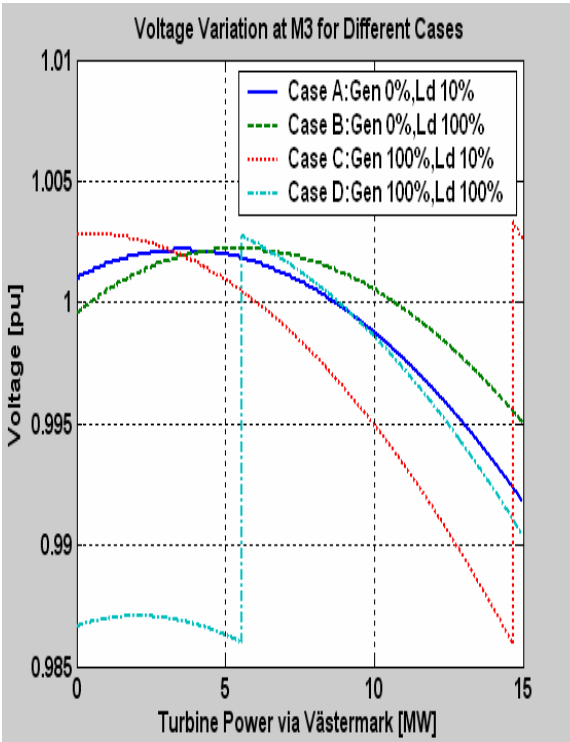

Figure 4.8-Voltage variation at M3 for different cases

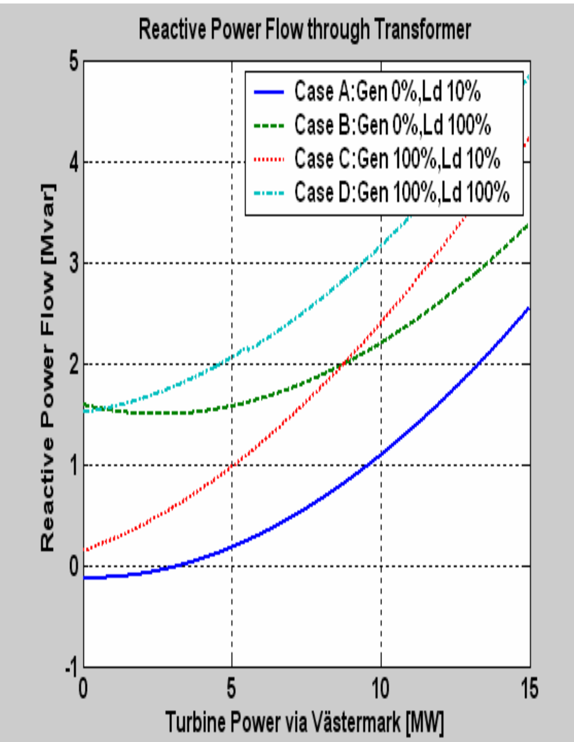

Figure 4.9-Reactive power flow through transformer

Two cases are expected to present the extreme conditions regarding the voltage magnitude at the buses in the network. When there is no generation from the installed turbines and maximum load (Case B), the voltage at various buses on the network should be the lowest but the transformer changes its tap and the voltages are improved. Actually the case with full generation and full load (Case D) has the lowest voltage on the buses. In case of full generation from the turbines and low load (Case C), the bus voltages will be the highest.

The power input from a turbine will cause the voltage at the bus to rise. The voltage for the buses which have the minimum and the maximum voltage magnitude, along with the transformer secondary voltage and voltage at the PCC are plotted in Figure 4.10 (a) & (b) for the worst cases for voltage.

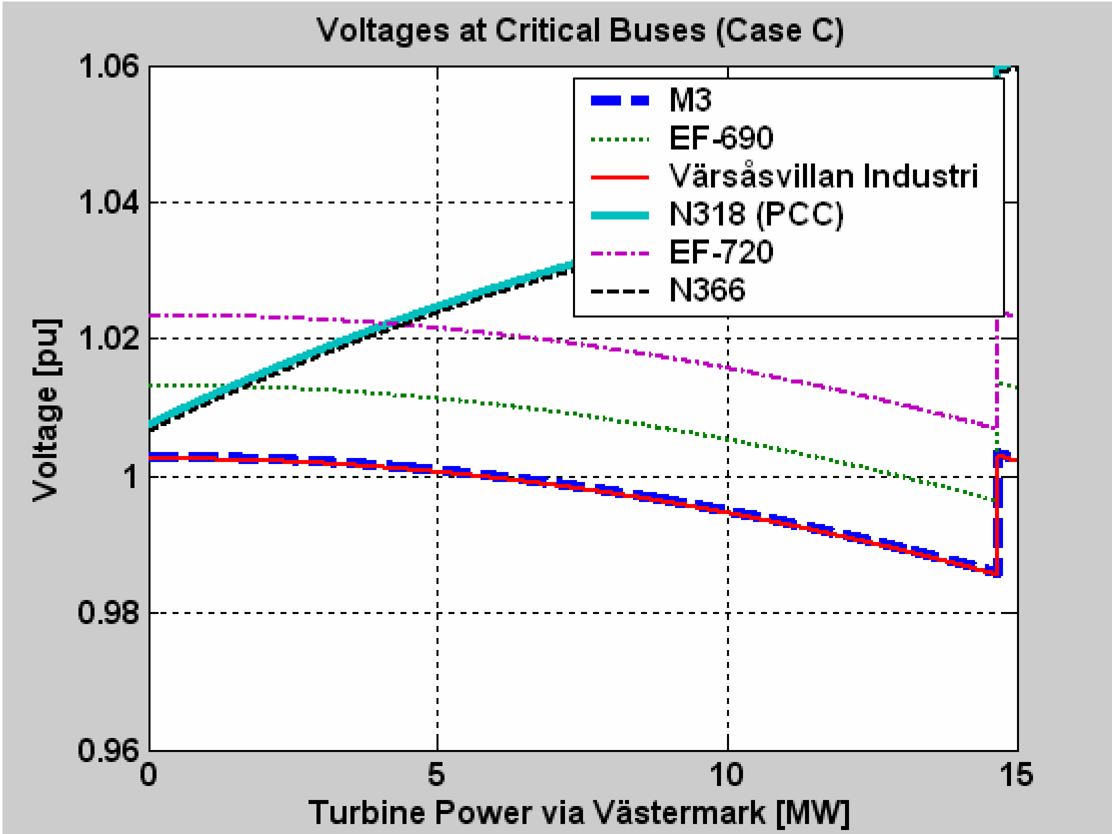

Figure 4.10 (a)-Voltage at load buses in network

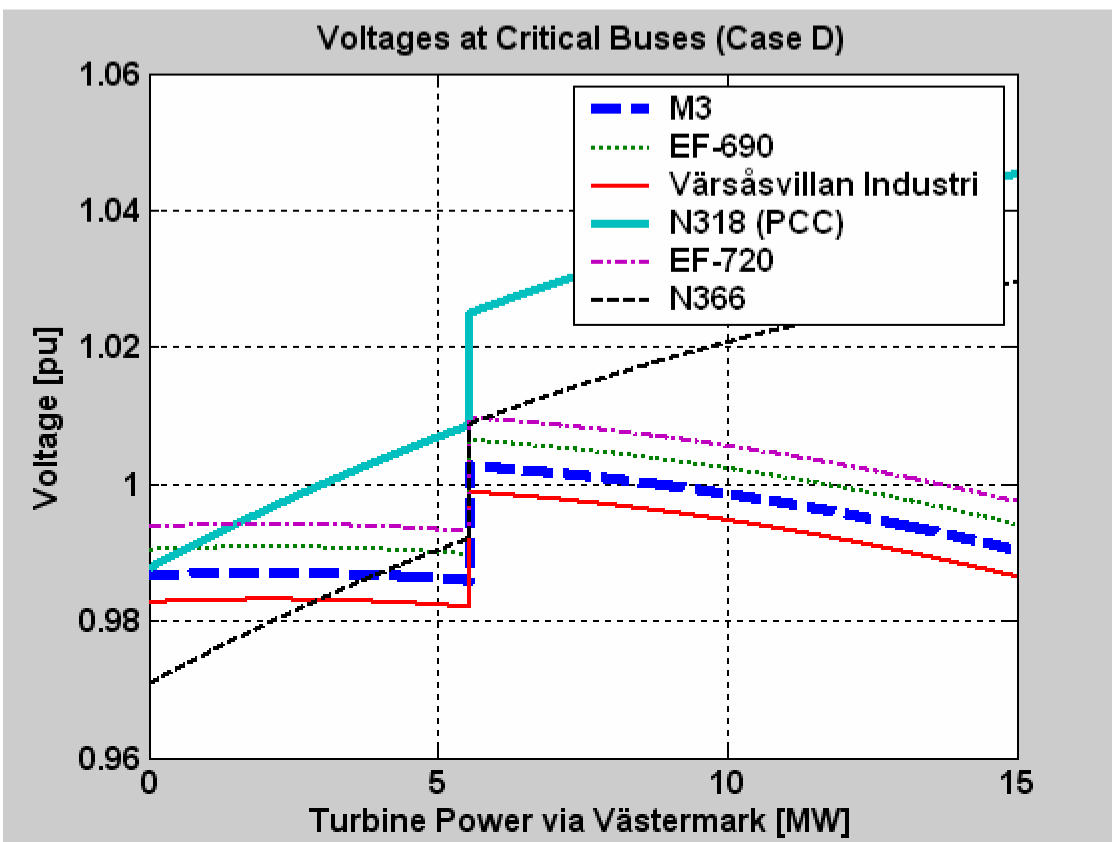

Figure 4.10 (b)-Voltage at load buses in network

It is seen that the voltage on bus EF-720 which is on Feeder 5 is outside the upper voltage limit of 1.02 p.u. This bus has two wind turbines installed at Erikstorp with a total generation capacity of 1 MVA. It might be possible for these turbines to absorb some reactive power to lower the voltage at the bus while generating their rated power alternately the tap setting of the wind turbine transformer could be adjusted.

4.5.1.3 Thermal Limits

The component loading is considered for Feeder 4. The loading on the other feeders does not change with the increasing power of the new turbine on Feeder 4 due to the constant power loads.

4.5.1.3.1 Thermal Loading Limits on Cable ACJJ70

The cable of type ACJJ70 has a 3.1 MVA rating and is the lowest rated component amongst those presented in Table 4.1. Its thermal limit is expected to be the first barrier. This cable connects the substation transformer to the overhead line (M3 to D17L-101). It is probably within the premises of the substation. The loading of this medium is presented in Figure 4.11 for different cases.

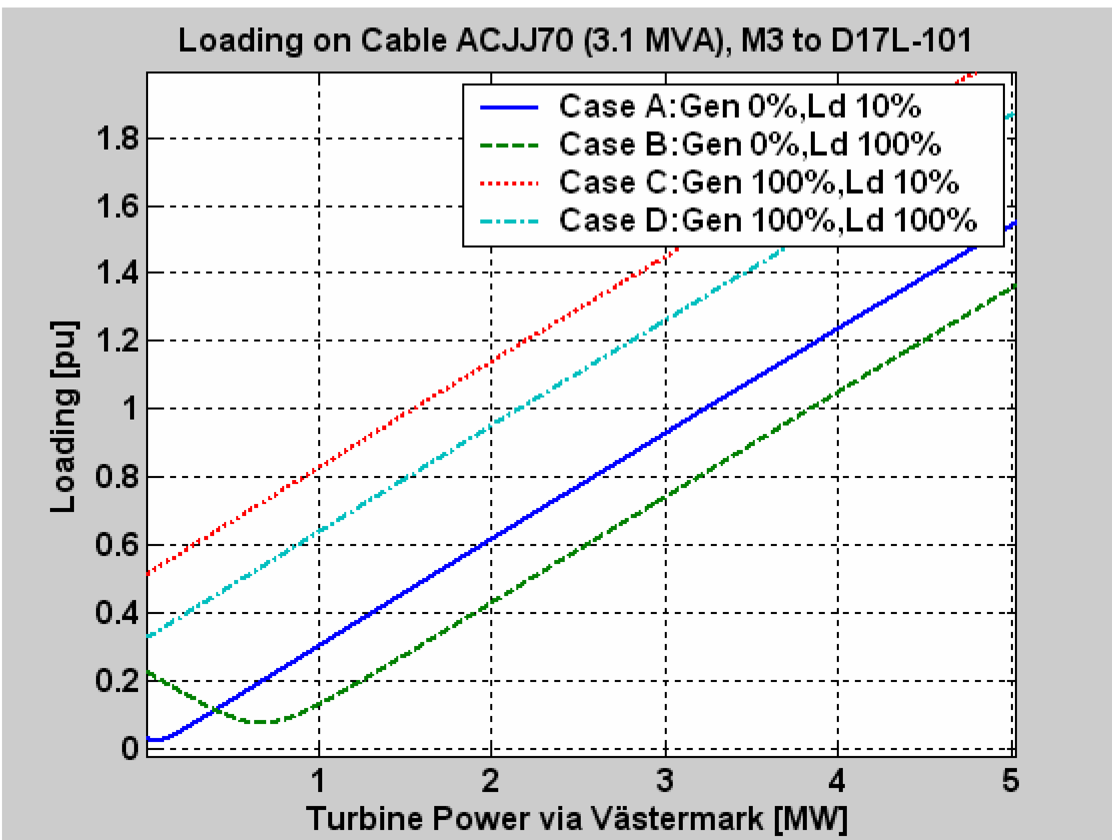

Figure 4.11-Loading on cable ACJJ70 between M3 and D17L-101 on Feeder 4

The generation in Case C and Case D, with the installed turbines on the feeder, is more than the load consumption but with Case A and Case D the loading first decreases and then increases when the power from the new turbine is in excess of that required in Feeder 4. The reason it does not go to zero is that only the requirement of active power is made for by the new turbine operated at a unity power factor. The reactive power required keeps some loading on the cable.

One more observation that is made is that the loading curves in Figure 4.11 become straight lines. This seems contrary to the earlier comment made, that with more flow of active power in the feeder the reactive power consumption increases exponentially. Thus it should be expected that the curves should not be straight lines. The fact is that the increase in the reactive consumption is not that significant when compared to the active power increase (below 1 Mvar up to 12 MW in all cases), see Figure 4.4. It renders itself negligible with a square in the apparent power calculation equation given as Equation (4.1).

$$S = \sqrt{P^2 + Q^2} \tag{4.1}$$

It is also possible here to quantify the load on the feeder. Consider Case B, the lowest point on its curve corresponds to about 0.67 MW of turbine power via Västermark on the x-axis and 0.073 p.u. of loading on the y-axis. In keeping with our discussion this indicates that we have 0.67 MW of active power load on the feeder and 0.226 Mvar of reactive power load on the feeder.

The limit on the turbine power via Västermark, posed by the thermal loading on Cable ACJJ70 is 1.55 MW as can be seen for Case C in Figure 4.11.

4.5.1.3.2 Thermal Loading Limits on Cable AXCEL95

This is the cable type used mostly throughout the Lundsbrunn site to transmit the powers of the turbines to the PCC. The rated power of this cable is 4.5 MVA.

At the Västermark location the new turbine (Västermark 2) will have this type of cable extending from the 0.850 MVA turbine (Västermark 1) already present and so it will have to share the cable from this turbine to N318 on Feeder 4 to transfer its power. This leaves a room for about 3.6 MVA contributions from the new turbine before the thermal loading limit for this part of cable is reached.

The active and reactive power loading of the cable length from Västermark1 to N318 is given in Figure 4.12 (a) & (b) respectively.

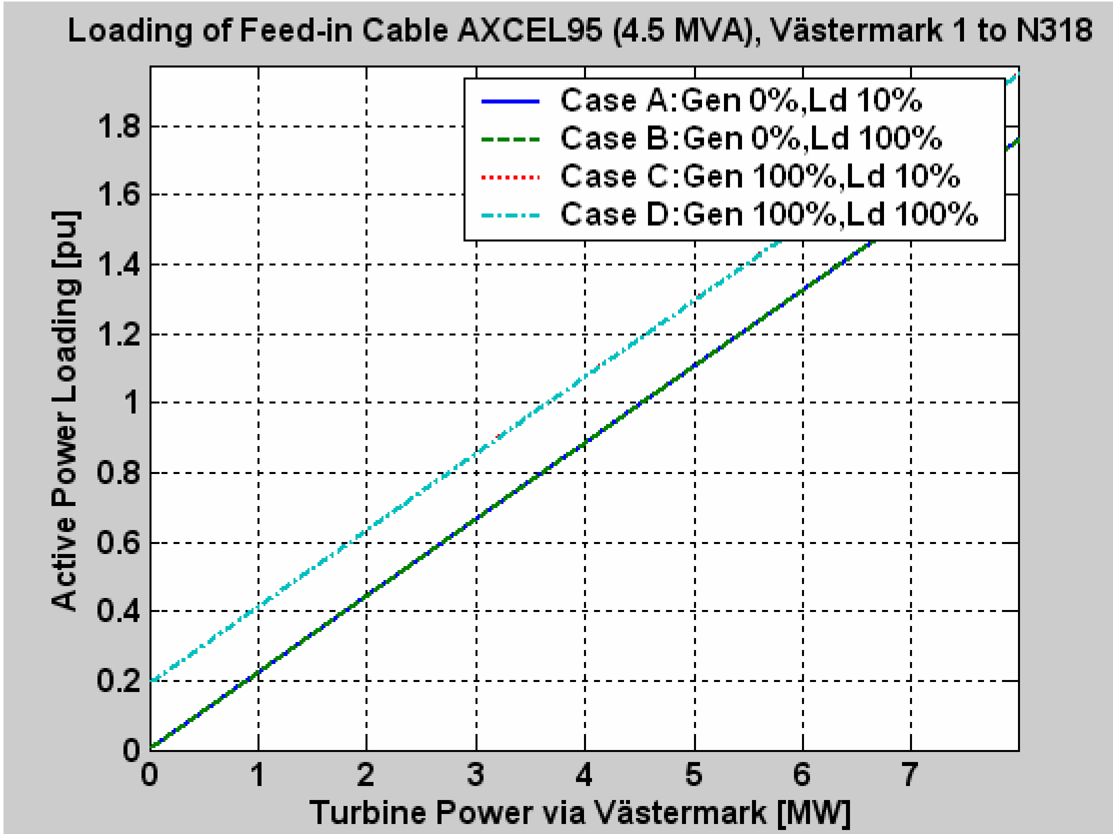

Figure 4.12 (a)-Active power loading of evacuation cable from Västermark 1 to N318

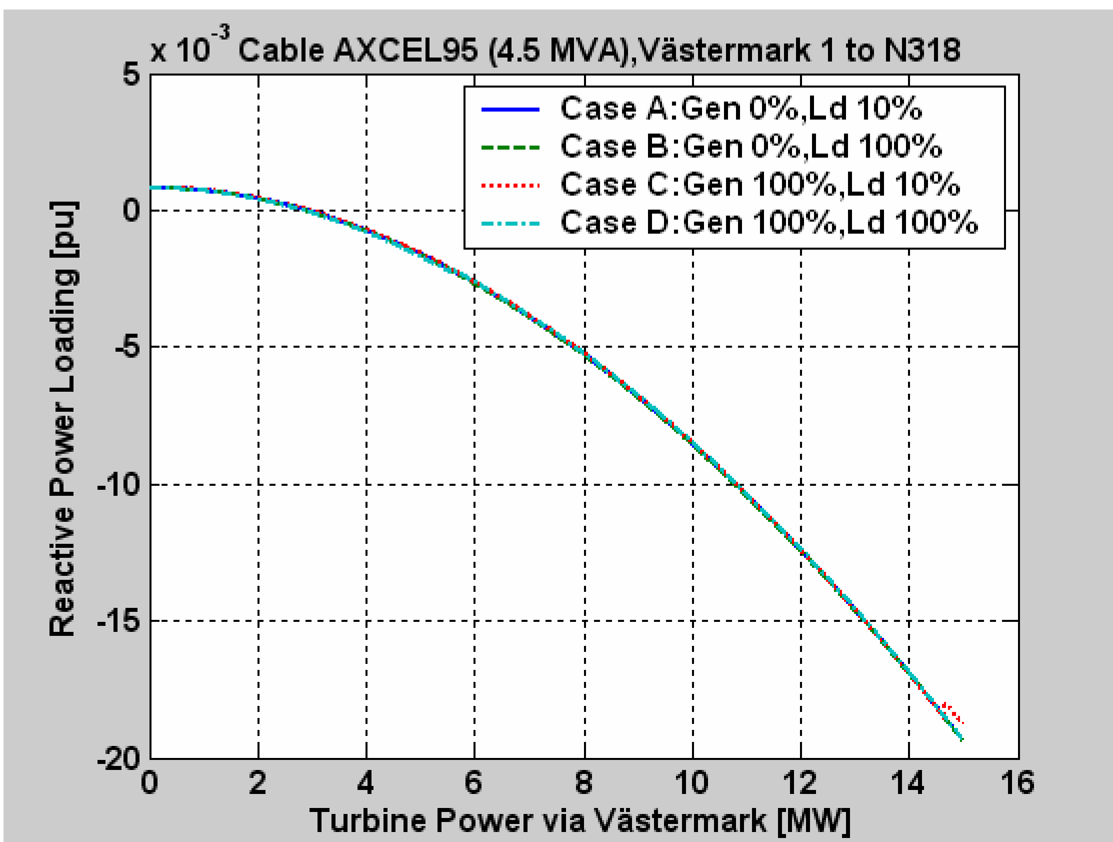

Figure 4.12 (b)-Reactive power loading of evacuation cable from Västermark 1 to N318

Figure 4.12 (a) shows that Turbine Power via Västermark is limited to 3.6 MW for cases with 100% generation for 1 p.u. loading of the AXCEL95 cable.

The reactive demand is almost the same in all cases; see Figure 4.12 (b).

4.5.1.3.3 Thermal Loading Limits on Overhead-line FeAl99

This over-head line runs from D17L-101 to D16K-106 on Feeder 4, see Figure 4.2. The segment of the over-head line between D17L-101 to 3005 is expected to reach the thermal limit the earliest due to the additional contribution from the 0.800 MVA turbine installed at Lunden.

The loading of the overhead lines is presented in Figure 4.13.

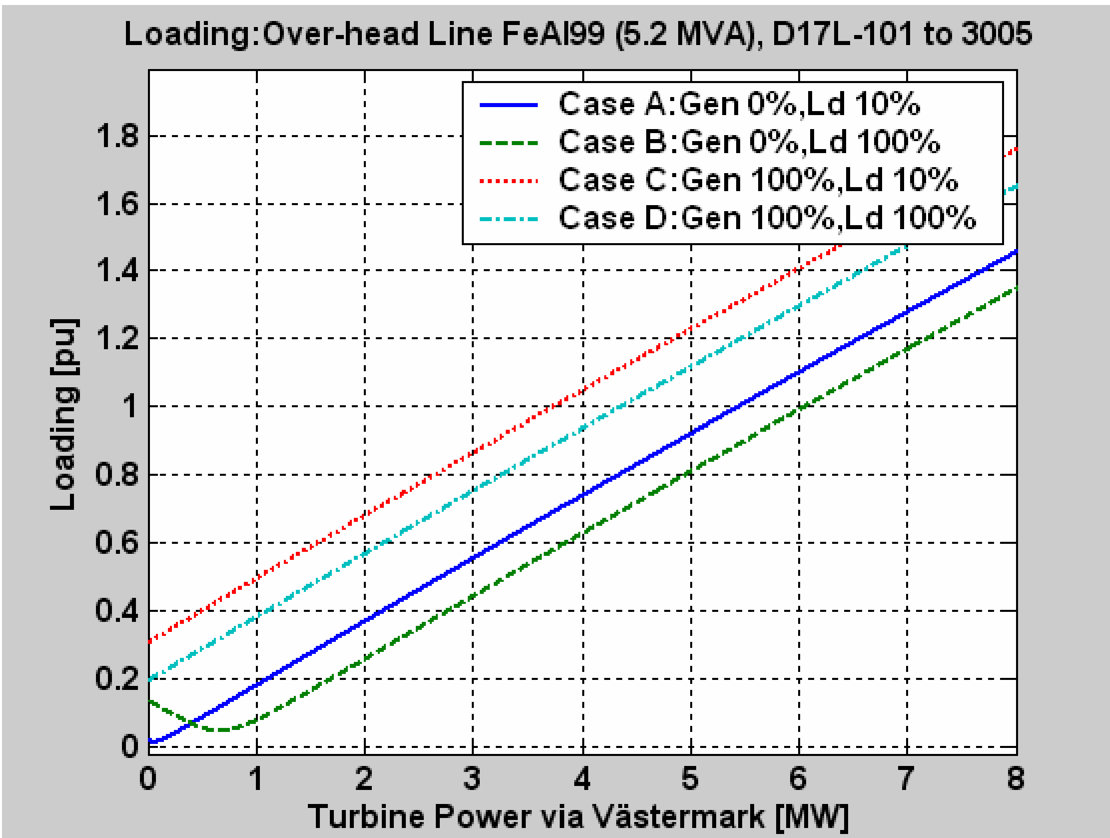

Figure 4.13-Loading of over-head line (5.2 MVA) from D17L-101 to 3005 on Feeder 4

The thermal limit of the over-head line is reached with an input of 3.7 MW of turbine power via Västermark in Case C. This is taken as the limit posed by the over-head line. In Case B the limit is reached at 6 MW because a 100% load of about 0.7 MW on the feeder is also supplied and the excess flows through the over-head line to the network. The overhead line rating is 5.2 MVA so the difference with turbine input is 0.8 which is consistent with the conclusion drawn above.

4.5.1.3.4 Transformer Loading

The loading of the transformer is given in Figure 4.14.

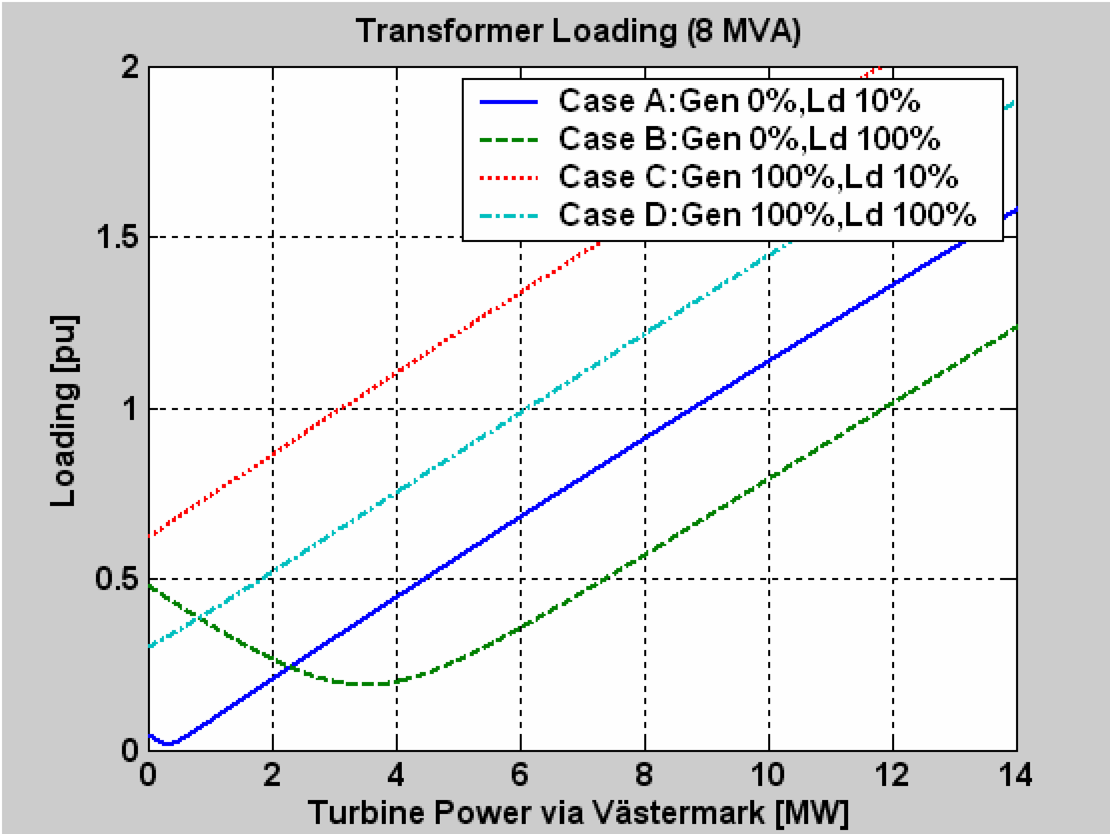

Figure 4.14-Transformer loading (8 MVA)

The transformer is fully loaded at about 3 MW in Case C which will be the limit regarding transformer loading. If Figure 4.7 is referred it is seen that the transformer is most loaded for active power in Case C and Figure 4.9 shows that the rate of the reactive power increase is also the highest for Case C. This leads to that the transformer is fully loaded for Case C first.

4.5.1.4 Results

Table 4.2 sums up the integration possible in different cases for a turbine supplying power via Västermark keeping all the limiting factors. The minimum of which should be selected to remain within the limits.

Table 4.2-Summary of possible power input from the new turbine for different cases with Transformer T1

Limiting Factors (100% Loading)	Generation 0%		Generation 100%	
	Load 10%	Load 100%	Load 10%	Load 100%
Voltage 1.02 p.u. at N318 (PCC)	4.6 MW	5.5 MW	3.5 MW	5.54 MW
Thermal Limit ACJJ70 (3.1 MVA)	3.23 MW	3.84 MW	1.55 MW	2.16 MW
Thermal Limit AXCEL95 (4.5 MVA)	4.52 MW	4.52 MW	3.67 MW	3.67 MW
Thermal Limit FeAl99 (5.2 MVA)	5.41 MW	6.03 MW	3.7 MW	4.3 MW
Transformer T1 (8MVA)	8.8 MW	11.9 MW	3.16 MW	6.0 MW

The condition with 100% generation from the already installed turbines and 10% load (Case C) presents the most critical case for the input of additional power from the wind turbine. This is because the generation already installed is more than the total load on the network. The voltages are the healthiest and the distribution medium is the most loaded in this condition.

The results with the other transformer T2 in operation only are found for the Case C. The results are summarized in Table 4.3.

Table 4.3-Summary of possible power input from the new turbine for different cases with Transformer T2

Limiting Factors (100% Loading)	Generation 100%
	Load 10%
Voltage 1.02 p.u. at N318 (PCC)	3.2 MW
Thermal Limit Cable ACJJ70 (3.1 MVA)	1.55 MW
Thermal Limit Cable AXCEL95 (4.5 MVA)	3.66 MW
Thermal Limit Over-head Line FeAl99 (5.2 MVA)	3.74 MW
Transformer T2 (8 MVA)	3.16 MW

The thermal limits allow the same amount of power input from the turbine but the voltage limit has further limited the power input possible. This is because the lower reactance of transformer T2 causes less reactive power loss in it for the same flow of active power through it. With less reactance and thus less reactive power consumption, the voltage on the secondary of the transformer T2 is higher. This results in improved voltages in the entire network down stream of the transformer. The voltage, active and reactive power comparison for the two transformers is presented in Figure 4.15 (a), (b) & (c) respectively.

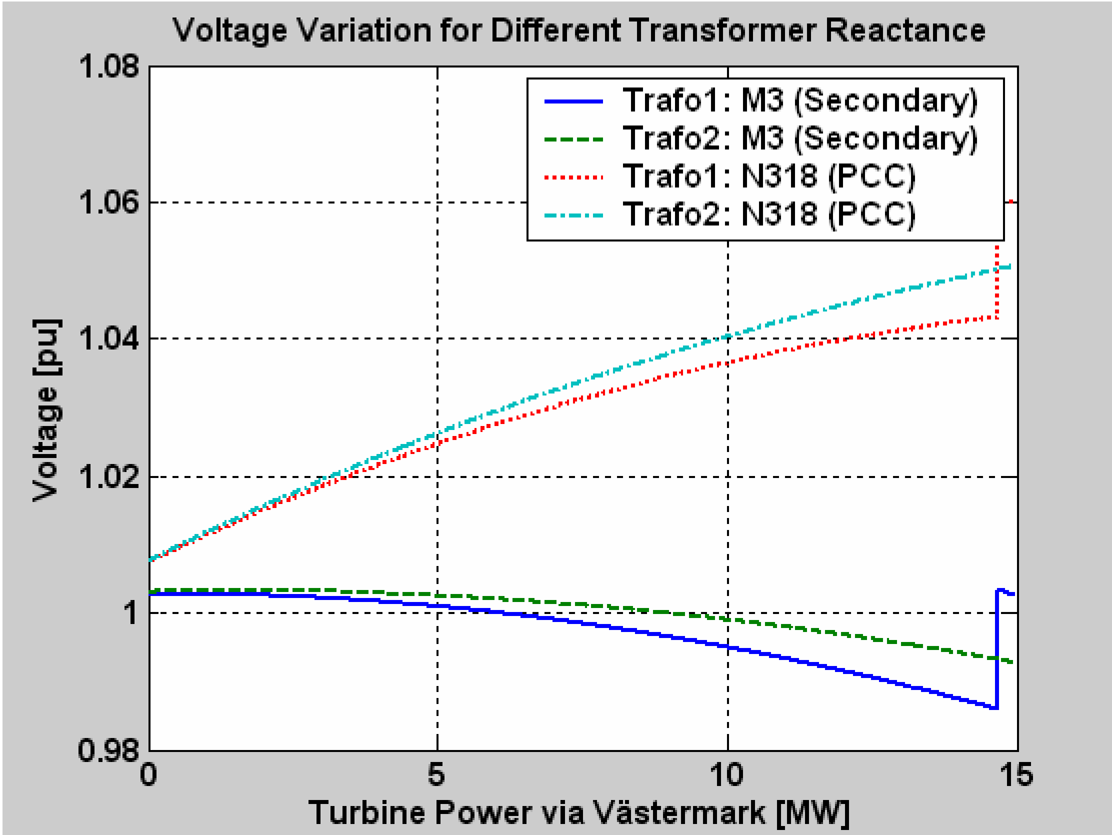

Figure 4.15 (a)-Voltage comparison at the transformer secondary and the point of common coupling for the transformers with a slightly different series reactance. Transformer T1 has 7.75% and Transformer T2 has 6.35%.

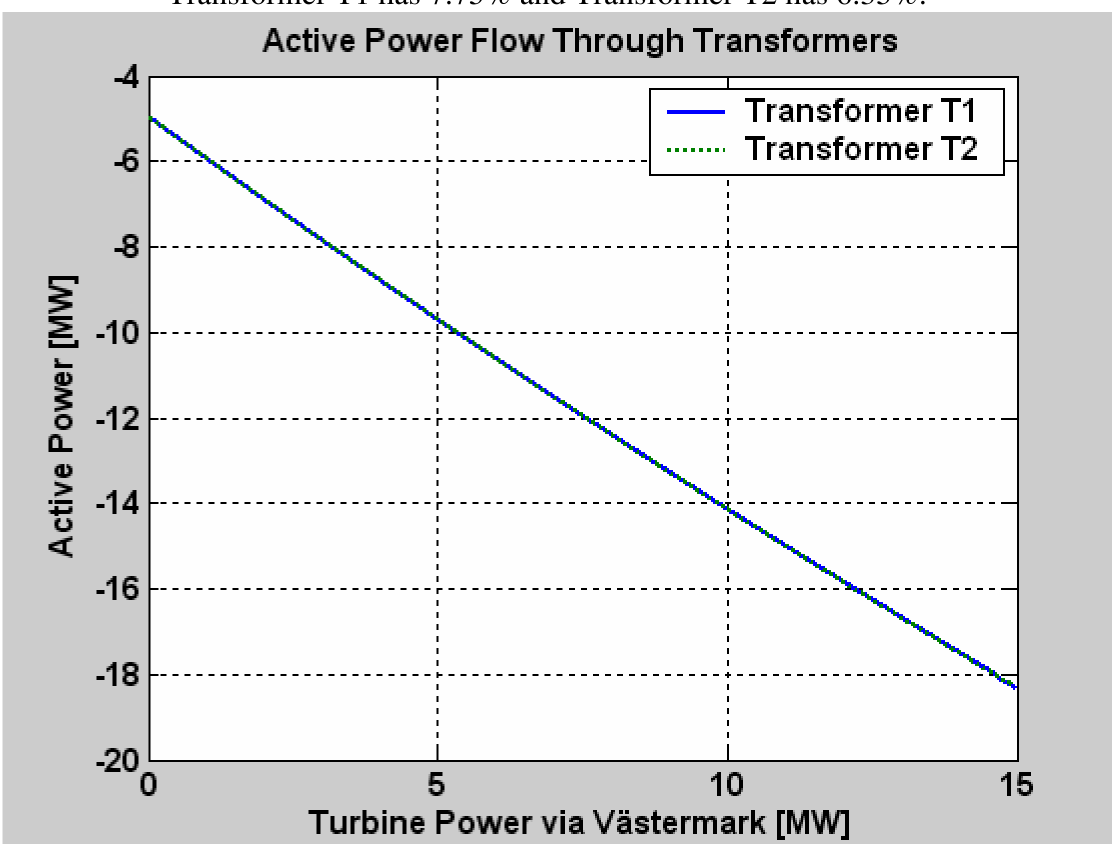

Figure 4.15 (b)-Active power flow comparison for the transformers.

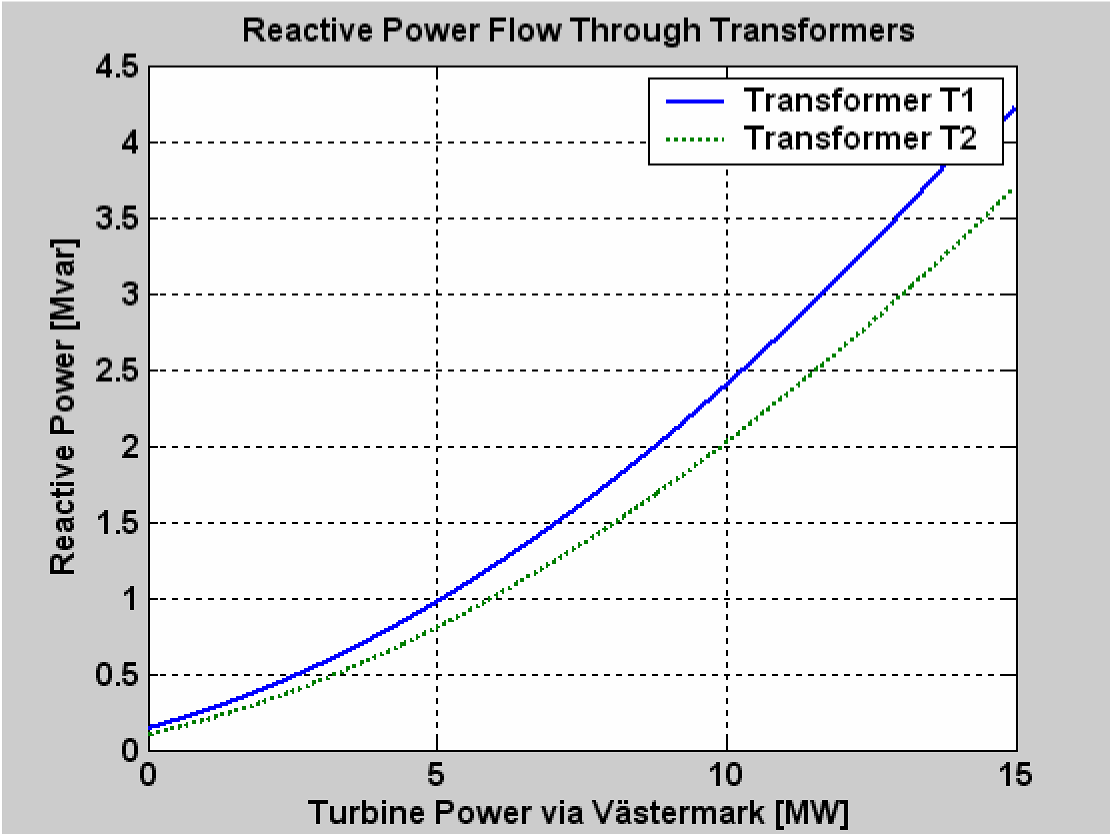

Figure 4.15 (c)-Reactive power flow comparison for the transformers.

4.5.2 Operation with Parallel Transformers

It was observed that the thermal limits on the cables and overhead lines allow the same amount of wind power injection before reaching their limit. The voltage limits and transformer loading are different and so presented. The analysis with parallel operation of the transformers follows.

4.5.2.1 Steady State Voltage Variation

The variation in voltage at the PCC for different cases is presented in Figure 4.16.

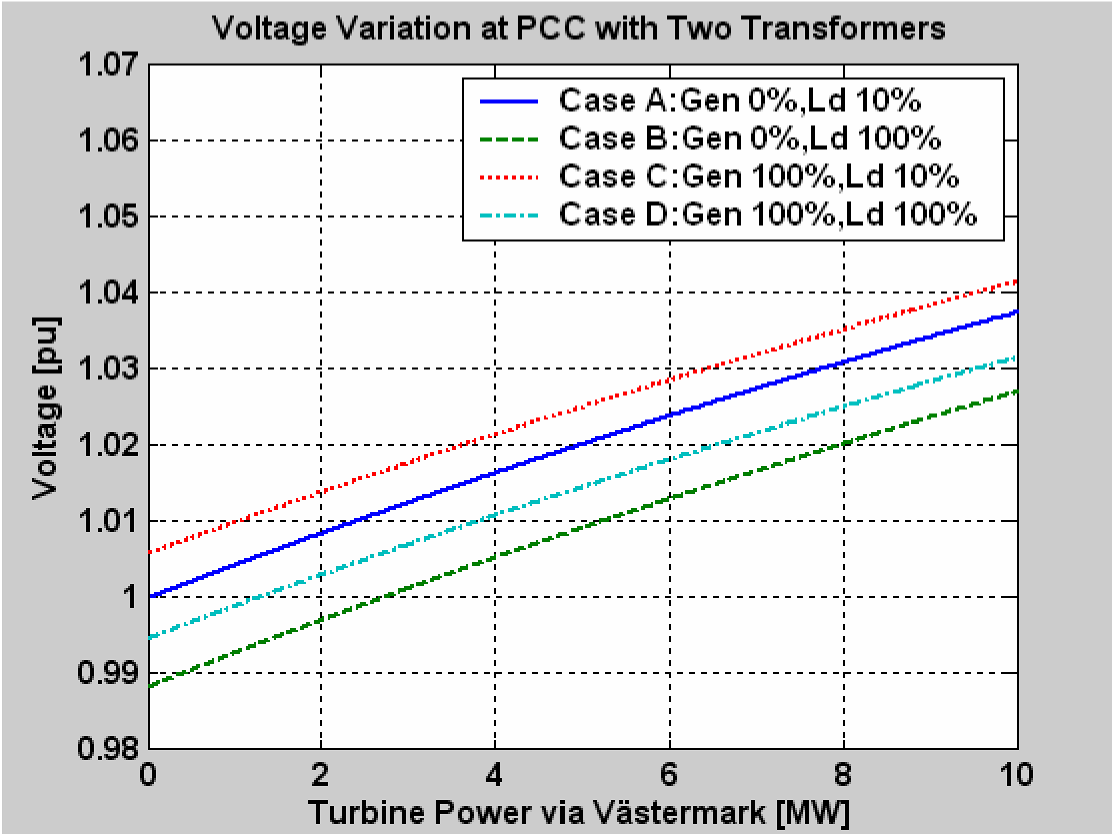

Figure 4.16-Voltage variation at PCC (N318) with two transformers

It is clear from Figure 4.16 that the turbine power input should be limited to 3.6 MW so that the voltage remains in the upper limit of 1.02 p.u. for the variation of power from the turbine over its full range.

4.5.2.2 Thermal Limits

4.5.2.2.1 Transformer Loading Comparison

Figure 4.17 (a) & (b) and Figure 4.18 (a) & (b) present the active and reactive power flow, for the different cases, through the transformers respectively.

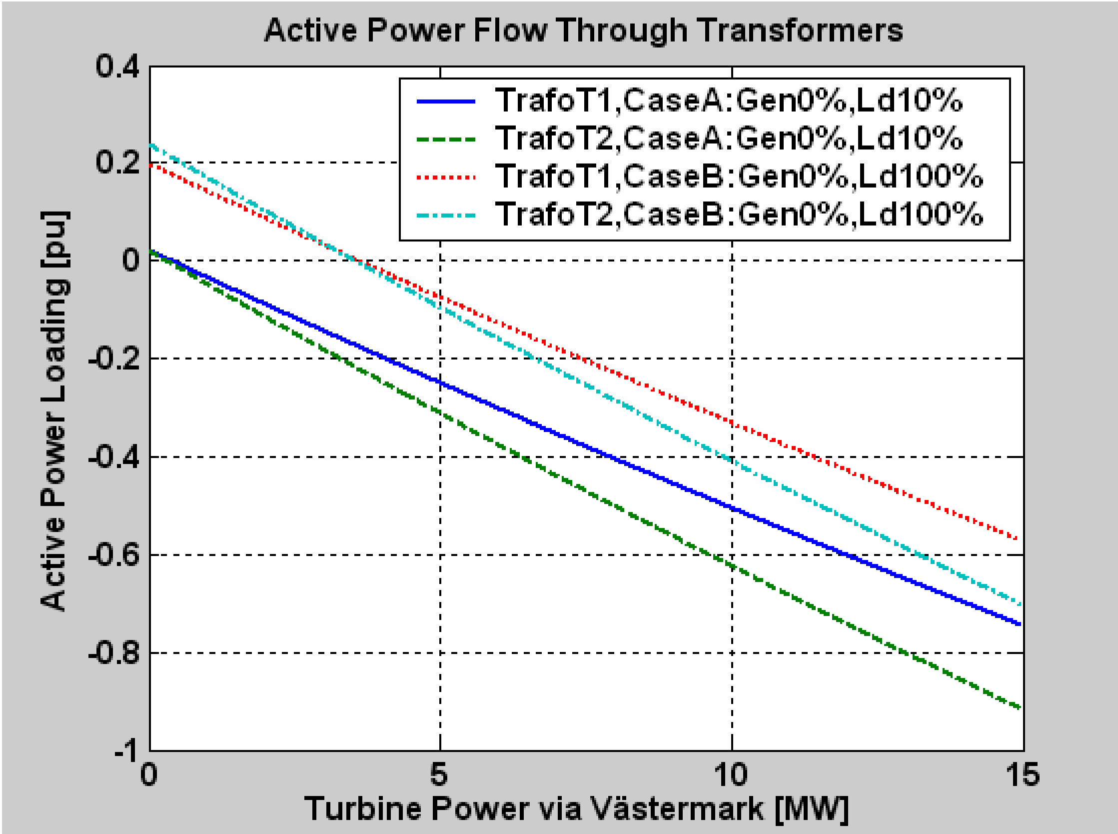

Figure 4.17 (a)-Active power flow through transformers Case A & Case B

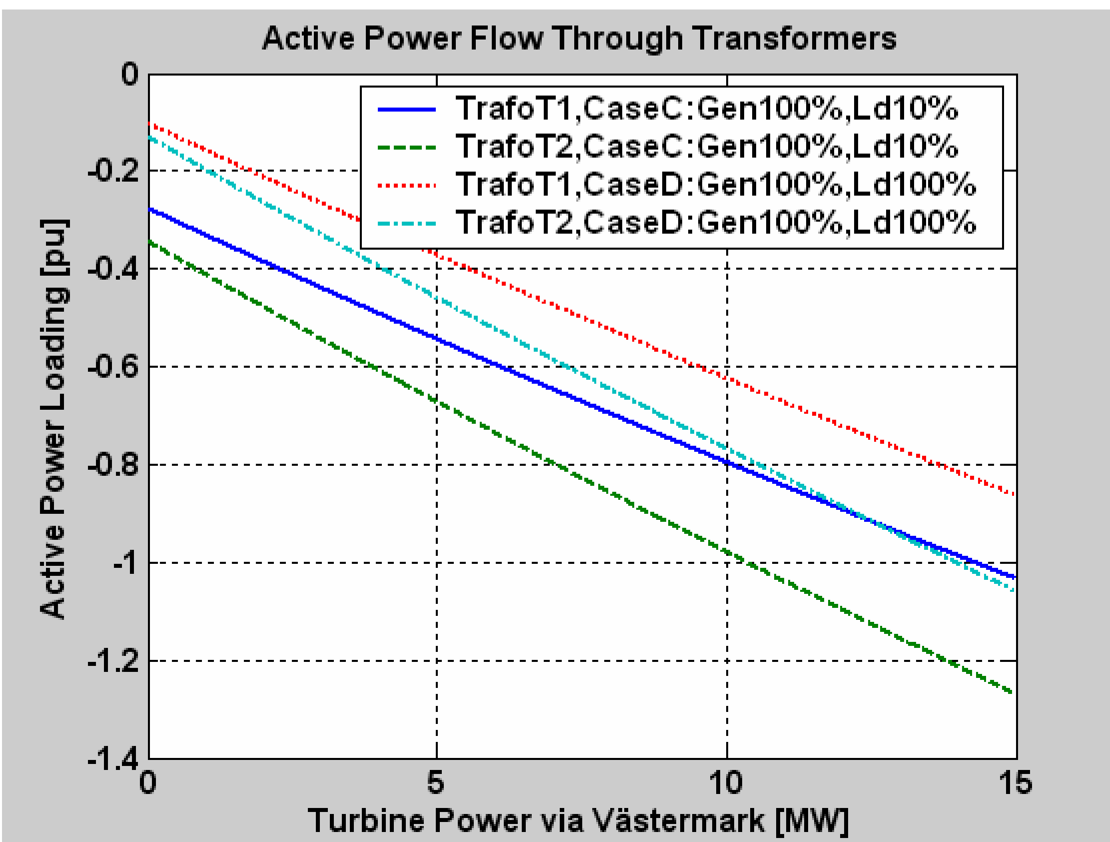

Figure 4.17 (b)-Active power flow through transformers Case C & Case D

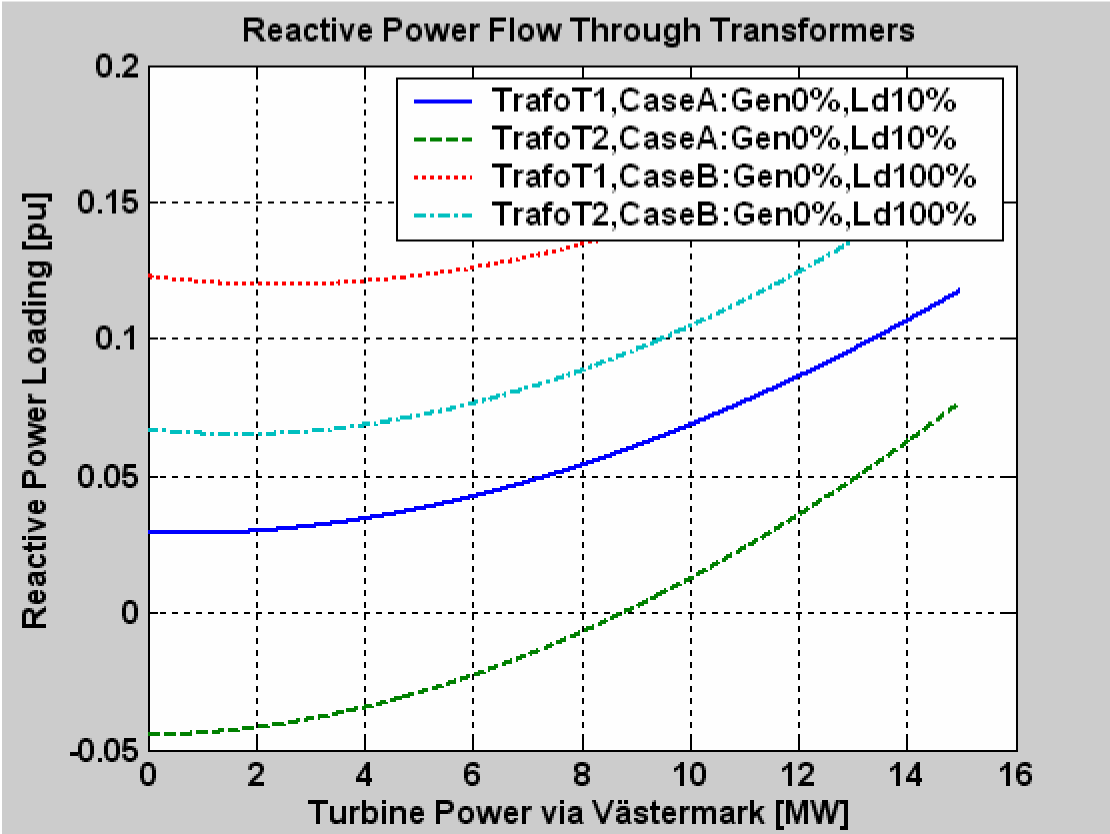

Figure 4.18 (a)-Reactive power flow through transformers Case A & Case B

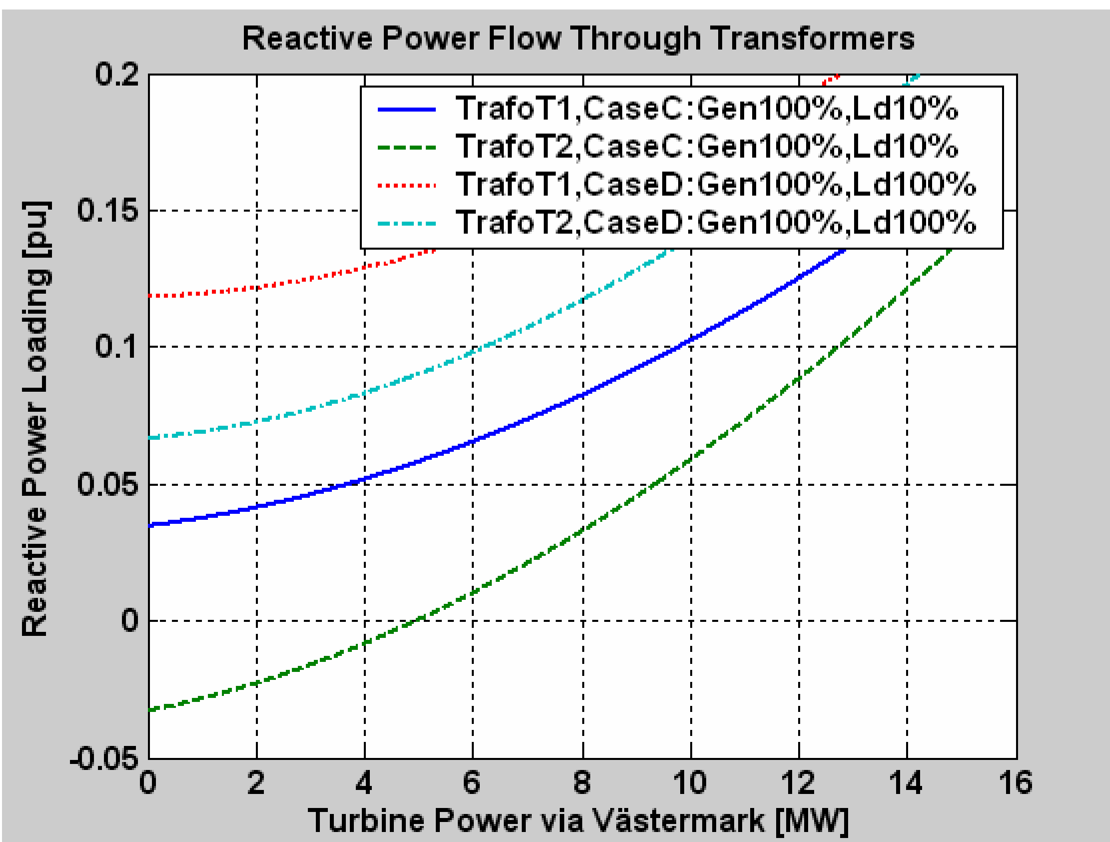

Figure 4.18 (b)-Reactive power flow through transformers Case C & Case D

It can be seen that the loading of transformer T2 which has a comparatively lower short circuit reactance is higher compared to transformer T1 which has a higher reactance. As seen in Figure 4.17 (a) for Case B the loading for T2 is greater no matter in which way the power is flowing.

It has already been seen in operation with one transformer that the reactive power generated in the system due to charging is in excess and flows out to the system in Case A, see Figure 4.9. In the case of operation with two transformers, it is seen that the reactive power through the transformers is in opposite directions in Case A and also in Case C which means that there is a reactive power flowing from T1 to T2. The actual flow on the outside of this loop can be seen in Figure 4.9 for Case A and Case C.

Observing Figures 4.17 (a) & (b) it is seen that Case C presents the lowest input possibility for turbine power with transformer T2 being fully loaded. The MVA loading of the transformers for Case C is shown in Figure 4.19.

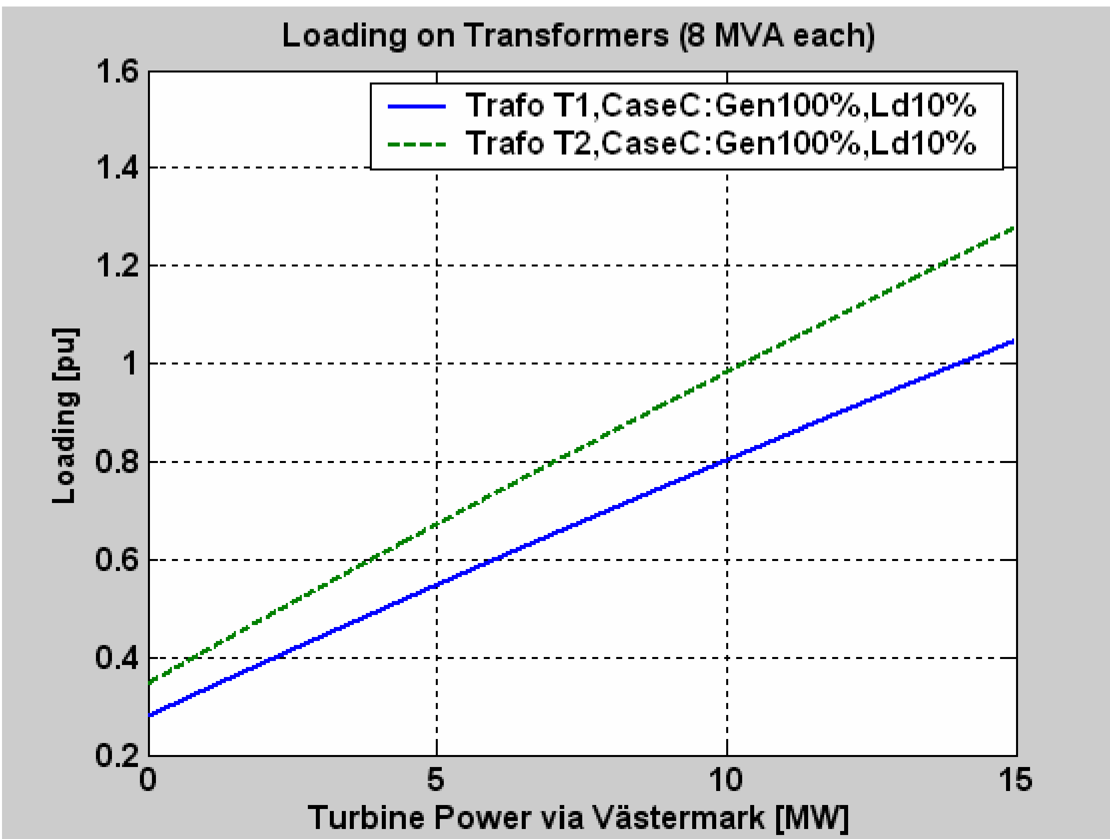

Figure 4.19-Loading on transformers Case C: Generation 100% and Load 10%

4.5.2.3 Results

Table 4.4 summarizes the parallel operation of transformers.

Table 4.4- Summary of operation with the two transformers in parallel

Limiting Factors (100% Loading)	Generation 0%		Generation 100%	
	Load 10%	Load 100%	Load 10%	Load 100%
Voltage 1.02 p.u. at N318 (PCC)	4.96 MW	7.95 MW	3.6 MW	6.53 MW
Thermal Limit ACJJ70 (3.1 MVA)	3.23 MW	3.84 MW	1.55 MW	2.16 MW
Thermal Limit AXCEL95 (4.5 MVA)	4.52 MW	4.52 MW	3.66 MW	3.66 MW
Thermal Limit FeAl99 (5.2 MVA)	5.41 MW	6.03 MW	3.7 MW	4.35 MW
TransformerT1 (8MVA)	20 MW	24 MW	14 MW	17.2 MW
TransformerT2 (8MVA)	16.5 MW	20 MW	10.2 MW	13.6 MW

4.5.3 Voltage Control using Reactive Power

It is possible to go above 3.2 MW, while operating with transformer T2, by absorbing reactive power to counter the voltage rise at the PCC, see Table 4.3. Since the network has to supply this reactive power, it will further increase the loading on the already overloaded transformer and the transmission medium.

However it is not possible to go up to 3.6 MW in active power because the reactive power absorption will also take up the MVA capacity of the medium.

The transformers installed at Lundsbrunn have been in service for over 37 years. It may not be feasible to overload the already aged transformers.

4.5.4 Discussion

It is found that the thermal limit of cable ACJJ70 is the first barrier to the increase in power input from the wind turbine installed at Västermark above 1.55 MW. This cable length could be replaced by a cable with a higher rating.

While operating with one transformer 3.16 MW seems to be the limit since the transformer is fully loaded, see Table 4.2 & 4.3.

When operating two transformers in parallel it is possible to go up to 3.6 MW before the voltage and thermal limit of the evacuation cable is reached, see Table 4.4. In case one transformer is removed from operation for reasons such as a fault or maintenance the voltage at the PCC will increase above the 1.02 p.u. limit since it is reached at 3.5 & 3.2 MW for transformer T1 & T2 respectively. The remaining transformer will be loaded to 1.04 p.u. for T1 and 1.05 p.u. for T2 at 3.6 MW. Also the reactive power absorption is not possible because of the thermal limit of the evacuation cable and the overhead line.

The voltages on the other critical buses remain in the limits with either 1.5 MW or 3.0 MW rated turbine installed and supplying power via Västermark as can be seen from Figure 4.10 (a) & (b).

There is no affect on the on-load tap changer. While operating with one transformer T1 the first tap change, for any of the above cases due to the lowest input of wind power, occurs at 5.5 MW in Case D, see Figure 4.3. For transformer T2 the first tap change was observed at 11.4 MW for the same case. With two transformers operated parallel the tap does not change even up to 15 MW.

Thus with 1.5 MW or 3.0 MW turbine installed, the tap change events are not increased.

4.5.5 Flicker Calculation

The impact of the coming wind turbines on the power quality in the short time frame should also be acceptable. At Lundsbrunn eight wind turbines are already present and the installation of one more wind turbine is in question.

The flicker calculation is done for a 3.0 MW wind turbine with the assumption that the cable ACJJ70 will be replaced.

4.5.5.1 Flicker Value at Individual Locations

Initially, the P_{st} value for the individual turbines is determined, by considering the flicker coefficient and calculating the short circuit power at the PCC, for each wind turbine already installed. It should be noted that during short circuit power calculation at the PCC for each wind turbine, the presence of loads and other wind turbines is neglected. This assumption can be justified by the fact that wind turbines are connected to the MV (Medium Voltage) network and these networks normally have other fluctuating loads. These loads may contribute to the flicker level at the terminals of the wind turbines and the load inclusion may not give the true flicker contribution from the wind turbine.

Table 4.5 summarizes the P_{st} value calculated at the connection point of each turbine.

Table 4.5-Pst value at various turbine connection points on the network

Sr. No.	Turbine Location	Connection Point C.P	Rating (kVA)	Flicker Coefficient	Fault Level at C.P (MVA)	Grid Angle (Degrees)	P_{st} Value
1	Nolebo	EF-690	850	3.05	39.5	55	0.06
2	S:t Lund	N351	850	3.05	65.8	73	0.04
3	L:a Lunden	3005	800	4.00	62.5	79	0.05
4	Väster-mark	N318	850	3.05	52.0	72.6	0.05
5	Kollbog & Kyrkebo	D16L-101	850 &150	3.05 & 6.50	57.4	71	0.05
6	Erikstorp	EF-720	850 &150	3.05 & 6.50	26.7	58	0.10

In Table 4.5 the entries with Serial No. 1 to 4 have been calculated using Equation (3.2) whereas Equation (3.3) is used for 5 and 6.

4.5.5.2 Flicker Contribution of New Turbine

At Lundsbrunn, a possible installation of a new wind turbine is under consideration. This new turbine is to be installed on feeder L4 via Västermark where already one wind turbine of 850 KVA is in operation.

From the analysis presented in the previous sections, it is found that 3 MW of wind power generation capacity can be connected via Västermark. The flicker severity index for the already installed wind turbine at Västermark is 0.05. The combined flicker severity index P_{st} of both turbines is presented against a varying flicker coefficient, for the new turbine, in Figure 4.20. This Figure is obtained using Equation (3.3).

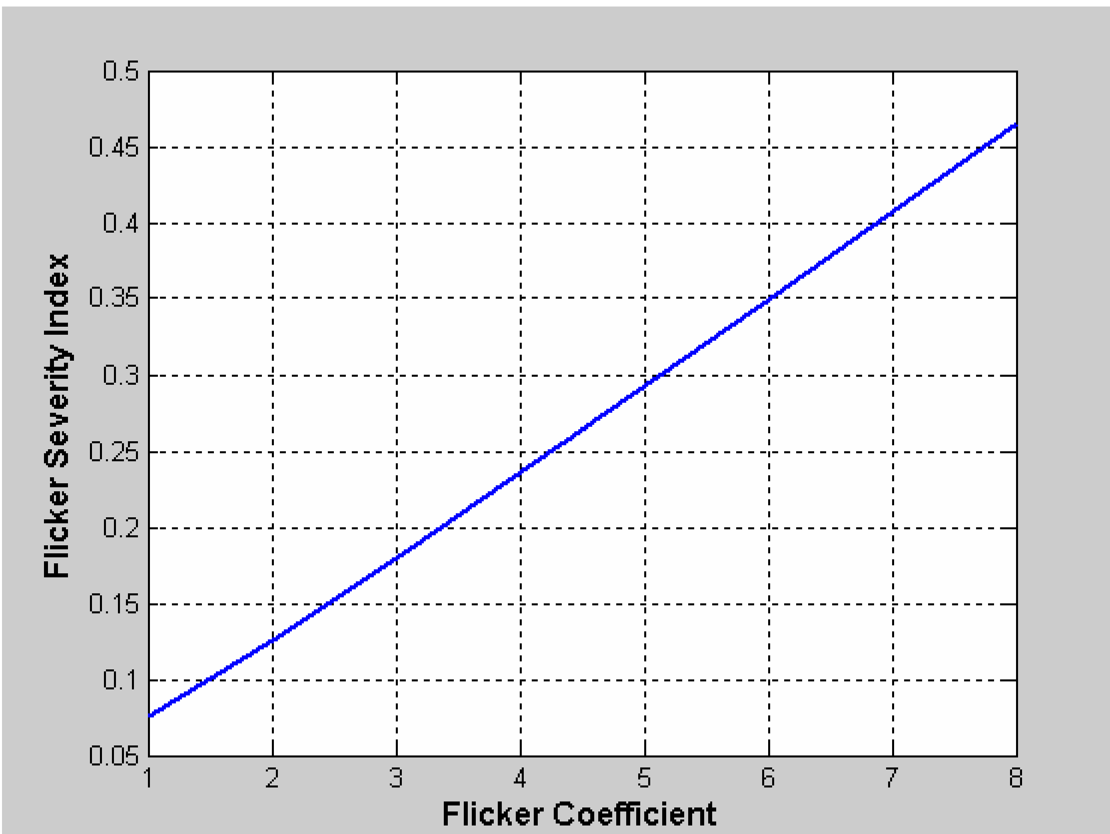

Figure 4.20-Combined flicker severity index at Västermark against a varying flicker coefficient of the new turbine

It is seen in Figure 4.20 that the operation of a new wind turbine with a flicker coefficient of 6 or more will increase the P_{st} value at Västermark beyond 0.35 which is the AMP limit for short term flicker severity index.

To calculate the combined P_{st} of all the wind turbines including the new 3 MW wind turbine is not simple since Equation (3.3) describes a method to calculate flicker severity index for more than one wind turbine connected at the same PCC. In Lundsbrunn wind turbines are connected at different locations with different short circuit powers.

To calculate the combined flicker severity index from all the wind turbines, substation bus M3 is considered as the PCC with all wind turbines generating their rated power, with respective flicker coefficients. For the new wind turbine, the flicker coefficient is increased from 1 to 8. The result is shown in Figure 4.21.

Figure 4.21-Combined flicker severity index of all wind turbines at M3 against the varying flicker coefficient of the new wind turbine.

It is seen that even with an integration of a 3 MW turbine with a flicker coefficient of 8 does not increase the P_{st} value above 0.35.

4.5.6 Conclusion

It is concluded that it is possible to integrate wind energy from a turbine supplying power via Västermark. With the current network of cable and lines, the amount of power found is 1.5 MW. It can be increased to 3.0 MW when the cable at the start of the feeder of type ACJJ70 from M3 to D17L-101 is replaced by a cable of 5.2 MVA rating or higher.

4.6 Turbine Connected to D16K-106

Another possibility is to connect a turbine at D16K-106 on Feeder 4. The turbine is to be connected by a 500 meter cable length of type AXCEL95, 4.5 MVA. The same procedure for analysis is applied here also.

4.6.1 Operation with One Transformer

4.6.1.1 Steady State Voltage Variation

The voltage variation at D16K-106 (PCC) for different cases is shown in Figure 4.22 below.

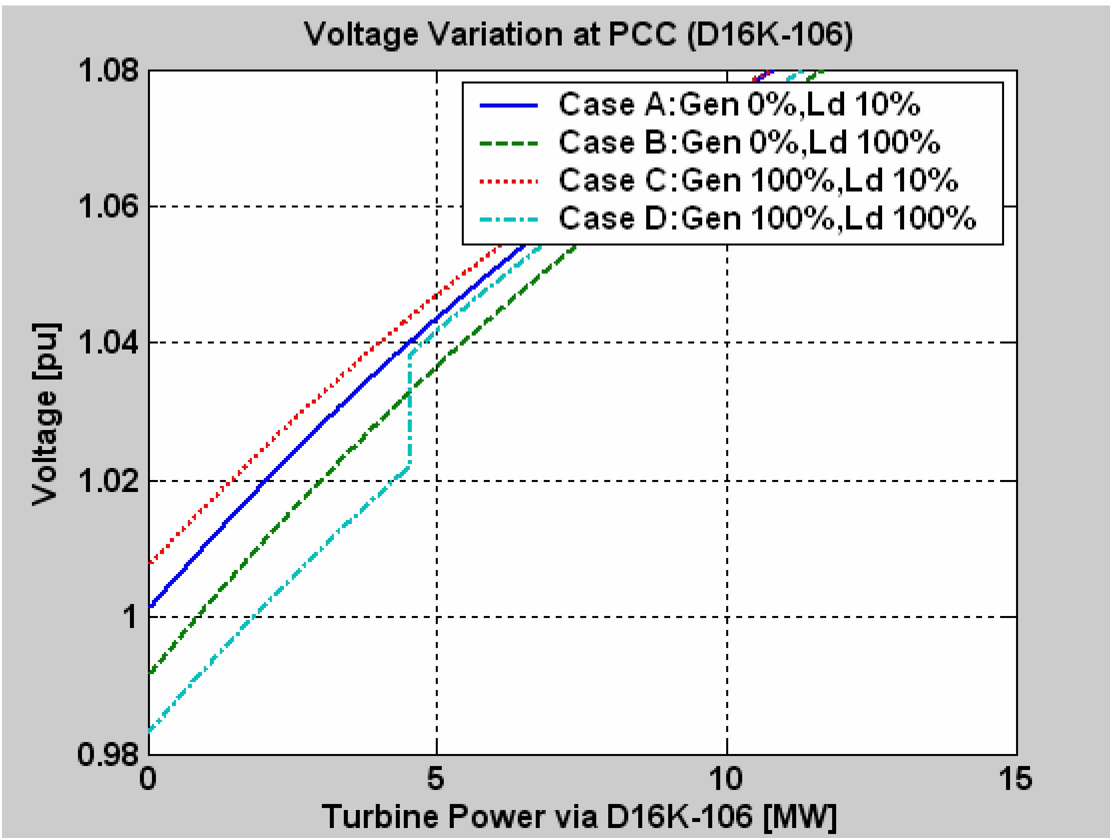

Figure 4.22-Voltage variation at D16K-106 (PCC)

The connection point D16K-106 is at a greater electrical distance than Västermark. It is observed that the voltage rise is more at the PCC with the same amount of power injection than with turbine operation via Västermark, see Figure 4.3.

This is explained by Equation 4.2 [4]

$$\Delta U = (R * P - X * Q) / U \tag{4.2}$$

Where,

ΔU= Voltage variation at the PCC
U= Nominal voltage

P= Magnitude of in-feed active power
Q= Magnitude of consumed reactive power
R= Resistance of the grid
X= Reactance if the grid

The X/R ratio decreases from 2.9 at Västermark to 1.9 at D16K-106 due to the fact that R increases more with increasing distance from the grid power source. This causes the voltage variation to increase for the same active and reactive power. This will have a pronounced effect on the power quality at the two different places (Västermark and D16K-106) for the power variation from the wind turbine.

By including the transformer impedance the X/R ratio becomes greater that 1 although the 10.7 kV network here is mainly resistive.

The details of per km values of resistance, reactance and susceptance for different types of cables and overhead lines are given in Appendix A.

Case C is again found to be the limiting case with voltage limits.

4.6.1.2 Thermal limits

The thermal limits posed by the different components are the same as given in Section 4.3.1.3.

4.6.1.3 Results

The results for different cases with one transformer operation are summarized in Table 4.6 & 4.7.

Table 4.6-Summary of results with a turbine installed at D16K-106 with the transformer T1 in operation

Limiting Factors (100% Loading)	Generation 0%		Generation 100%	
	Load 10%	Load 100%	Load 10%	Load 100%
Voltage 1.02 p.u. at D16K-106 (PCC)	2.05 MW	3.0 MW	1.45 MW	4.27 MW
Thermal Limit ACJJ70 (3.1 MVA)	3.27 MW	3.86 MW	1.55 MW	2.16 MW
Thermal Limit AXCEL95 (4.5 MVA)	4.52 MW	4.52 MW	4.52 MW	4.52 MW
Thermal Limit FeAl99 (5.2 MVA)	5.43 MW	6.04 MW	3.7 MW	4.4 MW
Transformer T1 (8MVA)	9 MW	12 MW	3.2 MW	6.2 MW

It is again found that Case C is the most critical case for integration and it is further studied for operation with transformer T2.

Table 4.7-Summary of results with a turbine installed at D16K-106 with the transformer T2 in operation for the most critical case, Case C

Limiting Factors (100% Loading)	Generation 100%
	Load 10%
Voltage 1.02 p.u. at D16K-106 (PCC)	1.4 MW
Thermal Limit Cable ACJJ70 (3.1 MVA)	1.56 MW
Thermal Limit Cable AXCEL95 (4.5 MVA)	4.52 MW
Thermal Limit Over-head Line FeAl99 (5.2 MVA)	3.7 MW
Transformer T2 (8 MVA)	3.2 MW

4.6.2 Operation with Parallel Transformers

The results of operation with parallel transformers are given in Table 4.8.

Table 4.8-Summary of results with a turbine installed at D16K-106 with both transformers operated in parallel

Limiting Factors (100% Loading)	Generation 0%		Generation 100%	
	Load 10%	Load 100%	Load 10%	Load 100%
Voltage 1.02 p.u. at D16K-106 (PCC)	2.22 MW	4 MW	1.6 MW	3.35 MW
Thermal Limit ACJJ70 (3.1 MVA)	3.26 MW	3.86 MW	1.56 MW	2.16 MW
Thermal Limit AXCEL95 (4.5 MVA)	4.52 MW	4.52 MW	4.52 MW	4.52 MW
Thermal Limit FeAl99 (5.2 MVA)	5.43 MW	6.04 MW	3.7 MW	4.4 MW
Transformer T1 (8 MVA)	19 MW	24 MW	14.5 MW	17.5 MW
Transformer T2 (8MVA)	17 MW	20 MW	10.5 MW	14 MW

4.6.3 Discussion

In case a turbine is supplying power via D16K-106 the voltage limit causes the integration to be almost half of what is possible via Västermark for a unity power factor operation.

The thermal limits are the same for the cables, lines and transformers as found in the analysis for Västermark in previous sections.

The reactive power absorption technique for voltage control although applicable will not be of much use. The turbine will be required to absorb a large amount of reactive power if it were to approach the active power input found in Västermark analysis which is not feasible.

4.6.4 Conclusion

It is concluded that only 1.4 MW can be installed to supply power via D16K-106. Since this amount is only half of that possible with Västermark, it will not be dealt with further.

4.7 Turbines at Both Locations on Feeder 4

A possibility of some generation at both places (N318 and D16K-106) on Feeder 4 was investigated to find out if the total input power could be maximized than with operation at either place only.

4.7.1 Operation with One Transformer

4.7.1.1 Steady State Voltage Variation

In this case the voltage rise at the point of common coupling for each of the turbines is dependent on both the turbines. This means that power input from either turbine will raise the voltage at both points. Due to the difference in the total R and X value (electrical distance from the infinite bus) the voltage rise is different for both points. So the voltage profiles intersect each other at some point. This is shown in Figure 4.23 for Case B (0% generation and 100% load). If the intersection point could be such that it is at 1.02 p.u. then this could be the optimum point. The result would be that when both the turbines generate their rated power, the point of common coupling for both the turbines will be at the same level and the voltage limit is respected.

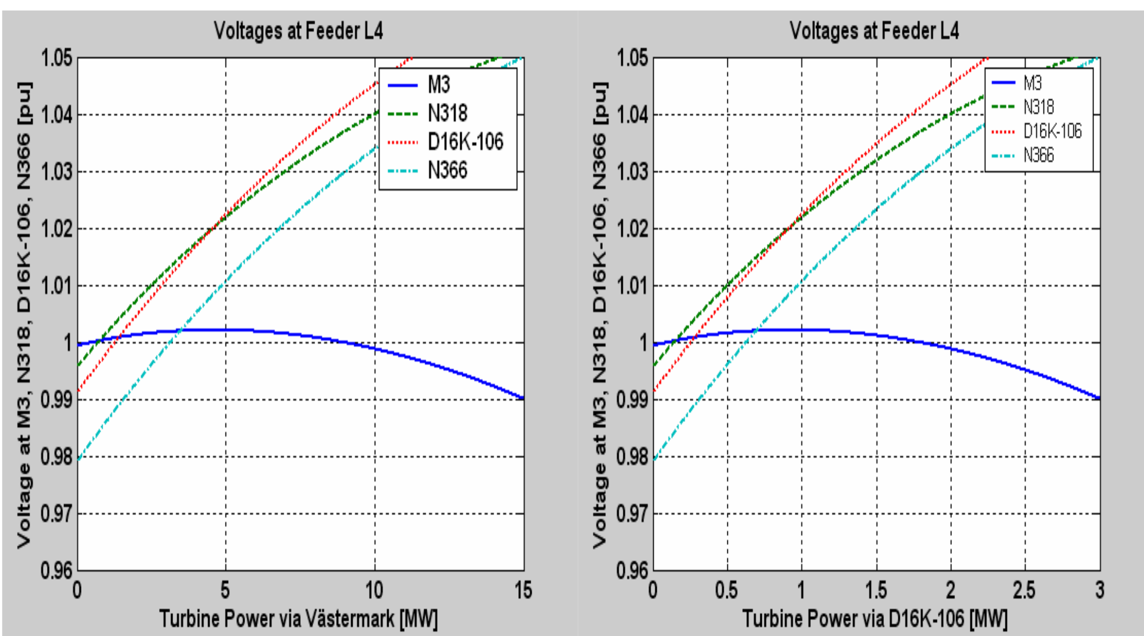

Figure 4.23-Variation of voltage along Feeder 4 with input from both turbines a) via Västermark and b) via D16K-106

It is seen in Figure 4.23 that the contribution through a turbine via Västermark can be 4.5 MW while a turbine at D16K-106 can contribute 0.9 MW at a voltage limit of 1.02 p.u. This gives a total of 5.4 MW which is almost equal to the amount that was found for a turbine installed via Västermark for the same case, see Table 4.2.

4.7.1.2 Thermal Limits

The thermal limits are found to be the same as in the previous cases, see Section 4.3.1.3.

4.7.1.3 Results

The maximum integration found for the different cases when placing turbines at the two locations is given in Table 4.9.

Table 4.9-Summary of results when operating with two turbines and Transformer T1 is in operation.

Limiting Factors (100% Loading)	Generation 0%		Generation 100%	
	Load 10%	Load 100%	Load 10%	Load 100%
Voltage 1.02 p.u. at PCC	3.72 MW	5.40 MW	2.76 MW	5.65 MW
Thermal Limit ACJJ70 (3.1 MVA)	3.23 MW	3.84 MW	1.56 MW	2.06 MW
Thermal Limit AXCEL95 (4.5 MVA) Västermark1 to N318	4.52 MW	4.52 MW	3.67 MW	3.67 MW
Thermal Limit AXCEL95 (4.5 MVA) Västermark3 to D16K-106	4.52 MW	4.52 MW	4.52 MW	4.52 MW
Thermal Limit FeAl99 (5.2 MVA)	5.4 MW	6.0 MW	3.72 MW	4.32 MW
Transformer T1 (8 MVA)	8.75 MW	11.75 MW	3.1 MW	6.1 MW

It is observed that 100% Generation and 10% Load is the restraining case. The thermal limits are the same as in the previous cases.

Operation with transformer T2 for the restraining case is given in Table 4.10 below.

Table 4.10- Summary of results when operating with two turbines and Transformer T2 is in operation.

Limiting Factors (100% Loading)	Generation 100%
	Load 10%
Voltage 1.02 p.u. at PCC	2.6 MW
Thermal Limit Cable ACJJ70 (3.1 MVA)	1.56 MW
Thermal Limit Cable AXCEL95 (4.5 MVA) Västermark1 to N318	3.67 MW
Thermal Limit Cable AXCEL95 (4.5 MVA) Västermark3 to D16K-106	4.52 MW
Thermal Limit Over-head Line FeAl99 (5.2 MVA)	3.72 MW
Transformer T2 (8 MVA)	3.16 MW

4.7.2 Operation with Parallel Transformers

The results of operation with the two transformers in parallel are given in Table 4.11 below.

Table 4.11-Operation with both transformer in parallel and turbines installed at both locations.

Limiting Factors (100% Loading)	Generation 0%		Generation 100%	
	Load 10%	Load 100%	Load 10%	Load 100%
Voltage 1.02 p.u. at PCC	4.3 MW	7.86 MW	3.12 MW	6.42 MW
Thermal Limit ACJJ70 (3.1 MVA)	3.22 MW	3.84 MW	1.55 MW	2.16 MW
Thermal Limit AXCEL95 (4.5 MVA) Västermark1 to N318	4.52 MW	4.52 MW	3.66 MW	3.66 MW
Thermal Limit AXCEL95 (4.5 MVA) Västermark3 to D16K-106	4.52 MW	4.52 MW	4.52 MW	4.52 MW
Thermal Limit FeAl99 (5.2 MVA)	5.4 MW	6.0 MW	3.73 MW	4.32 MW
Transformer T1 (8MVA)	20 MW	23.2 MW	13.8 MW	17 MW
Transformer T2 (8MVA)	16.3 MW	19.8 MW	10.2 MW	13.5 MW

4.7.3 Discussion

It is observed that the total power input (via Västermark and via D16K-106), through turbines installed at the two locations, does not exceed the power that can be added when a turbine is installed to supply power via Västermark only. As before, the case with 100% generation and 10% load (Case C) is the most limiting case.

4.7.4 Conclusion

It is concluded that a maximum of 2.6 MW can be fed into the system when turbines are placed at two different locations that is to supply power via Västermark and via D16K-106. This amount is less than what a turbine supplying power via Västermark alone can provide. Thus it will not be studied further.

4.8 Turbines Added via Dedicated Line

In this case more wind power generation capacity is added to the system through a dedicated line supplying power directly to the substation bus M3. This case builds upon the previous analysis with the assumption that a turbine of 3 MW rating has been installed to supply power via Västermark. The four possibilities of generation and load now include this turbine at Västermark in further analysis.

It was seen in the previous sections that a single transformer is fully loaded at about 3 MW. Thus to have integration of more wind energy converters through this line, parallel operation of transformers is necessary.

The new line is to be a total of 5 km with a proposed installation of a 2 MW turbine at 3 km (NuLineT1) and two 2 MW turbines at 5 km (NuLineT2) but that has to be investigated. The dedicated line is shown in Figure 4.1.

4.8.1 Analysis Procedure

Three possibilities of placement are considered again.

1) A turbine installed at 3 km and another turbine at 5 km.
2) A turbine installed at 3 km only.
3) A turbine installed at 5 km only.

The limiting factors for this analysis are the same as for the previous studies. These are the voltage at the connection point of the turbine, thermal limit of the evacuation line and thermal limit of the transformer. The thermal limit of the components is given in Table 4.12.

Table 4.12-Thermal limits of components

Component	Type	Rating (MVA)	Links
Transformers T1 &T2	Substation	8.0	42 kV grid to M3
Cable	AXCEL240	7.3	NuLineT1 to M3
Cable	AXCEL240	7.3	NulineT2 to NulineT1

The voltage on other buses of the network is also considered to ensure that it is in limit.

4.9 Turbines at Both Locations on Dedicated Line

In this case a Turbine of 2 MW (named in this report as Nuline Turb1 for easy reference) is installed at 3 km (NuLineT1) and operated with a fixed unity power factor. Another turbine (named as Nuline Turb2) is installed a further 2 km away (NuLineT2) operating with a variable reactive power to control voltage at the point of connection.

The appropriate rating of the second turbine Nuline Turb2 is to be investigated. As in the previous sections, different mix of load and generation are considered.

4.9.1 Steady State Voltage Variation

The results for voltage at the point of connection are presented below in Figure 4.24. The turbine is operated at unity power factor initially.

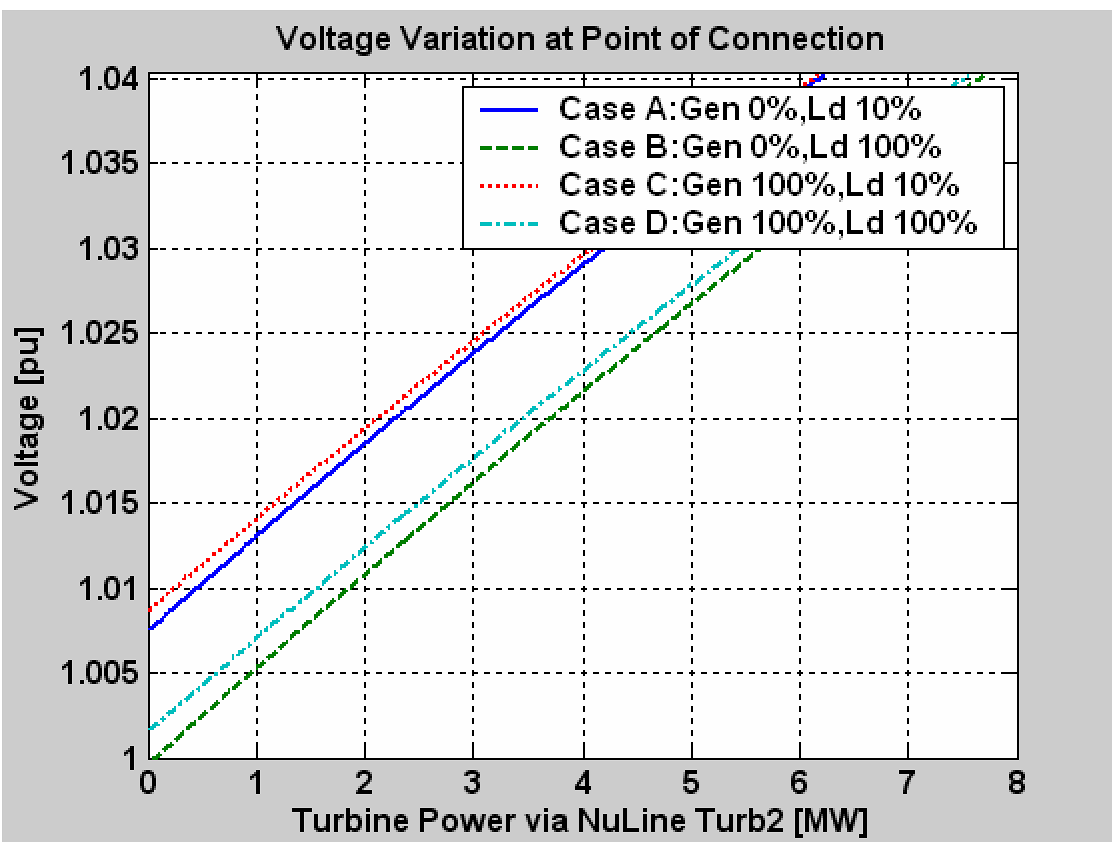

Figure 4.24-Voltage variation at the point of connection for different cases

The most limiting case is Case C with full (100%) generation and low (10%) loads. The voltage limit is reached at about 2 MW. The voltage at some of other buses in the network is shown in Figure 4.25 (a) & (b).

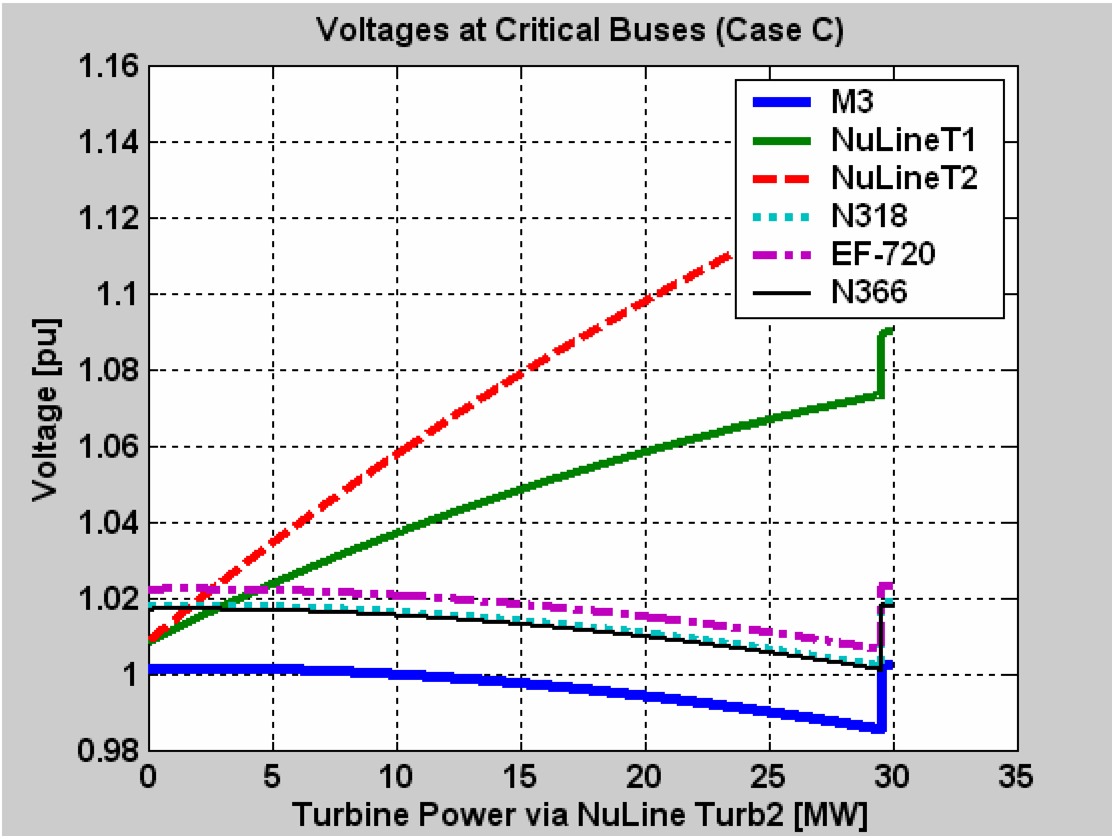

Figure 4.25 (a)-Voltage at critical buses in the network

It is clear from Figure 4.25 (a) & (b) that the voltages in the network are within limits for an input of 2 MW through Nuline Turb2 except for EF-720 on Feeder 5 which has 1 MW of wind power generation capacity installed. The voltage at Nuline Turb1 (the point of connection for the first turbine) is also within limits.

It means that with a unity power factor operation of both turbines it is possible to have a total wind power input of about 4 MW. This could further be increased by reactive power absorption to control voltage at the point of connection.

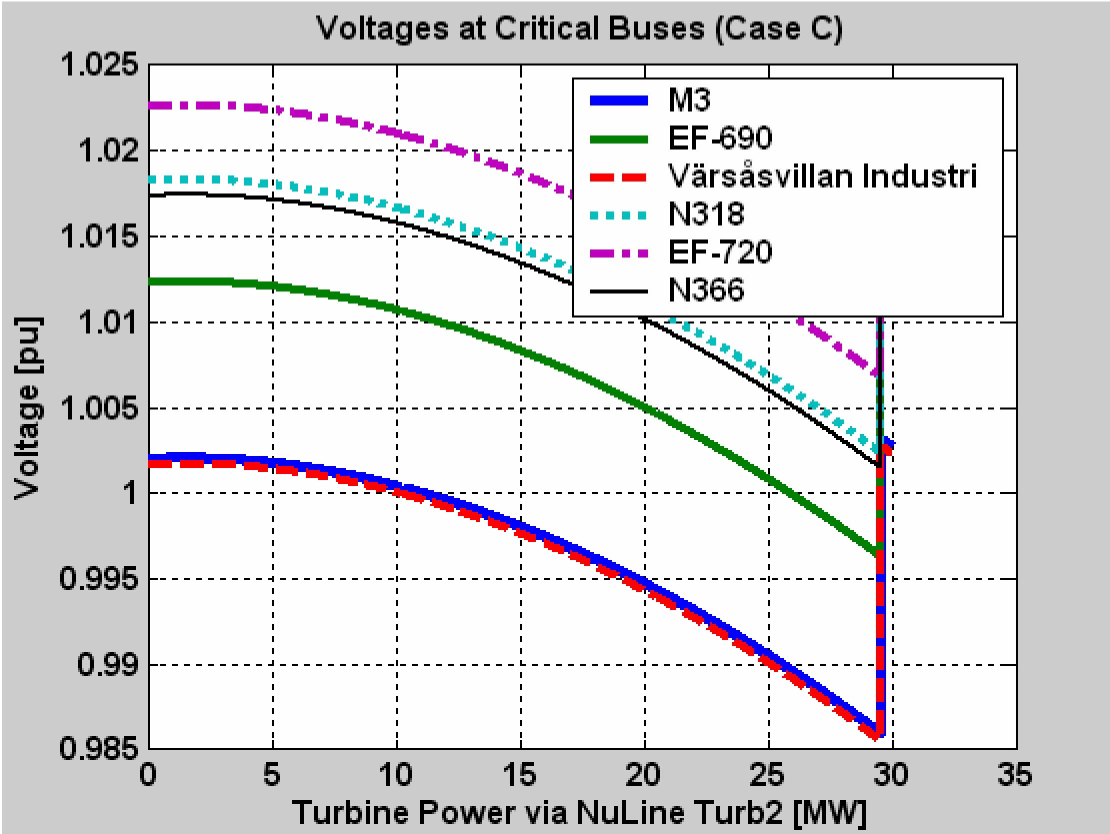

Figure 4.25 (b) -Voltage at critical buses in the network

4.9.2 Thermal Limits

The loading on the components of interest with increasing turbine power is presented below in Figure 4.26 for Case C.

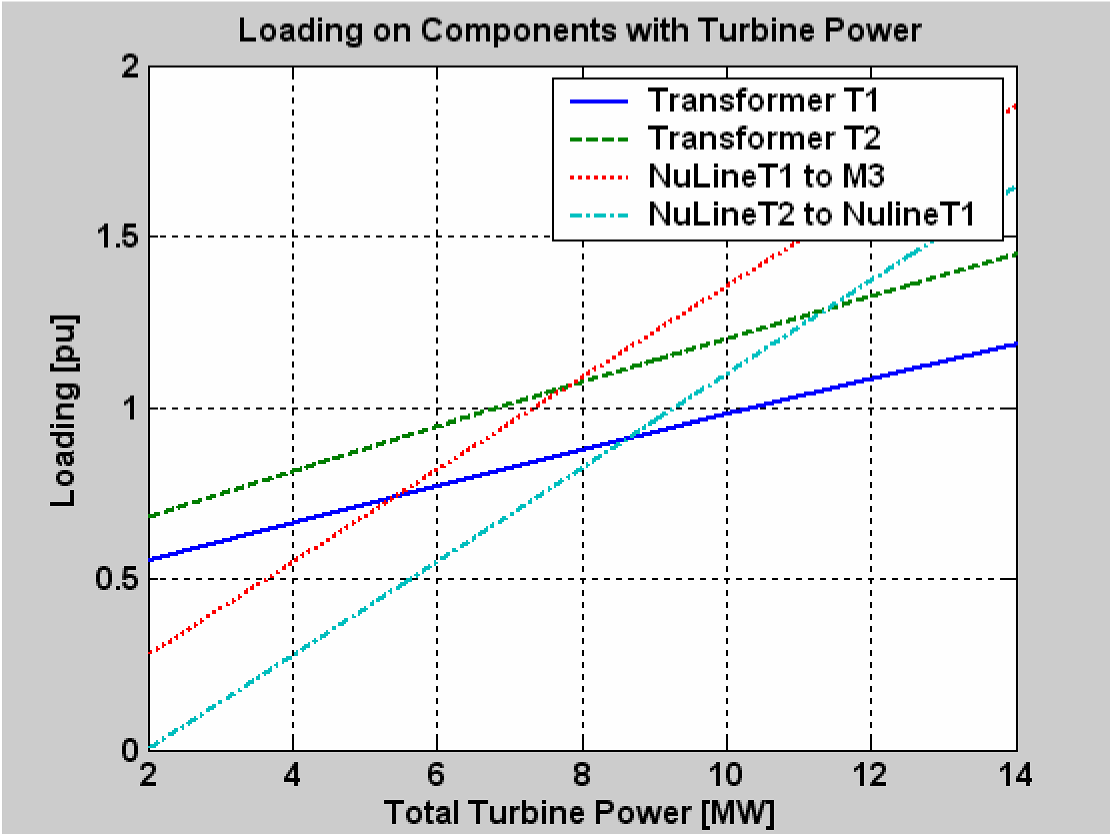

Figure 4.26-Component loading with increasing total turbine power for Case C.

It is seen that the transformer T2 is fully loaded at 6.9 MW with the turbine operated at a unity power factor.

4.9.3 Results

The results with both turbines operated at a unity power factor for the different cases of generation and load in the system are presented in Table 4.13. It is observed that Case C is the limiting case for both the voltage limits and the transformer loading.

Table 4.13-Summary of results for Turbines operated at both locations with unity power factor

Limiting Factors (100% Loading)	Generation 0%		Generation 100%	
	Load 10%	Load 100%	Load 10%	Load 100%
Voltage 1.02 p.u. at NuLineT2	4.29 MW	5.71 MW	4.13 MW	5.46 MW
Thermal Limit AXCEL240 (7.3 MVA) NuLineT1 to M3	7.36 MW	7.36 MW	7.35 MW	7.36 MW
Thermal Limit AXCEL240 (7.3 MVA) NulineT2 to NulineT1	7.3 MW	7.3 MW	7.3 MW	7.3 MW
TransformerT1(8MVA)	19.7 MW	23 MW	10.4 MW	13.5 MW
TransformerT2(8MVA)	16 MW	19.4 MW	6.88 MW	10 MW

4.9.4 Voltage Control using Reactive Power

In Figure 4.24 it is seen that the voltage level at the point of connection limits the turbine power from NuLine Turb2 to 2.1 MW in Case C. With NuLine Turb1 operated with a unity power factor and injecting 2 MW into the system, it makes a total of about 4 MW.

To inject more active power through NuLine Turb2, reactive power is absorbed to counteract the voltage rise above 1.02 p.u. at the point of connection. NuLine Turb1 can continue to operate with a unity power factor. This absorption of reactive power causes additional loading of the system components. The loading of components is presented below in Figure 4.27.

In Figure 4.28 the variation in power factor is presented.

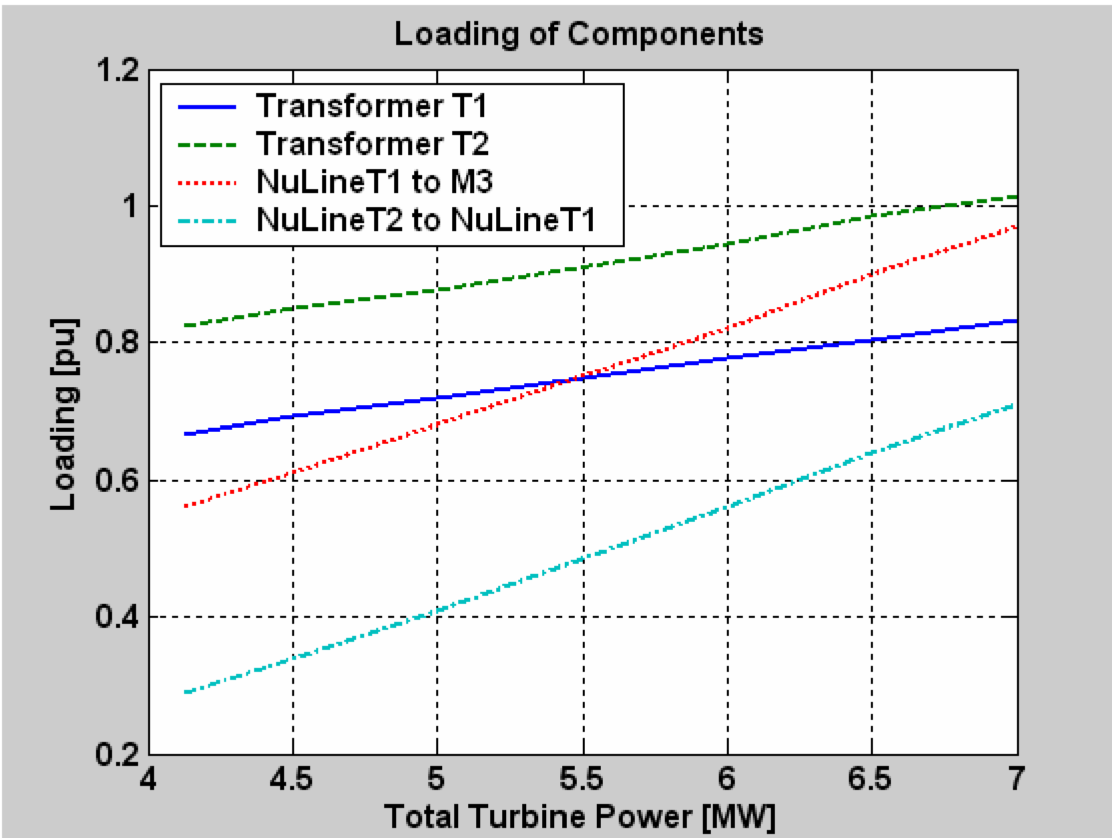

Figure 4.27-Loading of components with turbine active power and reactive power absorption.

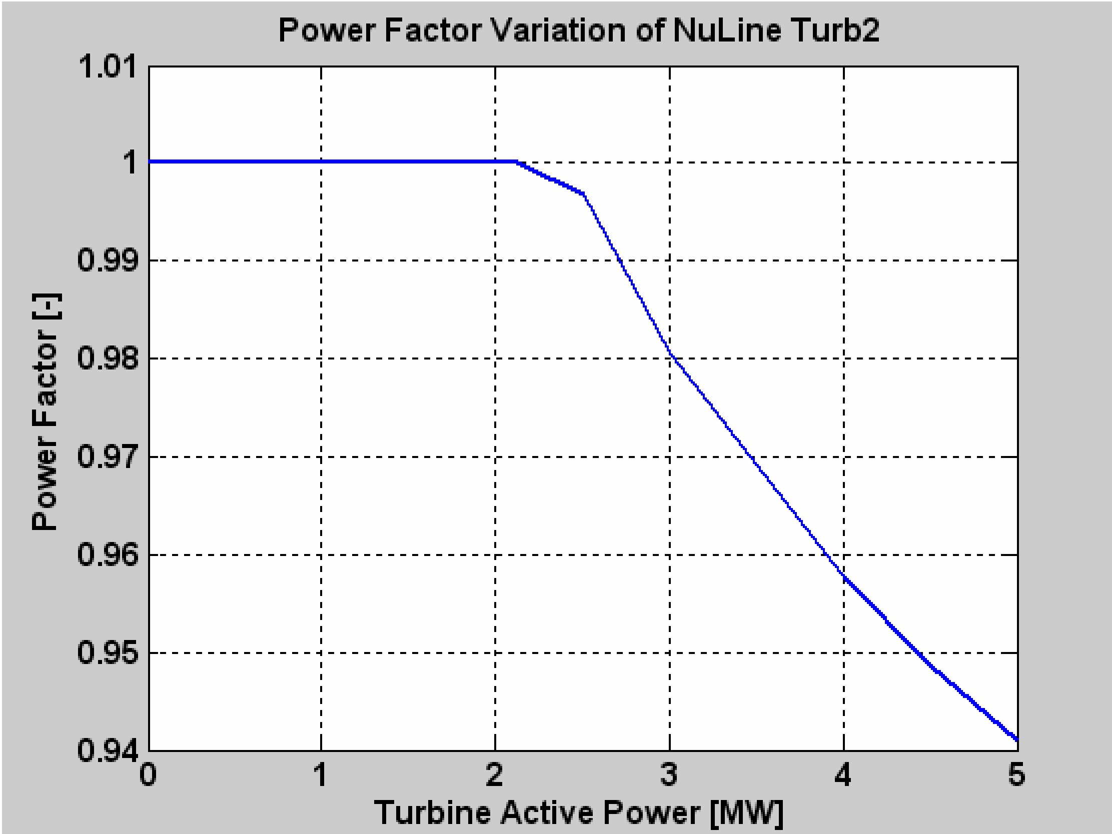

Figure 4.28-Power factor variation of turbine NuLine Turb2 to control the voltage.

4.9.5 Discussion

In the above analysis it was found that the Case C which has full (100%) generation from the installed turbines (including a 3 MW turbine at Västermark) and low (10%) load in the system presents the most limiting case.

The tap changer is not affected at low amount of turbine power and the first tap change occurs at about 25 MW for the full generation, full load condition.

It is possible to have about 4 MW of total wind power input with two turbines of 2 MW rating each, located at both locations and operated with a unity power factor.

When the power factor of the turbine NuLine Turb2 is varied an additional 3 MW can be added with 1.8 Mvar absorption of reactive power before the evacuation cable is loaded to the rated value and the transformer is overloaded by 1 %.

4.9.6 Conclusion

It is concluded that at the first location, a 2 MW turbine can be installed and at the second location 5 MW of wind energy converters with reactive power absorption capability of 1.8 Mvar can be installed. Thus a total of 7 MW can be installed with a transformer overload of 1%. There is no affect on the tap changer for the ratings found through the analysis.

4.10 Turbine Installed at NuLineT1 only

A possibility is also studied where a turbine is placed at the first location (NuLineT1, 3 km from the substation) only. It is done to find out if it is possible to feed in more power to the system, with a wind energy converter at this location than it is possible in the first case with two wind turbines at the two locations.

It was found in the previous sections that Case C provides the most limiting condition in the network to additional wind power input. The analysis is done with this case defining the condition prevalent in the network.

4.10.1 Steady State Voltage Variation

The variation in voltage at the point of connection with voltage at other buses in the network is presented in Figure 4.29.

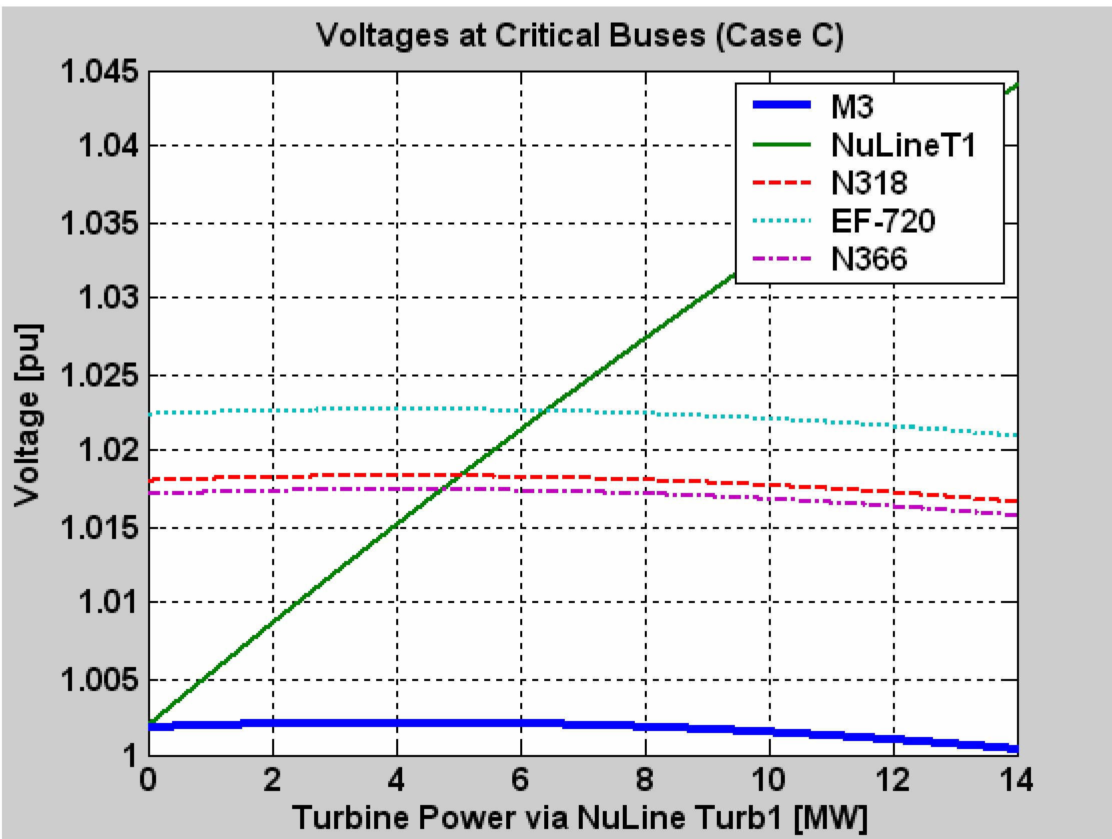

Figure 4.29-Voltage variation with increasing turbine power via NuLine Turb1

From Figure 4.29 it is seen that the voltage limit is reached at about 5.5 MW. The turbine is currently operated with a unity power factor. It is possible to increase the active power input if the power factor of the wind turbine is lowered to absorb reactive power. This can be done provided the thermal loading situation allows it. The thermal loading of components is presented in the next section.

4.10.2 Thermal Limits

The thermal loading is presented in Figure 4.30 for the components. It is seen that the transformer and the evacuation cable is loaded to rated value at about 7 MW.

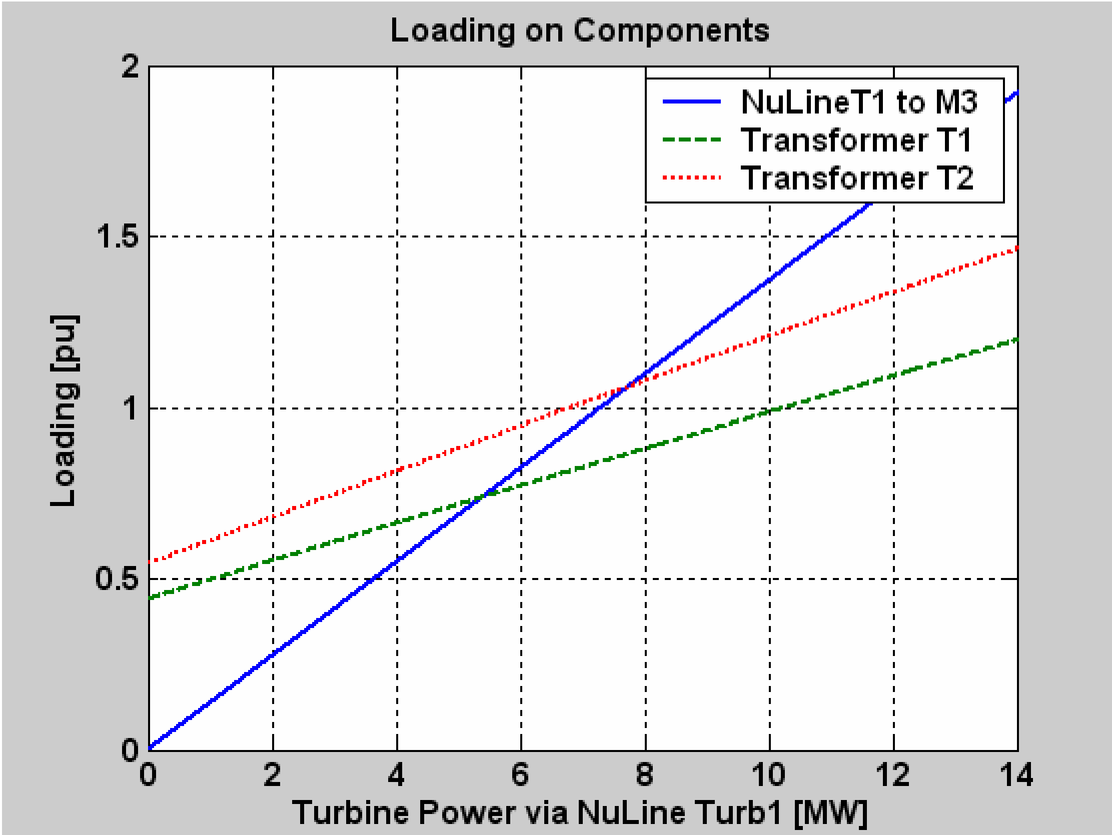

Figure 4.30-Loading of components with turbine power via NuLine Turb1

4.10.3 Results

The results of turbine operation are presented in Table 4.14.

Table 4.14-Power input possible for different limits with a turbine operated at the bus NuLineT1 with unity power factor.

Limiting Factors (100% Loading)	Generation 100%
	Load 10%
Voltage 1.02 p.u. at NuLineT1	5.55 MW
Thermal Limit AXCEL240 (7.3 MVA) NuLineT1 to M3	7.3 MW
TransformerT1 (8MVA)	10.3 MW
TransformerT2 (8MVA)	6.84 MW

4.10.4 Voltage Control using Reactive Power

From Table 4.14 it is seen that it is possible to increase the active power input of the turbine above 5.5 MW if it is capable of absorbing reactive power. The voltage is to be limited to 1.02 p.u. at the point of connection.

The loading of components with reactive power voltage control is presented below in Figure 4.31.

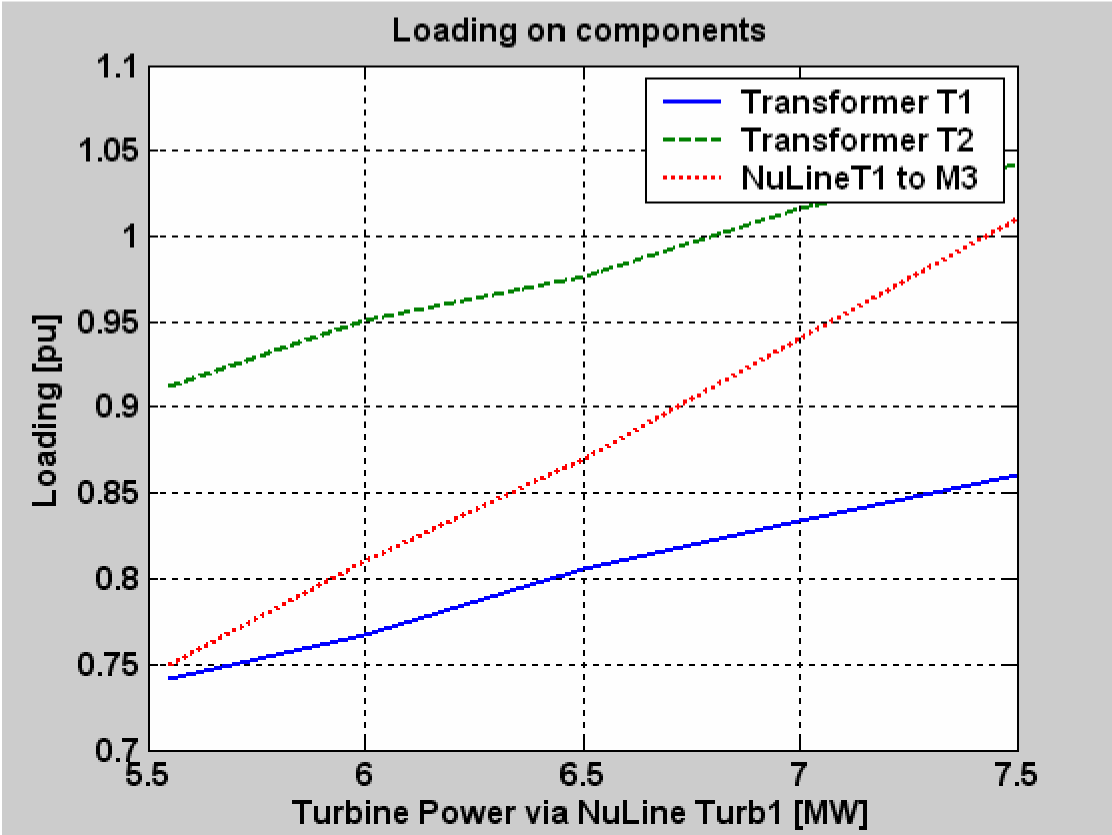

Figure 4.31-Loading of components with active power injection and reactive power absorption.

The power factor variation of the turbine to absorb reactive power is shown in Figure 4.32.

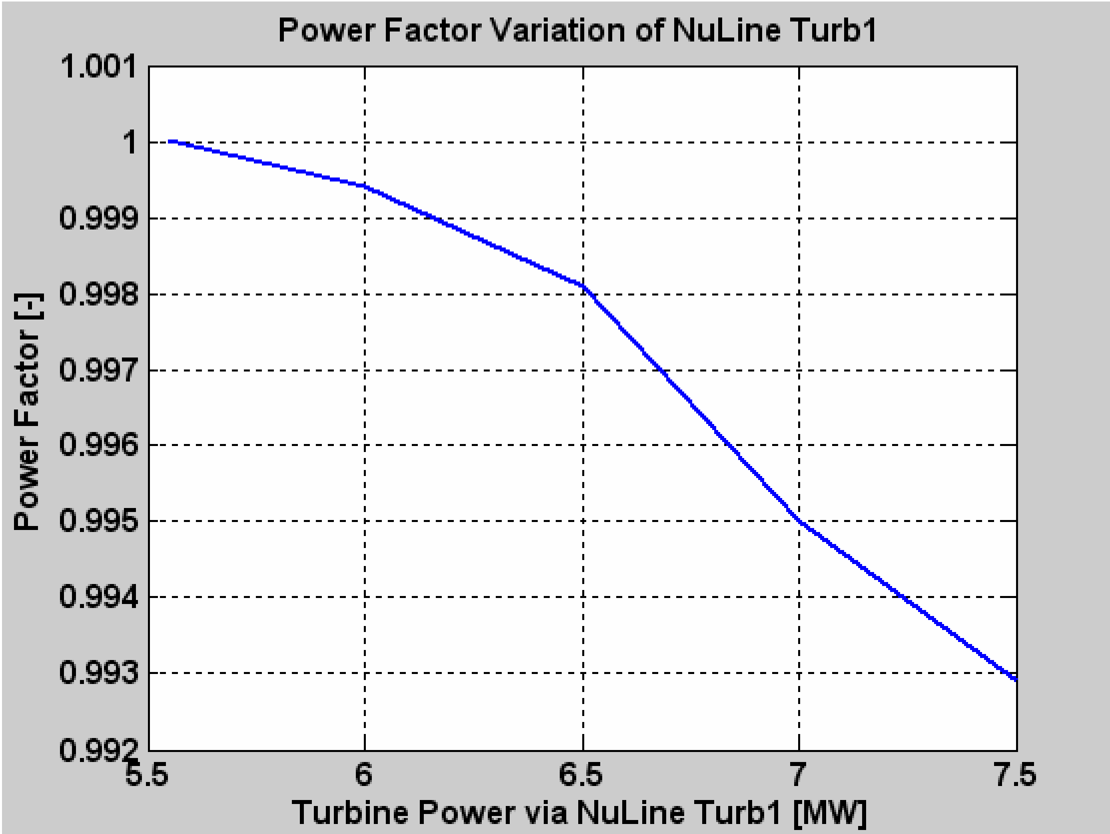

Figure 4.32-Power factor variation of NuLine Turb1 to control voltage at the point of connection while injecting more active power.

4.10.5 Discussion

It is seen from Figure 4.31 that it is possible to increase the turbine active power input up to 7.0 MW with a reactive power absorption of 0.7 Mvar at which the evacuation cable is loaded to 94% of its rated value and the transformer is overloaded by 2 %.

4.10.6 Conclusion

It is concluded that a total of 7 MW, with reactive power absorption of 0.7 Mvar can be injected into the system by installing a turbine at NuLineT1 via a cable length of 3 km, of type AXCEL240, connected directly to substation. The transformer will be overloaded by 2%.

4.11 Turbine Installed at NuLineT2 Only

An analysis is also done for the third possibility that a turbine is installed only at the second location (NuLineT2, with a cable length of 5 km).

4.11.1 Steady State Voltage Variation

The variation in voltage at the point of connection (NuLineT2) with the injection of active power by the wind turbine (NuLine Turb2) operated with a unity power factor is shown in Figure 4.33.

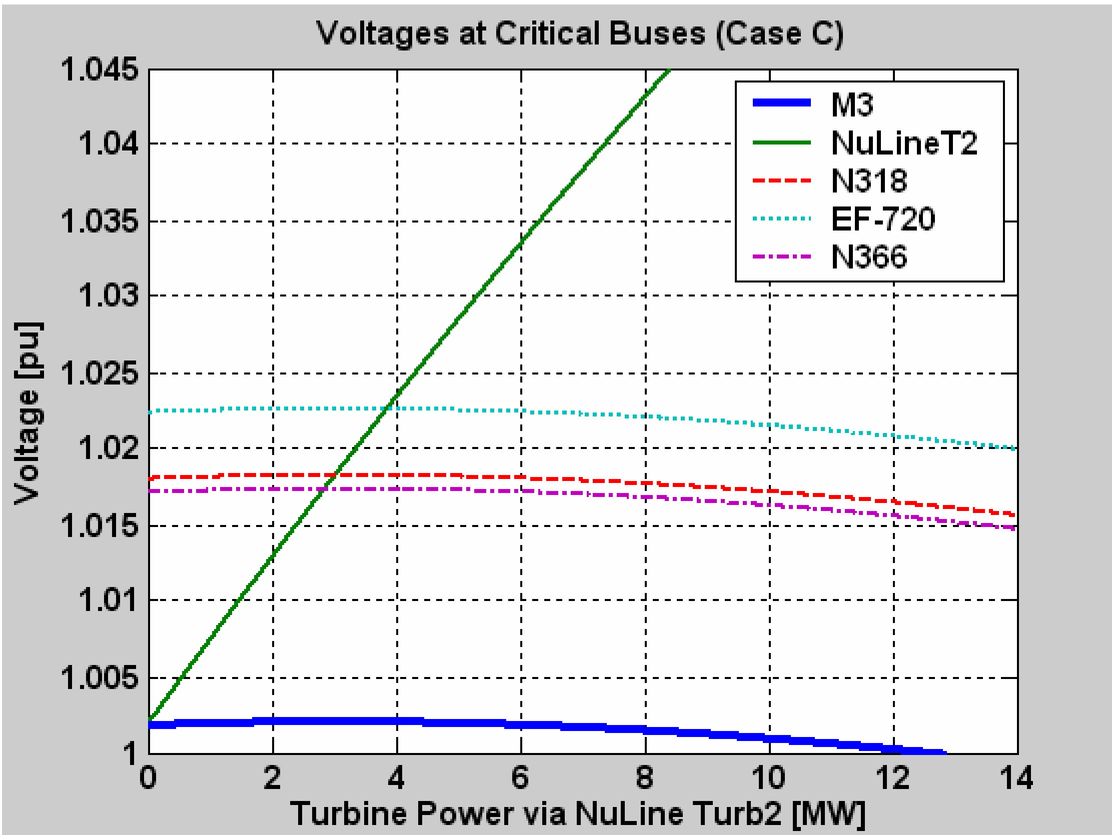

Figure 4.33-Voltage variation with increasing turbine power via NuLine Turb2

From Figure 4.33 it is seen that the voltage limit is reached at about 3.3 MW. It is possible to increase the active power input if the power factor of the wind turbine is lowered to absorb reactive power. This depends on the thermal loading situation. The thermal loading is presented in the next section.

4.11.2 Thermal Limits

The thermal loading for the components is presented in Figure 4.34 with a unity power factor operation of the turbine. It is seen that the transformer and the evacuation cable is loaded to its rated value at about 7 MW. The thermal limits are found to be almost the same as in previous sections.

One thing that can be noted nevertheless is the slight difference in the loading limits of the two cable sections NuLineT1 to M3 and NuLineT2 to NuLineT1. This can be attributed to losses. Some power is lost as resistive losses over the flow along 2 km of cable length from NuLineT2 to NuLineT1.

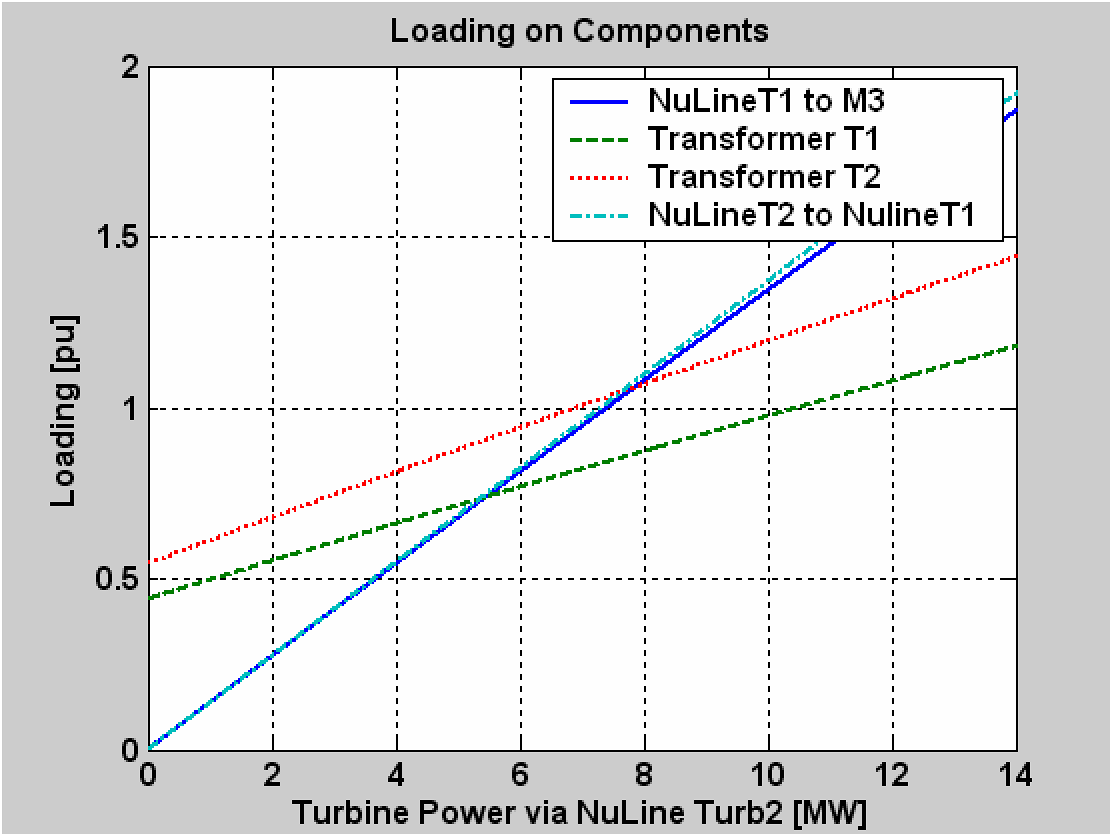

Figure 4.34-Loading of components with turbine power via NuLine Turb2

4.11.3 Results

The results of turbine operation are presented in Table 4.15.

Table 4.15-Power input possible for different limits with a turbine operated at a unity power factor and located at bus NuLineT2.

Limiting Factors (100% Loading)	Generation 100%
	Load 10%
Voltage 1.02 p.u. at NuLineT2	3.35 MW
Thermal Limit AXCEL240 (7.3 MVA) NuLineT2 to NuLineT1	7.3 MW
TransformerT1 (8MVA)	10.48 MW
TransformerT2 (8MVA)	6.93 MW

4.11.4 Voltage Control using Reactive Power

From Table 4.15 it is seen that it is possible to increase the rating of the turbine above 3.3 MW if it is capable of absorbing reactive power. The voltage is to be limited to 1.02 p.u. at the point of connection.

The loading of components with reactive power voltage control is presented below in Figure 4.35. The power factor variation to control the voltage is shown in Figure 4.36.

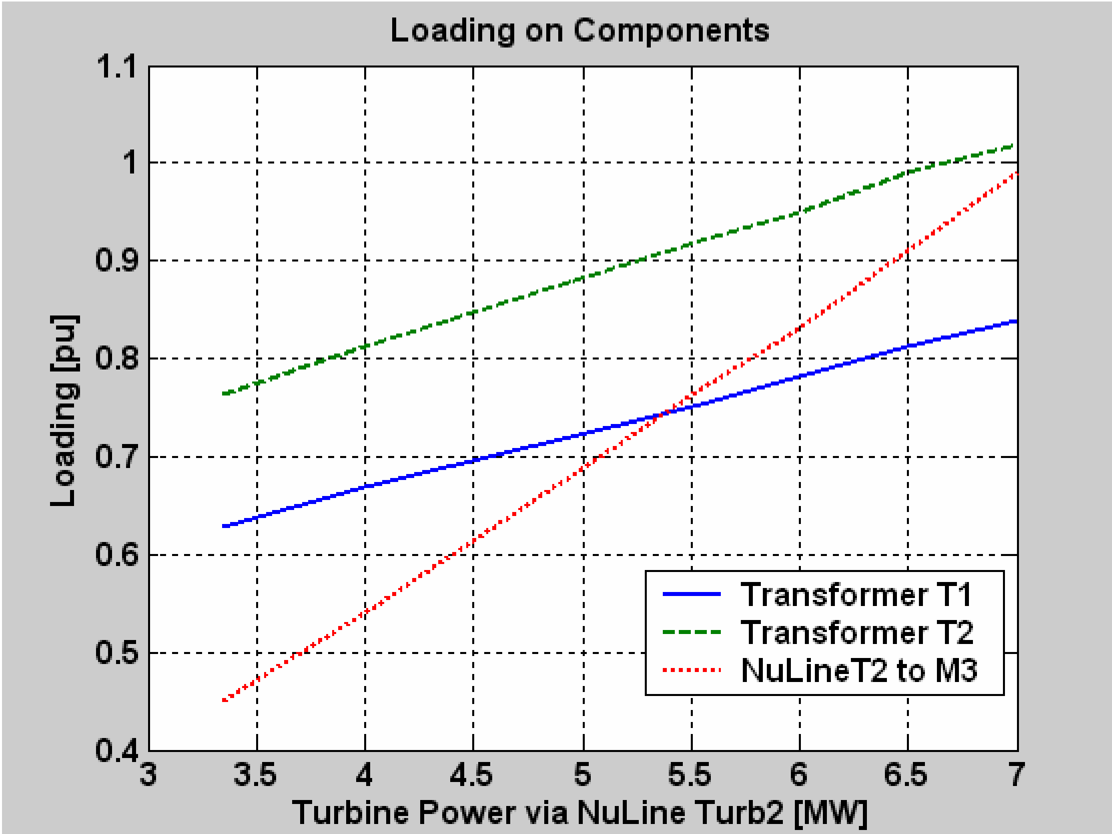

Figure 4.35-Loading of components with active injection and reactive power absorption.

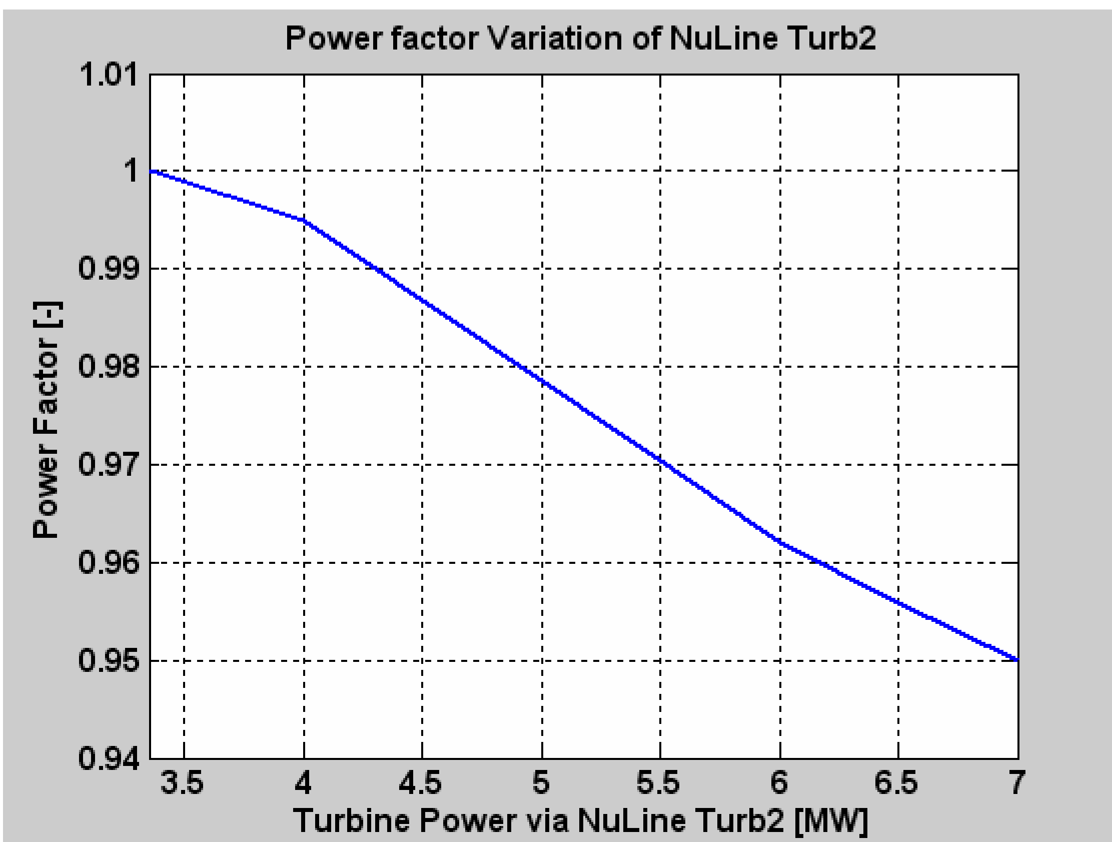

Figure 4.36-Power factor variation of NuLine Turb2 to control voltage at the point of connection while injecting more active power.

4.11.5 Discussion

It is seen from Figure 4.35 that it is possible to increase the turbine active power input up to 7.0 MW with reactive power absorption of 2.3 Mvar at which the evacuation cable is loaded to the rated value and the transformer is overloaded by 2 percent.

4.11.6 Conclusion

It is concluded that a total of 7 MW can be injected, with reactive power absorption of 2.3 Mvar, by installing a turbine at NuLineT2 via a cable length of 5 km connected directly to substation. The transformer is overloaded by 2 percent.

4.12 Comparison

It is observed that with reactive power absorption a total of about 7 MW of active power can be added to the system through wind energy converters. The limit is posed by the thermal loading of system components.

There are obviously some differences in the three options of turbine placement locations. These are the differences in the reactive power absorption required to limit the voltage at the point of connection and the power losses in the system.

4.12.1 Power Factor Variation Required

Figure 4.37 presents the variation in power factor required for the different placement location possibilities considered. It is seen that the need to lower the power factor below unity is required much later with a turbine installed at NuLineT1 (closer in distance physically and electrically from the infinite bus, at 3 km) and the amount by which it is lowered is also very less. It is desirable now days that the wind turbines operate at near unity power factor [5]. For the same amount of active power input a turbine at NuLineT1 meets this criterion.

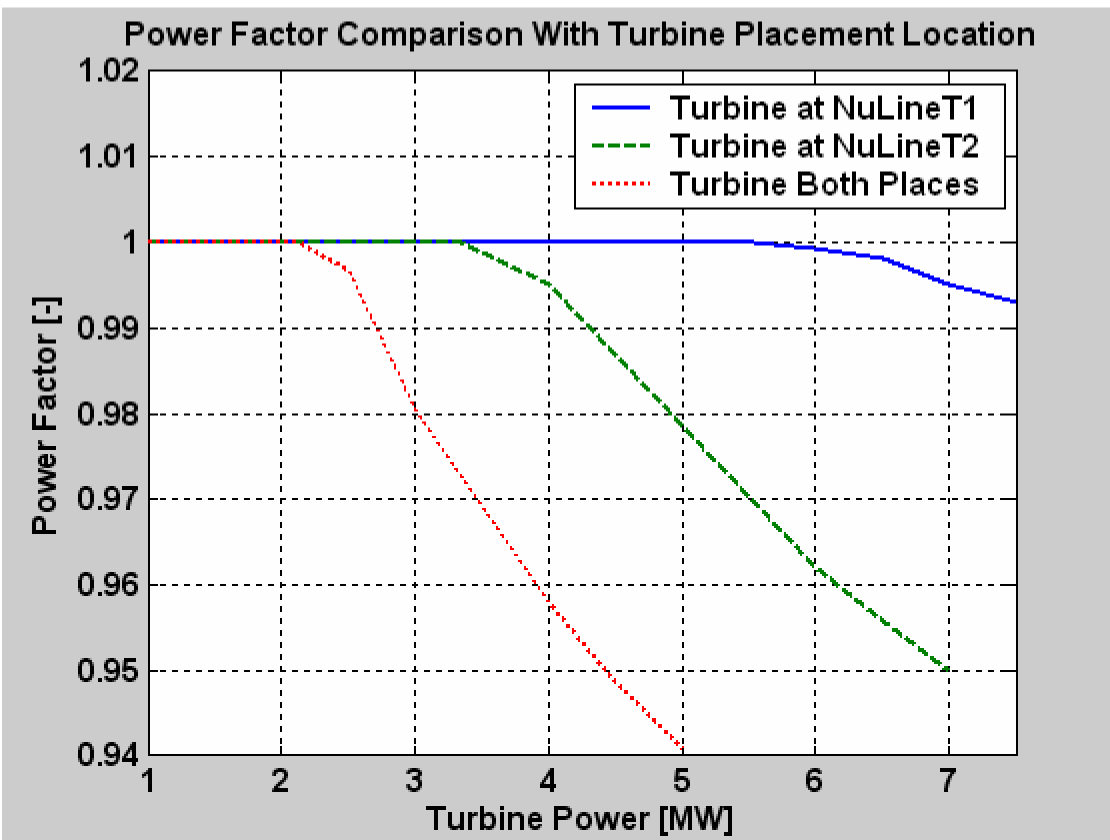

Figure 4.37-Power factor required to limit the voltage at the point of connection to 1.02 p.u. with turbine active power.

Figures 4.38 (a) and (b) present the amount of reactive power that has to be absorbed in Mvars and in percentage reactive of active power.

The fact that the power transfer medium is a cable, which has a low X/R ratio, the need to absorb reactive power to limit the voltage rise increases [6].

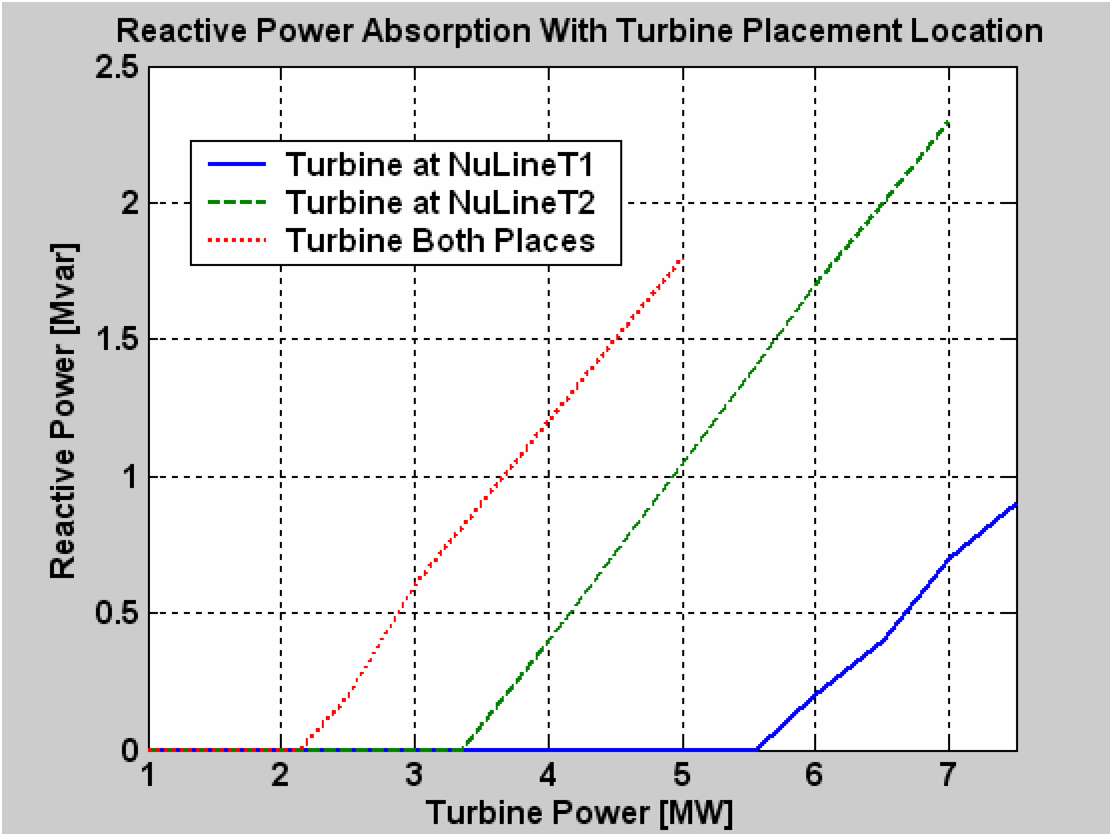

Figure 4.38 (a)-Reactive Power absorption required to limit the voltage at the point of connection to 1.02 p.u. with turbine active power.

One thing that should be remembered while considering Figures 4.37 and 4.38 is that the plot for turbines at both places shows the power factor and reactive power for the turbine at location 2. As already mentioned the 2 MW rated turbine at location 1 is operated at unity power factor due to the fact that the voltage at its point of connection remains within the voltage limit.

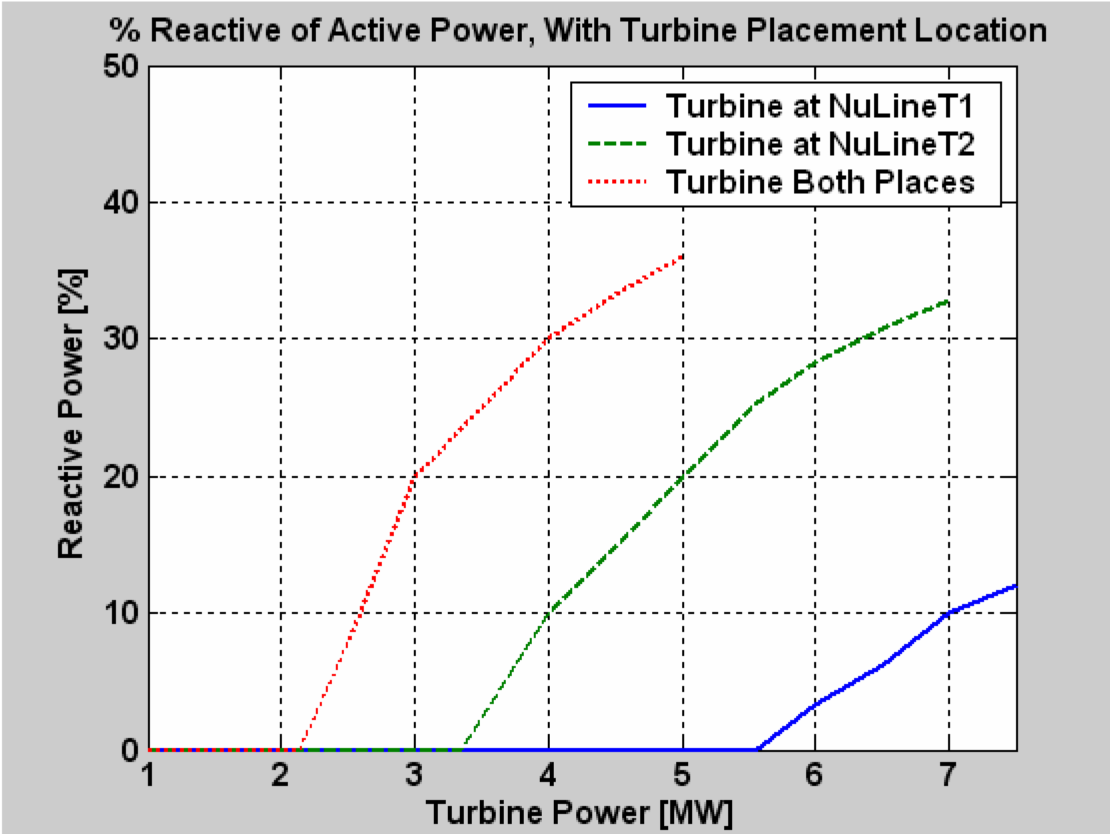

Figure 4.38 (b)-Reactive Power absorption required as a percentage of active power to limit the voltage at the point of connection to 1.02 p.u. with increasing turbine active power.

It is possible to calculate the X/R ratio (XR_{ratio}) of this system using the plot for the turbine at NuLineT2 in Figure 4.38 (a). The approximate relation between active power P injected and reactive power Q absorbed to keep the voltage constant at the point of connection follows from Equation (4.2) and is given as

$$P = XR_{ratio} * Q \tag{4.3}$$

This can be seen as an equation of a straight line through origin with a slope equal to XR_{ratio} , the ratio between the reactance and resistance. But this equation form is valid when reactive power absorption is applied throughout while injecting active power. In our case reactive power absorption is applied only when voltage rises above 1.02 p.u. and thus the straight line does not go through origin.

The straight line equation in our case is as follows

$$Q = XR_{Ratio}^{-1} * P + C \tag{4.4}$$

Where,

C= -2.14 =reactive power injection required to raise the voltage to 1.02 p.u. (y-axis intercept)

Q= Reactive power
P= Active power
XR_{Ratio}^{-1} = Inverse of XR_{Ratio} (Slope of the line)

By studying the plot, the value of the XR_{Ratio}^{-1} is found to be 0.64 which gives the XR_{ratio} to be 1.56. This agrees with the XR_{ratio} of 1.4 calculated, including the short circuit resistance and reactance values of the transformers, from the data provided for the cable and transformer in Appendix A.

4.12.2 Losses

Figure 4.39 shows the comparison of losses in the three placement possibilities.

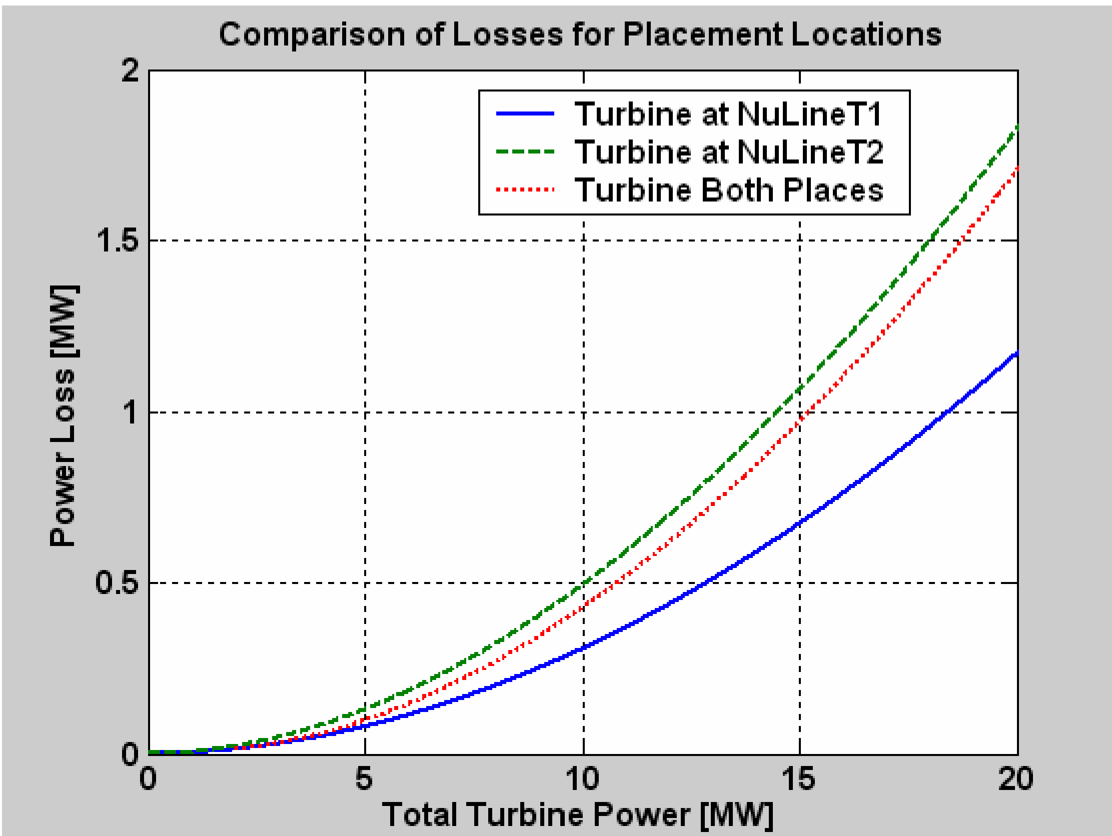

Figure 4.39-The comparison of losses in the three placement possibilities.

The comparison of losses shows that the active power losses for the turbine placement at NuLineT1 are the lowest amongst the three possibilities.

4.12.3 Power Factor at Point of Common Coupling (M3)

It is clear that our system is not a wind farm but since we have a dedicated line for wind energy converters we can see it as a wind farm. The power factor and the PQ curve of the 'wind farm' are given in Figure 4.40 (a) & (b) respectively. The PQ curve shows the total reactive power generated or consumed in the wind farm against the total active power generated for a certain voltage at the point of common coupling (M3). Now a days it is mostly required that the wind farms operate at near unity power factor [5]. The Figures also include the effect of absorbing reactive power to control the voltage at the point of connection of the turbine.

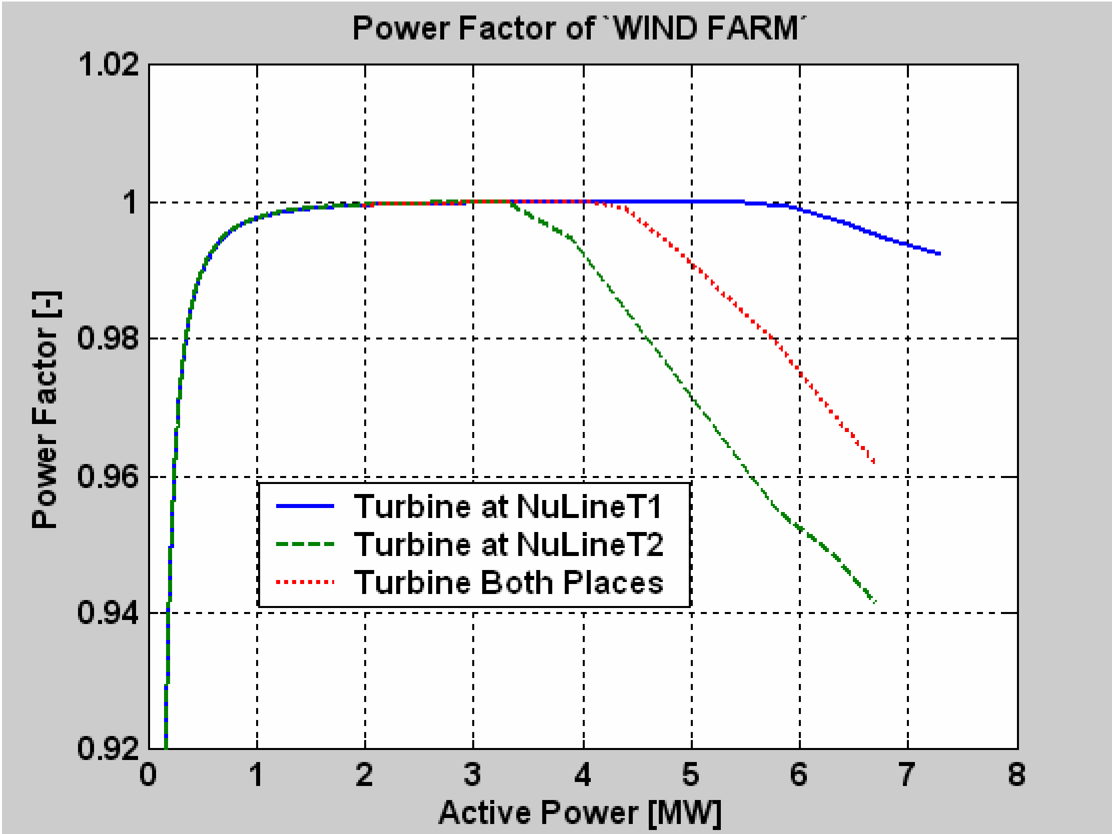

Figure 4.40 (a)-Power Factor of the wind farm against the total active power as seen from M3.

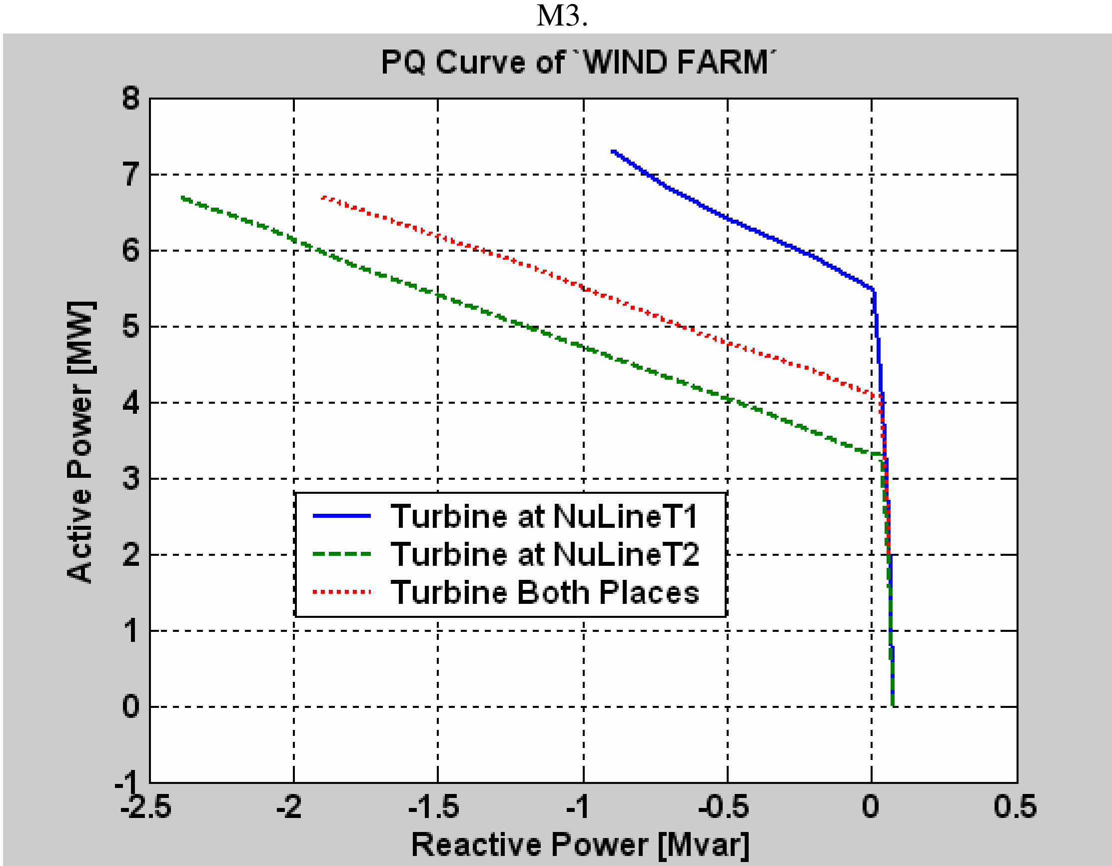

Figure 4.40 (b)-Reactive power consumption of the wind farm as seen from M3 (PCC).

It can be seen from Figure 4.40 (a) that with a turbine installed at NuLineT1 the capacitor compensation, if considered, at the substation to keep the power factor near unity would be smaller.

4.12.4 Flicker Calculation of New Line

There is a proposal to connect a new line at bus ‘M3’, connecting three new wind turbines of 2 MW each. After analysis for all the combinations of wind speed and load, it is found that a total of about 7 MVA can be integrated through this line. However, the flicker calculation is done for a total of 6 MVA of contribution considering the proposal.

To calculate the flicker severity index P_{st} for these wind turbines at M3 (PCC), Equation (3.3) is used. The flicker coefficient for all three wind turbines is assumed to be the same and increased from 1 to 8.

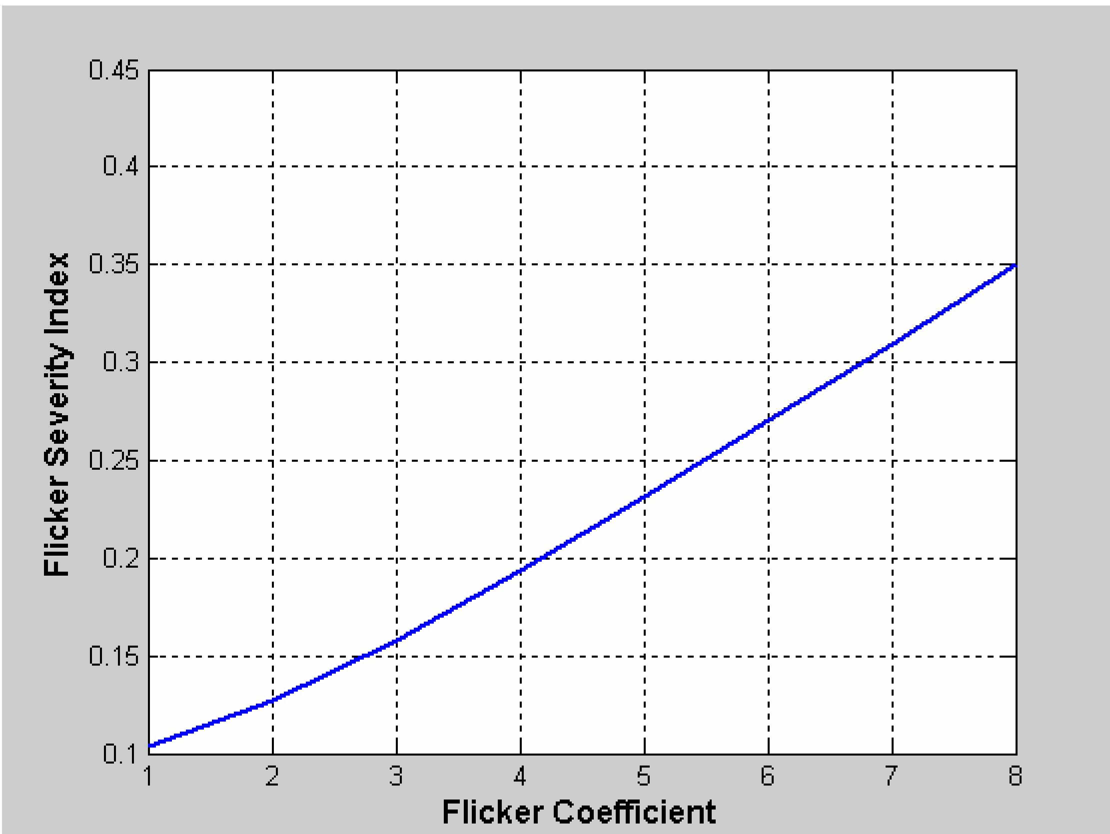

Figure 4.41-Combined Flicker Severity Index of the three new wind turbines at M3 against the same flicker coefficient assumed for all three.

It can be seen from Figure 4.41 that the sole contribution of these new wind turbines only reaches the critical value of 0.35 at a flicker coefficient value of 8.

To find the combined P_{st} of all the wind turbines at M3, each wind turbine is assumed connected at bus M3. The flicker coefficient of the new turbine at Västermark as well as the new turbines connected through the new line is assumed to be the same and varied from 1 to 8. The flicker severity index against this varying flicker coefficient is plotted in Figure 4.42.

Figure 4.42-Combined P_{st} of all the wind turbines at M3 against the flicker coefficient of the new turbine at Västermark and the three new turbines connected by the dedicated line.

Figure 4.42 shows that the P_{st} limit value of 0.35 suggested in AMP is not reached when taking into account all of the turbine installations, old and new. As a result of this analysis it is found that flicker due the turbines will not be a power quality issue at Lundsbrunn.

4.12.5 Discussion

It is seen in the above analysis that installation of a turbine at a closer electrical distance is much better in terms of the losses, reactive power absorption required through the wind turbine converter to limit the voltage at the point of connection and the overall power factor of the wind farm as seen from the PCC (the substation bus M3).

The proposed connection of the three new turbines of 2 MW each is possible with reactive power absorption used to control the voltage level.

4.12.6 Conclusion

It is concluded that a total of 7 MW more wind energy can be integrated through a new dedicated line connected directly to the substation bus. The proposed connection of the three new turbines of 2 MW each is possible with reactive power absorption to control the voltage level.

4.13 Conclusion for Lundsbrunn

It is concluded that the overall integration of wind power possible at Lundsbrunn is 10 MW. The installation of wind turbines can be at two places in the network. It is found that 3 MW of wind power generation capacity can be integrated into the system with a turbine installed to supply power via Västermark and with the parallel operation of transformers an additional 7 MW can be added later via a dedicated line that supplies power directly to the Lundsbrunn substation.

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Conclusion

The aim of this master thesis is to find how much wind energy that can be connected at a certain point in the distribution network without violating any restrictions for the grid regarding voltage levels and the line loading. The tolerable limits for the voltage and the thermal rating of all the lines and transformers are provided by the distribution company whereas Swedish standards are followed to decide the limits regarding flicker emission.

There are two sites under consideration for the wind power installations. These sites are Hällekis and Lundsbrunn.

At present, no wind turbines are installed in Hällekis. The power collection scheme for the proposed wind turbines makes the power generation rather concentrated instead of being distributed in nature. Analysis under different load conditions shows that it was the thermal limit of the line joining the wind power installations with the grid, which restricts the amount of wind power that can be connected at that point. It is found out that two turbines of 3.6 MW each can be connected at bus A10. Exchange of the reactive power from these wind turbines is also investigated since it is advantageous to maintain the voltage limits while load suddenly reduces or wind speed increases. It is found that exchange of reactive power from these wind turbines is not feasible in this case since the voltages remain in the tolerable limits and don't impose any restriction on the ratings of wind turbines. Further, the cable joining the wind turbines with the grid is already loaded to its rated value. Flicker emission for these wind turbines are also calculated and it is found that with the given fault level at the PCC, operation of both wind turbines with flicker coefficient equal to or above 6 will increase the flicker severity index beyond the tolerable limit of 0.35.

There are already eight turbines installed in Lundsbrunn. These wind turbines are installed at different feeders. Analysis for different combinations of load and wind speed with one and both transformers in parallel, shows that 3 MW of wind power can be installed at a point called Västermark along feeder 4. Utilizing the reactive power exchange possibility for this wind power installation is not feasible due to the thermal limits of the feed-in cable and the transformer. Flicker calculations are done for this case by considering one turbine of this rating. The result shows that the flicker coefficient of this turbine must stay below 6 to ensure satisfactory power quality; however installation of two or three wind turbines with the combined power rating of 3 MW at this point can allow the installation using turbines having higher flicker coefficients as well.

At Lundsbrunn, an investigation regarding addition of a separate line taking power from three wind turbines to the bus M3 is also done. In this case operation of both transformers is considered as it was found from previous analysis that one transformer is already hitting its thermal limit with the installation of 3 MW wind power along feeder 4. It is found out that a total of 7 MW can be installed along this line and the limiting factor in this case is the voltage at the terminals of the turbine. The reactive power absorption required to limit the voltage at the terminal of the turbine is quite different depending on the distance between the substation and the wind turbine location.

Flicker calculations are carried for three wind turbines of 2MW each. Flicker emission from these wind turbines at PCC as well as contribution of these wind turbines along with all other wind turbines is calculated. It is observed that even the flicker coefficient of 8 for these wind turbines doesn't violate the flicker emission limit.

Appendix A Fault Level Calculation at Different PCCs in Lundsbrunn & Hällekis

Flicker calculation for both locations is based on the relationships described in the document IEC 61400-21. These relationships are mentioned as equation (3.2) and equation (3.3) in chapter 3. According to equation (3.2) and equation (3.3), the flicker severity index of a single or more than one wind turbines at a PCC cannot be calculated without calculating fault level at PCC.

Fault level can be defined as the amount of power that can flow towards a point in a network due to occurrence of a three phase short circuit fault at that point. In a three phase system, fault level is calculated as

$$S_k = \frac{U^2}{Z} \tag{A.1}$$

Where,

S_k	Fault level at a point
U	Line voltage at that part of grid
Z	Impedance up to the point where fault occurs

In the following sections fault level is calculated at each PCC of both locations, where either wind turbines are already installed or new wind turbine is going to connect. It should be noted that charging of lines is neglected during fault level calculation.

Lundsbrunn

At Lundsbrunn fault level at 42 kV bus is 217 MVA with source impedance comprising of resistance R= 1.9 ohm and inductive reactance X = 7.5 ohm. To include source impedance in fault level, the source impedance is referred to low voltage side using turn ratio of transformer T1. The referred values of resistance and reactance are calculated as

$$R' = \frac{1.9}{\left(\frac{42}{10.7}\right)^2} = 0.1233\Omega$$

$$X' = \frac{7.5}{\left(\frac{42}{10.7}\right)^2} = 0.486\Omega$$

The short circuit impedance of transformer T1 is calculated from the percentage voltage drop across resistance and reactance given in the transformer data.

$$U_R = 0.49\ \%$$
$$U_X = 7.75\ \%$$

This voltage is first converted into real values using secondary voltage as base value.

$$U_R = 0.0049 \times \frac{10.7}{\sqrt{3}} \times 10^3 = 30.27 \text{ volts}$$

$$U_X = 0.0775 \times \frac{10.7}{\sqrt{3}} \times 10^3 = 478.76 \text{ volts}$$

The rating of transformer T1 is 8 MVA. The rated current at secondary side is found out to be

$$I = \frac{8 \times 10^6}{\sqrt{3} \times 10.7 \times 10^3} = 431.66 \text{ Amp}$$

The value of resistance and inductive reactance is calculated using Ohm's law.

$$R_{T1} = \frac{30.27}{431.66} = 0.0701\Omega$$

$$X_{T1} = \frac{478.76}{431.66} = 1.109\Omega$$

The values of resistance and inductive reactance of lines are expressed in per unit length (in km). To find the value of these parameters for each line segment in ohms, given values are multiplied with specified length. The values of resistance, inductive reactance and susceptance per unit length, for each type of cable and overhead line used in both networks are given in Table A.1.

Table A.1-Values of resistance, inductive reactance and susceptance for different cables and overhead lines.

Conductor	**Area (mm^2)**	**Type**	**R (Ω/km)**	**X (Ω /km)**	**B (Ω /km)**	**S_{max} (MVA)**
AXKJ	95	CABLE	0.316	0.097	0.000094	4.4
AXKJ	150	CABLE	0.200	0.091	0.000094	5.6
AXKJ	240	CABLE	0.125	0.085	0.000126	7.3
AXLJ	95	CABLE	0.316	0.097	0.000094	4.3
AXCEL	50	CABLE	0.600	0.107	0.000063	3.1
AXCEL	95	CABLE	0.320	0.110	0.000063	4.5
FCJJ	25	CABLE	0.720	0.360	0.000063	2.2
FCJJ	150	CABLE	0.120	0.094	0.000126	6.1
ACJJ	70	CABLE	0.429	0.097	0.000188	3.1
ACJJ	185	CABLE	0.162	0.091	0.000220	5.5
FeAl	62	O/H	0.532	0.351	0.000000	3.8
FeAl	99	O/H	0.333	0.336	0.000000	5.2
FeAl	157	O/H	0.210	0.320	0.000000	7.2
Al 59	99	O/H	0.333	0.336	0.000000	5.2

The source impedance is added with transformer and line impedances to find total impedance to the PCC. Equation (A.1) is used to find fault level. Total impedance up to each PCC and respective fault level is given in the table.A.2.

Table.A.2 Fault level at different PCC in Lundsbrunn

Fack	**Location**	**PCC**	**Resistance (Ohms)**	**Reactance (Ohms)**	**Impedance (Ohms)**	**Grid Angle (Degree)**	**Fault Level (MVA)**
	Lundsbrunn	M3	0.193	1.595	1.607	83.10	71.28
L1	Nolebo	EF-690	1.66	2.373	2.899	54.92	39.492
L2	St. Lund	N351	0.506	1.666	1.741	73.10	65.76
L4	Lunden	3005	0.356	1.798	1.833	78.78	62.46
L4	Västermark	N318	0.658	2.102	2.203	72.61	51.97
L4	New turbine	D16K-106	1.236	2.686	2.957	65.28	38.718
L5	Kollbog + Kyrkebo	D16L-101	0.652	1.886	1.995	70.92	57.38
L5	Erikstorp	EF-720	2.357	3.588	4.293	56.69	26.66

The above table shows the fault levels at different locations in Lundsbrunn when only one transformer is in operation. During investigation of a new line connecting three wind turbines of 2 MW each with bus M3, it is found that integration of these turbines is only possible when both transformers are in operation. The operation of both transformers in parallel would change the fault level at Lundsbrunn network significantly. For calculation of flicker emission from all wind turbines, fault level is calculated at bus M3 only since M3 is considered as PCC for all wind turbines.

The short circuit impedance of transformer T2 is calculated in the same manner, as it is done for transformer T1 and the values came out as

$R_{T2} = 0.0704$ ohms
$X_{T2} = 0.912$ ohms
$Z_{T2} = 0.914\angle 85.58^\circ$ ohms

The values for transformer T1 are

$R_{T1} = 0.0701$ ohms
$X_{T1} = 1.109$ ohms
$Z_{T1} = 1.11\angle 86.38^\circ$ ohms

Since both transformers are going to operate in parallel, the combined impedance of both transformers is calculated as

$$Z_{T1//T2} = \frac{Z_{T1} \times Z_{T2}}{Z_{T1} + Z_{T2}} = 0.500\angle 85.937^\circ \text{ ohms}$$

The total impedance up to bus M3 is calculated by adding $Z_{T1//T2}$ with source impedance Z_s.

$$Z_T = Z_S + Z_{T1//T2} = 0.996\angle 80.87^{\circ} \text{ ohms}$$

Fault level at bus M3 is calculated by using equation (A.1)

$$S_k = \frac{(10.7\times 10^3)^2}{0.996} = 114.94 \text{ MVA}$$

Hällekis

At Hällekis fault level at 42 kV bus is 279 MVA and source impedance is comprising of resistance R = 0.5 ohms and X = 6.3 ohms. There are two transformers in operation at Hällekis. The source impedance is referred to low voltage side using the turn ratio of transformer T3 only because both transformers are feeding separate buses and PCC for new wind turbines is located at secondary side of transformer T3.

$$R' = \frac{0.5}{\left(\frac{45}{11.5}\right)^2} = 0.0326\Omega$$

$$X' = \frac{6.3}{\left(\frac{45}{11.5}\right)^2} = 0.411\Omega$$

$$Z_s' = 0.0326 + i0.411 = 0.412\angle 85.46^{\circ}\, ohm$$

The short circuit impedance of transformer T3 is calculated from the percentage voltage drop across resistance and reactance given in the transformer data.

$$U_R = 0.55\,\%$$
$$U_X = 8.41\,\%$$

This voltage is first converted into real values using secondary voltage as base value.

$$U_R = 0.0055\times\frac{11.5}{\sqrt{3}}\times 10^3 = 34.92 \text{ volts}$$
$$U_X = 0.0841\times\frac{11.5}{\sqrt{3}}\times 10^3 = 558.384 \text{ volts}$$

The rating of transformer T3 is 13 MVA. The rated current at secondary side is found out to be

$$I = \frac{13\times10^6}{\sqrt{3}\times11.5\times10^3} = 652.65 \text{ Amp}$$

The value of resistance and inductive reactance is calculated using Ohm's law.

$$R = \frac{34.92}{652.65} = 0.053\Omega$$

$$X = \frac{558.38}{652.65} = 0.855\Omega$$

The total short circuit impedance up to bus A10 is calculated by adding source and transformer T3 short circuit impedance.

$$Z_T = Z_S + Z_{T3} = 1.26\angle 86.13^\circ \, ohms$$

Fault level at bus A10 is calculated by using equation (A.1)

$$S_k = \frac{(10.7\times10^3)^2}{1.26} = 90.86 \text{ MVA}$$

Appendix B Calculation of Power Flow between Transformers

1) Transformer T1:

42000/10700 V
8 MVA
$U_r = 0.49$ %
$U_x = 7.75$ %
$U_{reg} = 97.5$ % of 11000 V

2) Transformer T2:

42000/10700 V
8 MVA
$U_r = 0.49$ %
$U_x = 6.35$ %
$U_{reg} = 97.0$ % of 11000 V

In Lundsbrunn the voltage on bus M3 is maintained at 10.7 kV which is taken as the base voltage for per unit calculations. Thus the voltage on the secondary U_{reg} of transformers T1 and T2 become 1.0023 p.u and 0.9972 p.u respectively.

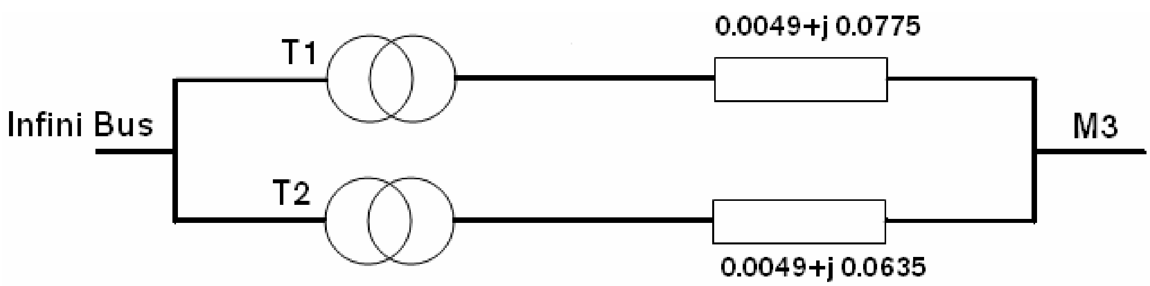

Figure B.1-Equivalent circuit representation of parallel transformers

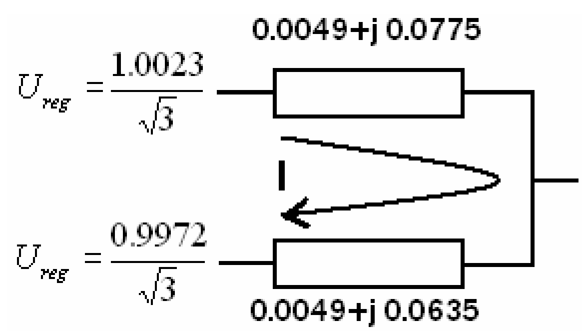

Figure B.2-Current loop between transformers

Using Kirchoff's Voltage Law (KVL) on the loop in Figure B.2, we get

$$\frac{1.0023}{\sqrt{3}} - I(0.0049 + j0.0775) - I(0.0049 + j0.0635) - \frac{0.9972}{\sqrt{3}} = 0$$

$$I = \frac{1.0023 - 0.9972}{(0.0098 + j0.141)\sqrt{3}} = 0.021\angle -86°\, pu$$

$$P_{pu} = \sqrt{3}VICos86 = \sqrt{3} * 1 * 0.021 * Cos86 = 0.0025\, pu$$

$$Q_{pu} = \sqrt{3}VISin86 = \sqrt{3} * 1 * 0.021 * Sin86 = 0.036\, pu$$

Using the component value as power base

$$P = 0.0025 * 8 = 0.02MW$$

$$Q = 0.0363 * 8 = 0.29M\ \text{var}$$

Appendix C Modelling of Power System Components in PSS/E

The following document has been adopted from the PSS/E™ 29 VOLUME I: PROGRAM APPLICATION GUIDE.

Model of Overhead Line and Cables

Normally the conductors for overhead lines are provided with resistance and reactance per kilometre. In case of cables, admittance is also provided along resistance and reactance per kilometre. These values are taken as input data by the software PSS/E® and propagation constant γ and surge impedance z_s is calculated for each line. The relations used for the calculation of propagation constant and surge impedance are give in equation (C.1) and (C.2).

$$\gamma = \sqrt{ZY} \tag{C.1}$$

$$z_s = \sqrt{\frac{Z}{Y}} \tag{C.2}$$

Where Z = R+jX ohms/kilometer
Y = jB mhos/kilometer

These parameters are used to calculate transmission coefficients. Transmission coefficients can be expressed in terms of propagation constant and surge impedance by the equation (C.3), (C.4), (C.5) and (C.6).

$$A = \cosh \gamma L \tag{C.3}$$

$$B = -z_s \sinh \gamma L \tag{C.4}$$

$$C = \frac{-1}{z_s} \sinh \gamma L \tag{C.5}$$

$$D = \cosh \gamma L \tag{C.6}$$

where L is the length of the line.

Transmission line parameters relate the sending end voltage and current with receiving end voltage and current. These relations are described in the form of equation (C.7) and (C.8).

$$v_r = A.v_s + B.i_s \tag{C.7}$$

$$i_r = C.v_s + D.i_s \tag{C.8}$$

Where,

v_s , sending end voltage
v_r, receiving end voltage
i_s, sending end current
i_r, receiving end current

Equation (C.7) and (C.8) are rearranged to form an admittance matrix as shown in equation (C.9).

$$\begin{bmatrix} i_s \\ i_r \end{bmatrix} = \begin{bmatrix} \dfrac{1}{Z_s \tanh\gamma L} & \dfrac{-1}{Z_s \sinh\gamma L} \\ \dfrac{-1}{Z_s \sinh\gamma L} & \dfrac{1}{Z_s \tanh\gamma L} \end{bmatrix} \begin{bmatrix} v_s \\ v_r \end{bmatrix} \tag{C.9}$$

Equation (C.10) shows the admittance matrix of a circuit shown in Figure C.1.

$$Y_{ij} = \begin{bmatrix} \left(\dfrac{1}{Z_{ex}} + \dfrac{Y_{ex}}{2}\right) & \dfrac{-1}{Z_{ex}} \\ \dfrac{-1}{Z_{ex}} & \left(\dfrac{1}{Z_{ex}} + \dfrac{Y_{ex}}{2}\right) \end{bmatrix} \tag{C.10}$$

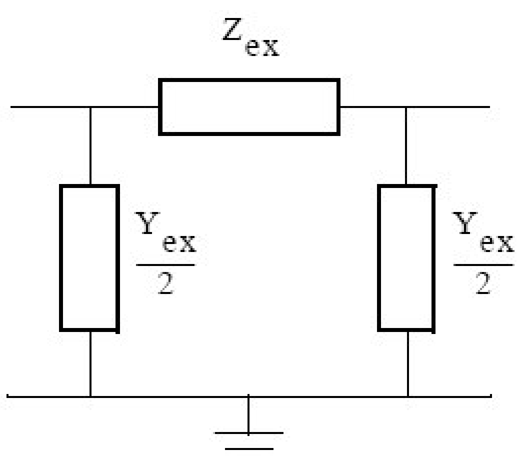

Figure C.1-Pi-Form Transmission Line Equivalent Circuit

The comparison of equation (C.9) and (C.10) gives the following values of Z_{ex} and Y_{ex} as shown in equation (C.11) and (C.12).

$$Z_{ex} = z_s.\sinh \gamma L \tag{C.11}$$

$$Y_{ex} = \frac{2}{z_s}.\tanh \gamma L \tag{C.12}$$

The transmission line model in terms of Z_{ex} and Y_{ex} is shown in Figure C.2.

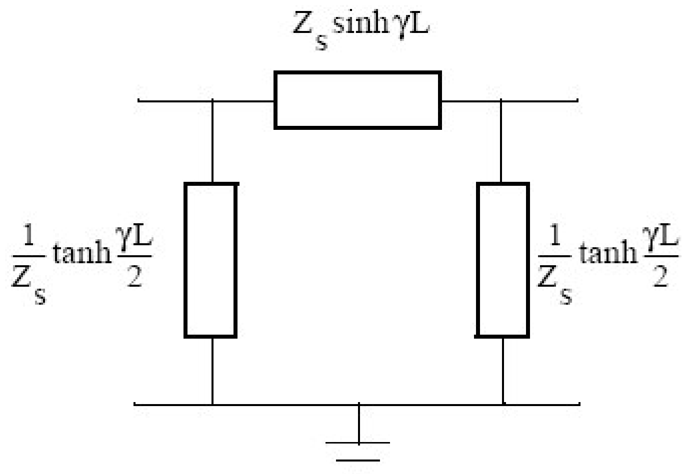

Figure C.2-Exact Equivalent of Circuit of Transmission Line

Two-Winding PSS/E Data Model Entry

PSS/E represents a two-winding transformer as shown in Figure C.3. This model allows representation of the magnetizing impedance that is often neglected on the i-side (primary) of the transformer. Data entry for this model unburdens the user from having to calculate the equivalent impedance and effective taps, tap step, and tap limits. Data flexibility also allows the user to specify the impedance on either system or transformer base, or by specifying load loss and impedance magnitude. The user can also choose to enter tap position by specifying voltages in kV rather than in per unit.

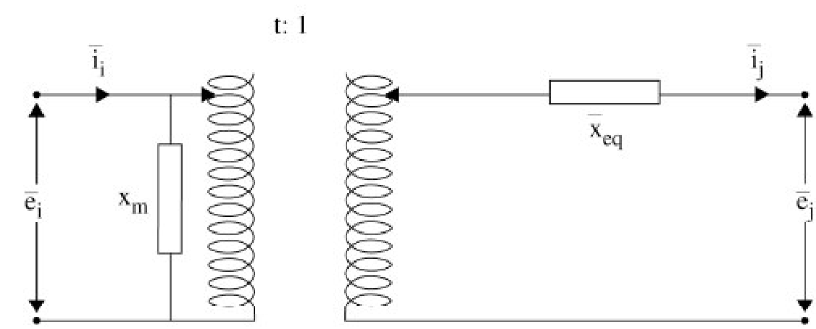

Figure C.3-Standard PSS/E two winding transformer circuit

In Figure C.3,
x_m is the magnetizing impedance
x_{eq} is the short circuit impedance
t is the per unit turns ratio
e_i is the primary terminal voltage
e_j is the secondary terminal voltage

Tap Changing Transformers

The transformer equivalent of Figure C.4 has as parameters:

- Per-unit turns ratio, t.
- Equivalent impedance, x_{eq}.

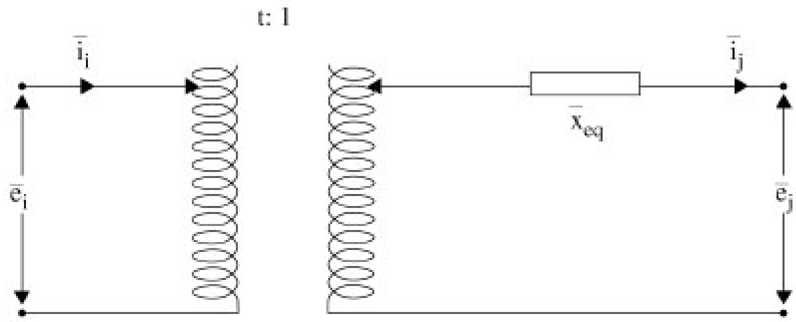

Figure C.4-Standard per-unit form transformer equivalent circuit

The equivalent impedance is dependent on the number of turns on the j-side winding, but independent of the number of turns on the i-side winding.

A tap-changing transformer may, therefore, be represented accurately by Figure C.4 with a constant value of x_{eq} as long as tap-changing affects the number of turns on one winding only. Figure C.4 does not require nominal number of turns, or tap position, on one side of the transformer. It can give accurate representation of a transformer with a fixed, or off-load, tap in one winding and an adjustable, or on-load, tap-changer in the other. This is achieved by:

- Assigning the i-side of Figure C.4 to the variable-tap winding.
- Assigning the j-side of Figure C.4 to the fixed-tap winding.