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# Fault analysis and investigation of voltage dips for wind energy integration into an existing distribution network

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# Abstract

The role of wind power in the form of distributed generation in the distribution networks is rapidly increasing in view of its environmental friendly nature and short duration constructional feature. Many factors influence the implementation of the wind turbines in distribution networks and one of them is the connection to the grid. Since the wind parks are connected in the transmission level because of its rigid nature, integration of single units in distribution networks is a challenging task which has to be carefully accomplished to make the wind generation economically viable.

This thesis investigates the integration of wind turbines into two distribution networks situated in the county of Västergötland, Sweden, to discuss the issues related to the interconnection of distributed generations. These issues treated are the affect of voltage dips when these generations are disconnected from the network due to the faults and also the fault currents and settings of the protection systems that need to be configured to allow a safe operation of these distributed generations.

It was observed that a voltage dip at a point depends on the location of the fault relative to the investigated point. Comparing the pre-fault, during fault and post-fault voltages, it was observed that the network suffers from a severe voltage drop when a feeder containing large amount of generation is disconnected due to a fault. For all the cases investigated in this thesis, necessary suggestions are made where the relay settings for the feeders and/or the transformers need to be reconfigured for a stable operation of the network.

# Acknowledgements

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# Contents

# Chapter 1

# Introduction

## *1.1 Problem Background*

Electric power systems providing energy to a large number of customers are spread over vast areas stretching from huge cities to remote locations and rural places. This task is achieved through various power system components like generators, transformers, motors, and transmission and distribution lines etc., which run thousands of miles, satisfying the customer needs through careful planning, design, installation and operation of such very complex networks. The network is subjected to constant disturbances, both natural and component generated, which may prove dangerous not only to the faulty component, but also to the neighbouring equipment. It is, therefore, impervious that the damage caused by the disturbances is limited to a minimum by speedy isolation of the faulted section without hampering the functioning of the rest of the system.

## *1.2 Purpose of Thesis*

The purpose of this thesis is to investigate two medium voltage distribution networks located at Lundsbrunn and Hällekis in the county of Västergötland, Sweden, for short circuit faults and voltage dips. Both the networks are subjected to three-phase short circuit faults, two-phase faults and single phase-to-ground faults. Investigating the networks for three-phase short circuit faults could be helpful in configuring the protection settings so that the worst of the fault conditions can be handled correctly. Similarly, since the single phase-to-ground faults are the most frequent ones that occur in a power system [1], these unsymmetrical faults are also investigated in the thesis. The operation of the Petersson coil used as resonant grounding system to suppress the total capacitive earth current of the network during an earth fault is also investigated.

## *1.3 Layout of Thesis*

The thesis starts with a brief description of both the networks mentioned in section (1.3). The analysis is categorized into two sections; one dealing with the affect of voltage dips on the network when large parts of power produced by the wind turbines are disconnected following a fault in the feeder in which they are connected, the other dealing with the short circuit currents and issues related to the settings of the protection systems in both the networks. The assumptions made in modelling the networks using the software PSS/E® are also discussed.

For the voltage dip part, faults are applied to each feeder considering various combinations of generation and load and the resulting voltage dips are reported. As far as the short circuit current analysis is concerned, faults are applied to the feeders and the fault currents along with the configurations of the protection systems are discussed. Both these analyses are carried out for the existing networks and the same networks after installing new turbines. the fault types used in this thesis are (i) three-phase short circuit faults, (ii) two-phase faults and (iii) single phase-to-ground faults.

Additionally, the Lundsbrunn network is operated with two transformers in parallel and then investigated for short circuit faults and voltage dips to make a comparison with the single transformer operation for the same network.

Finally, conclusions are drawn in the form of suggestions for the existing protection settings if they require to be reconfigured to facilitate the introduction of the new turbines under the assumptions made in modeling and analyzing the network.

The steady state analysis dealing with the same networks is presented in another master thesis work titled "*Integration of Wind Energy Converters into an Existing Distribution Grid*"

## References

[1] Till Welfonder, Volker Leitloff, Member, IEEE, René Feuillet, Senior Member, IEEE, and Sylvain Vitet, Member, IEEE, Location Strategies and Evaluation of Detection Algorithms for Earth Faults in Compensated MV Distribution Systems.

# Chapter 2

# Power System Protection

## *2.1 Characteristics of Protection System*

The primary objective of a protection system is the speedy isolation of the faulted network or the equipment to minimize the impact on other power system components. Power supply loss, voltage dips, overvoltages still occur because it is not possible to avoid the occurrence of natural events. Following are the basic characteristics a protection system should possess in order to operate satisfactorily although it is not practical to design a protection system that satisfies all the characteristics.

### 2.1.1 Reliability

Reliability is a quantitative term that has two facets: *Dependability* and *Security.* Dependability is "the degree of certainty that a relay or relay system will operate correctly" (IEEE C37.2). Security is "the degree of certainty that a relay or relay system will not operate incorrectly" (IEEE C37.2) [2]. As such, dependability is concerned with the operation of the relay when a fault is detected and security is concerned with the relay not operating when there is no fault. Power systems are subjected to both short duration transient faults which get cleared instantly and long duration severe faults that require the relay system to trip the faulty portion of the network and minimize the losses. Bearing in mind the fact that the relays operate in the power system for a lifetime, they cannot be misoperated i.e., they cannot be operated for a short transient of negligible time period that gets cleared by itself. While dependability is easy to ascertain through testing of the power system, security remains a question of difficulty as there are infinite types of transients that affect the power system.

### 2.1.2 Selectivity

The primary protection zone for a relay is the area assigned to the relay in which it should operate whereas overreached or backup zone is the area to which the relay can reach out and operate properly as a backup or secondary protection. Selectivity is the property by which the settings of the relay are graded such that the relay responds instantly to the primary protection zone and with a time delay to the back up zone, when the primary protection fails, so that a fault is not acted upon by both the relay systems.

### 2.1.3 Speed

One of the important features of a relay is the speed with which it detects the fault. The faster the speed of operation of the relay, lesser is the damage caused to the system associated with the increased probability of incorrect operations.

A high-speed relay is one that operates in less than 50ms (three cycles on a 60 Hz basis) (IEEE 100).The term instantaneous is defined to indicate that no delay is purposefully introduced in the action of the device (IEEE 100). The total clearing time (relay plus breaker) typically ranges from approximately 35 to 130ms.

### 2.1.4 Simplicity

Simplicity of the protection system is that feature by virtue of which the design of the protective system becomes simpler and adaptive. Each added unit to the protection system increases the complexity of the system in terms of added maintenance, increased probability of misoperation and problems related to coordination with other protective equipment which could result in catastrophic problems in the power system. All the accessories should be carefully evaluated so as to ensure that they contribute to the improved performance of the protective system.

### 2.1.5 Economics

Initial cost of the protective system is always an important factor while designing the protective system. High-speed relays will provide continuous service by reducing the fault damage to the power system, but its initial cost is high. Both low and high speed-relays are used in protective systems. Saving on initial costs allows it to be spent on repair or maintenance of the equipment when the damage occurs.

Along with the above mentioned characteristics, others which are of significant importance are

- The ability of the protection system to *discriminate* between the fault current and load current even when the maximum load current is greater than the fault current.
- *Stability*, which describes the quality of the protective system by virtue of which it stays inoperative for faults outside its zone of protection [5].
- *Sensitivity*, which refers to the minimum level of fault current at which operation occurs [5].

## *2.2 Power System Faults*

### 2.2.1 Protective device operation

The protective devices test the system state taking several elements into account, make decisions regarding the normality of the observed variables and take action as required.

The protective system always measures certain quantities such as voltages and currents using potential transformers and current transformers and compares these system quantities against a threshold setting that is set into the device. If this comparison indicates an alert condition, a decision element is triggered.

The time taken for any necessary corrective action is called the clearing time and is defined as follows

$$T_c = T_p + T_d + T_a$$

Where $T_c$ = clearing time

$T_p$ = Comparison time

$T_d$ = decision time

$T_a$ = action time, including the circuit breaker operating time.

The clearing time is very important since other protective systems in the network and this protective device could be time-coordinated with each other in order to ensure that the necessary portions of the network are disconnected.

### 2.2.2 System disturbances

A disturbance is defined as follows by the IEEE [4]

**Disturbance (General)**: An undesired variable applied to a system that tends to affect adversely the value of a controlled variable.

There are many ways to classify disturbance types and characteristics. One reference divides the disturbances into two major groups, load disturbances and event disturbances. These are defined as follows.

Load disturbances: Small random fluctuations superimposed on slowly varying loads.
Event disturbances:

a) Faults on transmission lines due to equipment malfunctions or natural phenomena such as lighting.
b) Cascading events due to protective relay action following severe overloads or violation of operating limits.
c) Generation outages due to loss of synchronism or malfunction.

As defined in [1], load disturbances are a part of the system normal operating conditions.

### 2.2.3 Faults in the Power System

The flow of current towards an undesired path is termed as fault. Faults are classified as symmetrical triple line to ground or triple line fault (R-Y-B-g or R-Y-B), double line faults (R-Y, Y-B and B-R), double line to ground faults (R-Y-g, Y-B-g and B-R-g) and line to ground faults (R-g, Y-g and B-g).

Approximate percentages of occurrence of faults are as follows:

Single phase-to-ground: 70-80%
Phase-to-phase-to-ground: 17-10%
Phase-to-phase: 10-8%
Three-phase: 3-2%

Line to ground fault is the most common fault and can occur because of a flashover across the line insulators, due to lightning or switching over voltages or due to defective insulators. Triple line to ground fault can occur in case of switching ON of circuit breaker when the earthing switch is kept on. Two phase faults occur due to failure of insulation between the phases either in the transformers or in the machines.

### 2.2.4 Functions of protective relay schemes

A protective relay scheme detects the fault and performs the following four functions [5]

1. Operate the correct circuit breakers so as to interrupt only the faulted equipment in the system as quickly as possible and minimize the damage due to the faults.
2. Operate the correct circuit breakers so as to isolate the faulty network from the system in case of abnormalities like overloads, unbalance, under voltage etc.
3. Make the system stable by clearing the fault.
4. Detect where the fault has occurred.

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# Chapter 3

# Components of Power System Protection Scheme

The basic elements of a power system protection scheme includes transducers, relays, circuit breakers and battery as shown in Figure (3.1).

## *3.1 Transducers*

The transducers are the sensing elements that detect an abnormal behavior in the power system. Current transformers and voltage transformers, collectively known as transducers in the power system protection, continuously monitor the currents and the voltages in the network and feed the information to the protection relay logic.

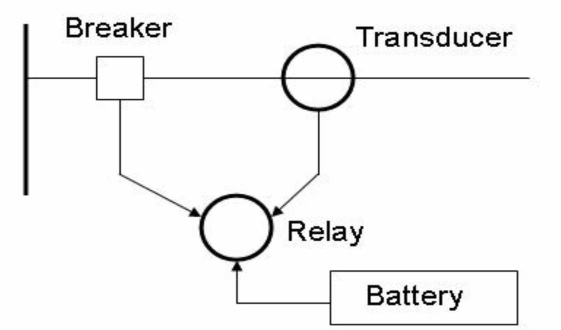


**Figure 3.1 Components of a protection system [4]**

## 3.2 Relays

Protective relaying deals with the removal of equipment from service that behave in an abnormal manner when exposed to abnormal conditions [4]. This does not mean that relaying protects the equipment from getting damaged at all. Infact, the protective relaying starts acting after the equipment has begun to get damaged and prevents it from getting damaged any further in order to minimize the danger to the people, reduce stresses on the remaining equipment and above all, to remove the faulted equipment from the system as quickly as possible so as to maintain stability in the system. According to the IEEE, a *relay* is defined as "an electric device that is designed to respond to the input conditions in a prescribed manner and, after specific conditions are met, to cause contact operation or similar abrupt change in the associated electric control circuits"(IEEE C37.90). The change may be tripping of the circuit breaker, closing of the circuit breaker or in some cases, issue of an alarm.

### 3.2.1 Basic operation of protective relays

All relays used for short-circuit protection, including many other types, operate by virtue of the current and/or voltage supplied to them by the current and voltage transformers connected in various combinations to the system elements that are to be protected. Through individual or relative changes in these two quantities, protective relays detect the presence, type and location of the faults. For every type and location of the failure, there is some distinctive difference in these quantities, and there are various types of protective-relaying equipments available, each of which is designed to recognize a particular difference and to operate in response to it.

Differences in each quantity are possible in one or more of the following

- Magnitude
- Frequency
- Phase angle
- Duration
- Rate of change
- Direction or order of change
- Harmonics or wave shape

### 3.2.2 Operating logic of the protective relays

Protective relays for power systems consists of one or more fault-detecting or decision making units, along with other logic networks required to take the necessary action. A number of these decision making units are used in a number of relays and are as such called the basic units. Basic units fall into several categories

- Electromechanical units
- Sequence networks
- Solid-state units
- Integrated circuits
- Microprocessor architecture

Combinations of these units are then used to form the basic logic circuits applicable to protective relays [2]. Figure (3.2) shows the typical logic representation of an electric relay. The logic functions are quite general irrespective of whether the components are electromechanical, solid-state or both such that they can be combined in any particular unit [3]. The sensing unit comprises of instrument transformers that continuously monitor the state of the currents and voltages in the power system. The integration and timing circuit provides the basic time delay during which, if the sensing unit detects abnormal behavior of the equipment, causes the relay to take an appropriate action, for instance the tripping of the faulted part.

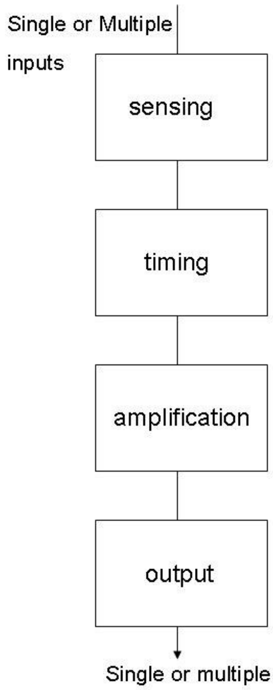


**Figure 3.2 Logic representation of electric relays [3]**

The amplification circuit provides both power amplification for a breaker trip coil and isolates the control circuitry from the tripping energy source. The output conveys the signal of the relay logic to the external device. Two types of circuits, one for circuit-breaker-trip operations and the other for a general use, are provided.

## 3.2.3 Classification of relays

Protective relays are classified into many types based on various parameters as follows [5]

- **Number of operating quantities**: Relays are classified with reference to the number of inputs as single input relays and multi input relays. e.g., an overcurrent relay measures the level of the current and as such falls under single input relay whereas differential and distance relays come under multi input relays.
- **Quantity measured**: Relays are also classified by the quantity they measure or by the functions performed by them. e.g., overcurrent relays, distance relays, directional relays, under/over voltage relays, thermal relays, ohm relays, reactance relays, under power relays etc.,
- **Time of operation**: Another classification of relays is by their time of operation e.g., instantaneous relays, time-delay relays, inverse time current relays. Also the relays are classified as high speed relays that operate in less than a specified time (50ms in practice) and low speed relays whose operation time is over 3 cycles.
- **Constructional features**: Relays are also classified based on the constructional features of the electromechanical units e.g., attracted armature relays which are

further classified as plunger, clapper and polar types, induction cup type relays, balanced beam relays etc.,

- **Operating components used**: Relays that fall under this category are electromagnetic relays, static or electronic relays and microprocessor based relays.

Based on the above theory, all relays are defined under four classes:

1. **Auxiliary relays** - used to assist other relays or devices to perform their functions.
   Examples: timing relays, interposing relays, etc.
2. **Protective relays** - used to detect faults and to initiate switching (i.e., send a signal to the breakers to open)
   Examples: overcurrent relays, impedance relays, etc.
3. **Regulating relays** - used to detect a deviation from a predetermined quantity and to initiate corrective action to get the quantity back to its limits.
   Examples: frequency relays, voltage relays used for voltage regulation, etc.
4. **Verification relays** - used to verify conditions of the power system.
   Examples: alarm relays, etc.

### 3.2.4 Types of relays

Relays are available in many different types, serving a variety of purposes and having different design characteristics. A limited sampling of the many devices that are available commercially is presented in this section.

According to the functional description, the relays may be classified as:

**Overcurrent relay**: It is a relay that operates when its current exceeds a preset value. A typical overcurrent relay is shown in Figure (3.3)

There are two types of overcurrent relays; instantaneous and time overcurrent.

**Instantaneous Relays** operate without intentional time delay. They are used for faults close to the source when the fault current is very high. The operating time is approximately 10 ms. The constructional feature of the instantaneous relays is usually moving armature, plunger, or induction disk.

**Time Overcurrent Relays** operate with a time delay. The time delay is adjustable. For a given setting, the actual time delay depends on the current through the relay coil. In general, higher current will cause a faster operation of the relay. The minimum current at which the relay operates (pick-up current) is also adjustable. Figure (3.4) shows the typical characteristics of an overcurrent relay.

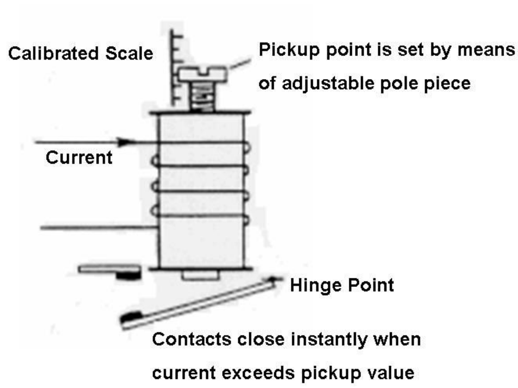


**Figure 3.3 Overcurrent relay**

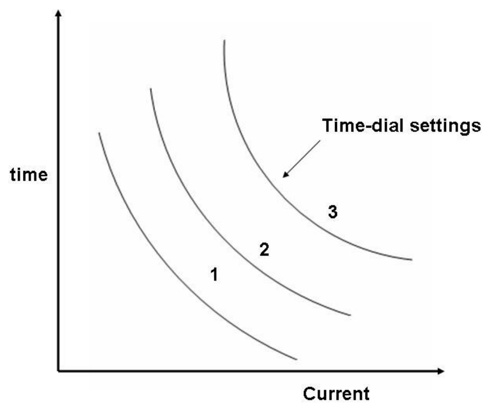


**Figure 3.4 Typical characteristics of an overcurrent relay**

Time overcurrent relays come in five different versions that are defined by the steepness of the time-overcurrent characteristic as shown in Figure (3.5).

- definite time
- moderately inverse
- inverse
- very inverse
- extremely inverse

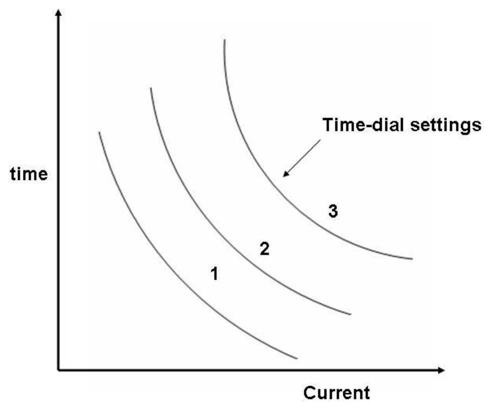


**Figure 3.5 Typical characteristics of time-overcurrent relays**

The most commonly used overcurrent relay incorporates both the instantaneous unit and the time overcurrent unit. The instantaneous response is provided by a moving armature unit. Its purpose is to operate on very large currents. The inverse time response is provided by an induction disk unit and is set to operate for lower fault currents.

A **Differential relay** responds to the difference between incoming and outgoing electrical quantities associated with the equipment to be protected.

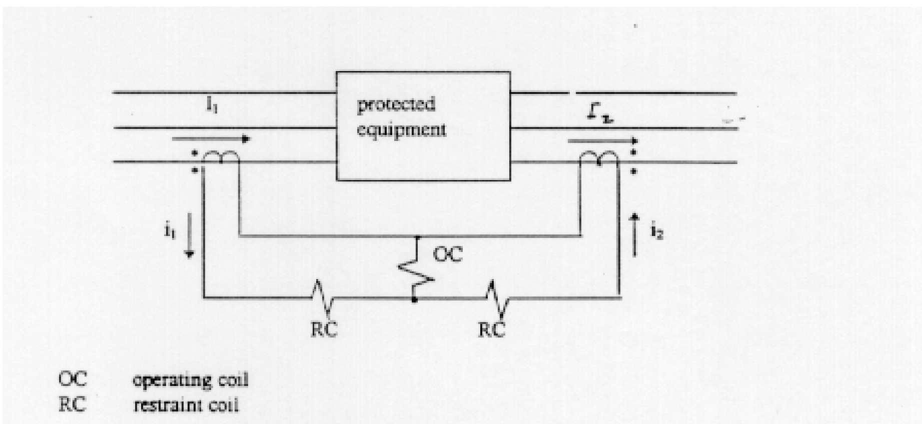


**Figure 3.6 Typical differential relay**

Figure (3.6) shows a typical differential relay in which the restraint coil is used to prevent undesired relay operation due to current transformers errors and the operating coil is used to detect the fault current when the current differential $i_1 - i_2$ exceeds a preset value.

A **Directional relay** responds to the relative phase position of a current with reference to another voltage or current. Knowledge of the direction of the current flow helps to device a better protection system that is less likely to fail.

A **Distance relay** is one in which the response to the input quantities is a function of the distance between the relay location and the location of the fault. Distance relays monitor the impedance between the relay location and the fault. If the impedance falls within the relay setting, the relay will operate. Figure (3.7) shows the general operating characteristics of a distance relay.

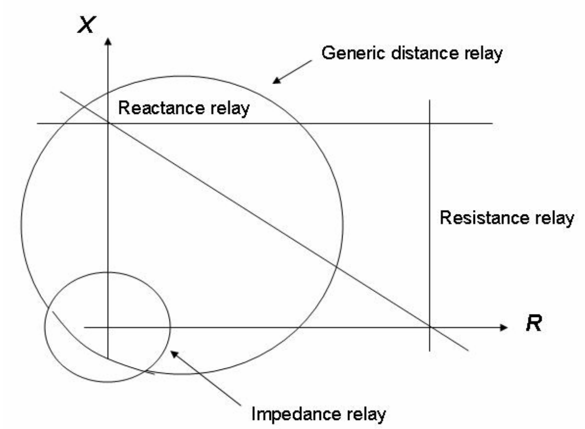


**Figure 3.7 General operating characteristics of distance relays**

## *3.3 Circuit Breakers*

While protective relays can sense the presence of a fault or an abnormal behavior of the equipment or a part of the power system, being low-energy devices, they cannot perform the action of isolating the faulted part from the power system. For this purpose, high energy circuit breakers are provided in conjunction with protective relays to detect the fault and safely isolate it so as to protect the power system. One of the first designs incorporated an oil tank in which the breaker contacts are immersed. The oil provides insulation between the tank which is at ground potential and the contacts which are at line potential. Also, it acts as a cooling agent to quench the arc that is produced when the main contacts open to interrupt the load current. One of the most important criteria to be considered while specifying a circuit breaker is the interrupting medium. Oil and $SF_6$ are the two major contenders for this. Economically, oil as an interrupting medium is feasible whereas, from environmental point of view, circuit breakers incorporating $SF_6$ as interrupting medium forms a viable solution. [3] [4]

### 3.3.1 Coordination between Relay and Circuit Breaker

Protective relays are connected to the power system through current and voltage transformers which are together known as instrument transformers. They provide insulation from high voltage power system by stepping down the voltages so that the low-energy relay devices can use them to detect a fault condition in the power system.

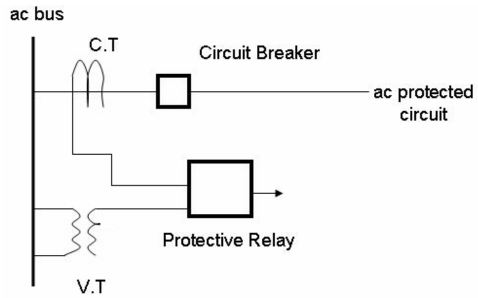


**Figure 3.8 One-line ac connections of a protective relay**

Figure (3.8) shows the typical single-line ac connections of a protective relay that is connected through the current and voltage transformers.

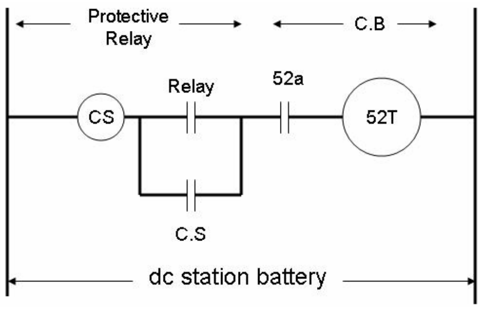


**Figure 3.9 dc trip circuit of a protective relay**

The dc schematic in figure (3.9) shows the contacts to be always in their de-energized position. Hence, when circuit breaker is closed, 52a is closed and when the fault occurs, output circuit energizes the circuit breaker trip coil 52T which then opens the breaker contacts. The relay contacts cannot directly act upon the breaker trip coil, thereby paving a way for the introduction of a bypass designated as CS. When the circuit breaker opens, 52a switch also opens to de-energize the trip coil 52T and this occurs after the relay has opened its contacts because it has seen the circuit breaker interrupt the fault. [3]

## *3.4 Instrument Transformers*

Instrument transformers are used for measurement and protection applications, together with equipment such as meters and relays. Their role in the electrical systems is of primary importance as they are a means of stepping down the current or voltage of a system to measurable values, such as 5A or 1A in the case of current transformers or 110V or 100V in the case of voltage transformers. These provide galvanic isolation between the power network and the relays and other instruments that are connected to the secondary of the instrument transformer (transducer). This offers the advantage that the measurement and protective equipment can be standardized on a few values of current and voltage. The transducers must be designed to tolerate higher values of currents and voltages for abnormal system conditions. The current transformers are designed to withstand fault currents as high as 50 times the load current for a few seconds, while the voltage transformers are designed to withstand the power system dynamic overvoltages in the order of 20 percent above the normal value almost indefinitely for long durations.

### 3.4.1 Current Transformer

A current transformer (CT) is defined as an instrument transformer in which the secondary current is proportional to the primary current under normal conditions of operation. This highlights the accuracy requirement of the current transformer. Also important is the isolating function, which means that irrespective of the system voltage, the secondary circuit needs to be insulated only for a low voltage.

The current transformer works on the principle of variable flux. In the "ideal" current transformer, secondary current would be exactly equal (when multiplied by the turns ratio) and opposite to the primary current. But, as in the voltage transformer, some of the primary current or the primary ampere-turns is utilized for magnetizing the core, thus leaving less than the actual primary ampere turns to be "transformed" into the secondary ampere-turns. This naturally introduces an error in the transformation. The error is classified into two; the current or ratio error and the phase error.

Current transformers select the correct transformation in order to provide maximum the load current. Under steady state conditions, the CT secondary current will flow through the relay circuits all the time. The relay is designed such that it must not exceed the maximum load current. Most of the relays are designed for 5A rated current, hence under normal load conditions, CT provides 5 amperes.

Since current transformers are iron core transformers, the quality of the iron and saturation characteristics are important. Current transformer might saturate when a fault occur. Quality of transformers must be as high as possible to reduce problems and to provide better relay accuracy. Transformer accuracy is important in differential relay schemes where the relay senses the difference in current.

Saturation of the current transformer can be determined by one of the three methods

1) The excitation (saturation) curve method.
2) The formula method.
3) The computer simulation method.

ANSI Standard CT Accuracy Classes: The ANSI relaying accuracy classes are mentioned in ANSI standard C57.13.1993 [5]. This Standard uses letter designation and voltage rating to define the capability of the current transformer. The letter designation code is given as follows:

Code C- indicates that the transformer ratio can be calculated.

Code T- indicates that the ratio must be determined by test.

The C classification includes most bushing current transformers with uniformly distributed windings and any other transformers whose core leakage flux has negligible effect on the ratio, within the defined limits. The T classification includes the most wound-type current transformers and any other transformers whose core leakage flux has an affect on the ratio.

Bushing CT's are usually used for relaying because of their low cost and accuracy that is adequate for relay applications. The bushing transformers are placed in the bushings of power transformers and circuit breakers. The bushing CT is less accurate at low currents because of its large exciting currents. This means that the bushing CT is not suitable for metering (measurements).

### 3.4.2 Voltage or Potential Transformer

There are two types of transformer:

1) Instrument potential transformer

2) Coupling capacitor voltage transformer

Instrument potential transformer is used at lower voltages where as CCVT is used at higher voltages. In distribution system instrument potential transformers are used.

## *3.5 Resonant Grounding System*

The single phase-to-ground faults are the most common faults in the medium voltage distribution network [8]. Most of the faults in the medium voltage distribution network occur either in the cable/overhead line or cable joints. On many occasions, the faults on the cables begin as earth faults and develop into short circuit [8]. In order to avoid this problem, the distribution network is grounded with variable inductance (arc suppression coil or Petersen coil). This method is known as resonant grounding.

Resonant grounding in the distribution network self extinguishes instant arcs due to single phase-to-ground faults. This improves the security and the reliability of electric power system. When a single phase-to-ground fault occurs, the reactance of the arc suppression coil, connected between the neutral point and the earth, forms a resonant circuit with the total earth capacitance of the distribution network which consists of earth capacitance of the faulted lines and the non faulted lines. The resonant circuit is supplied by the phase voltage through the fault impedance. The inductive current through the arc suppression coil will compensate the current flowing through the earth capacitances of the faulted and non faulted lines. A resistor is connected in parallel to the arc suppression coil so that it increases the fault current when the single-phase to ground fault is not instantaneous [9].

### 3.5.1 Principle of Resonant Grounding

The equivalent resonant circuit of a distribution network with single-phase to ground fault is shown in Figure (3.10) where, L is the variable inductance of the arc suppression coil, C is the total earth capacitance of distribution network, $\grave{U}_0$ is the voltage between the neutral and the ground, R is the total load resistance of the compensating network. $\grave{I}_\delta$ is residual current, $\grave{I}_R$ is the current flowing through the load resistance, $\grave{I}_L$ is the compensating inductance current of the arc suppression coil, $\grave{I}_C$ is the total earth capacitance current. The residual current is divided into three parts.

$$\grave{I}_\delta = \grave{I}_R + \grave{I}_L + \grave{I}_C$$

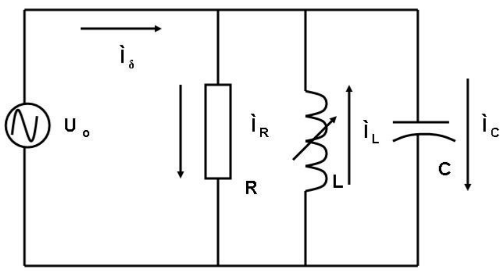


**Figure 3.10 The equivalent parallel resonant circuit of the distribution network during a single phase-to-ground fault.**

## *3.6 Wind Turbine Used*

In principle, a wind turbine converts kinetic energy of streaming air into electric power. With the size of the wind turbines rapidly increasing during the past two decades with the generating capacities reaching 4MW, variable speed turbines are being used that can withstand mechanical stresses. Wind turbines as single units are connected to a medium voltage networks while the wind farms should be connected to the high voltage networks [10].

The most common type of generator is the asynchronous generator. In recent times, inverter technology has paved the way for the use of variable speed systems, where the power output can be maintained at constant even for wind speed variations.

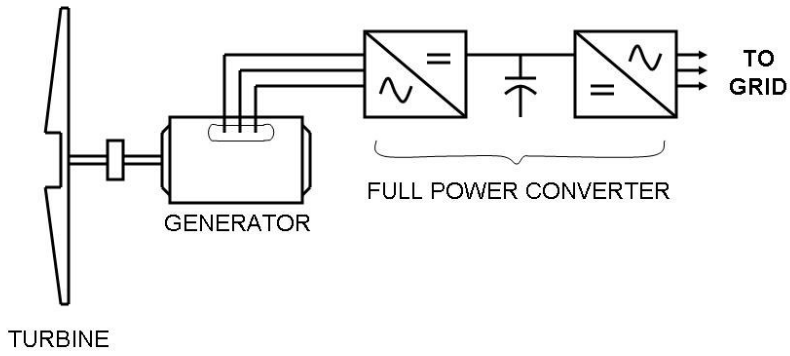


**Figure 3.11 Typical wind turbine layout comprising the generator, a full power converter connecting to the medium voltage distribution grid**

For this thesis, variable speed turbines are considered with fault ride-through capability. This means that the turbine remains online even during the fault without being tripped by the undervoltage relays. The main focus in this thesis is the protection of the distribution Side of the network and hence the generator protection is not considered. The transformer which connects the turbine to the grid is delta-wye grounded with the delta on the grid side. For this reason, the turbine does not contribute to the earth faults. This point is made use of during investigating the single phase-to-ground fault during the thesis. The ratings of this transformer are shown in Table (4.44). The turbine contributes a current equal to the rated current during the three phase and two phase short circuit faults throughout this thesis.

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# Chapter 4

# Analysis of Lundsbrunn Network

## *4.1 Brief Description of the Network*


**Figure 4.1 Map showing the locations of the two distribution networks investigated in this thesis work namely Lundsbrunn and Hällekis. These networks are run by the company Gotene elforening situated in the county of Västragotland, Sweden**

The Lundsbrunn network consists of two 8MVA rated transformers of which only one transformer is in operation at a time. The short-circuit power of the grid to which the Lundsbrunn network is connected is 217MVA. The supply voltage source of 42kV and the short-circuit impedance with R=1.9Ω and X=7.5Ω represents the Thevenin equivalent at the point of connection of this grid with the medium voltage distribution network. The nominal voltages at the high voltage and low voltage sides of the transformer are 42kV and 10.7kV respectively. The existing network consists of five feeders emanating from the substation in which a total wind generation of 5.35MVA is installed. A total load of 3.87MVA is connected to the network. Since the wind power generation in the network is less compared to the short-circuit capacity of the grid that precedes this distribution network, a change in the wind power generation is viewed as a fluctuating load by this grid. The load is calculated from the current measured at the beginning of each feeder, the data for which is provided by the company *Gotene elforening,* Figure (4.1).

In Figure (4.2), an industrial load of 350kVA is connected in feeder 3. The Lundsbrunn network is connects residential loads, an industrial load and some farms. The Lundsbrunn network consists of 8 wind turbines bearing a capacity of 850kVA each, one turbine of 800kVA and two turbines of 150kVA each. The loads in the feeders of the network are considered to be distributed along the feeder. The layout of the Lundsbrunn network is shown in Figure (4.2).

The feeders in the Lundsbrunn network are assumed to be radially connected. The circuit breakers are connected at the beginning of each feeder in the substation. The relays in the network are constant time over current relays. The earth fault relays are of the type directional over current and trips for earth faults on outgoing line which means that they also need the zero sequence voltage besides the zero sequence current to trip.

## *4.2 Objectives*

The main objectives of this study is to observe

1. The variations in the voltage level at different locations by disconnecting certain amount of power produced by the wind turbines due to symmetrical and unsymmetrical faults applied in the network.
2. The variation in the voltage level at different locations after symmetrical and unsymmetrical faults are cleared in the network with different load combinations.
3. How the line and transformer protection systems are affected by the over currents in the feeders due to symmetrical and unsymmetrical faults.

All the above tasks are investigated for both one transformer operation and the parallel operation of two transformers in Lundsbrunn network.

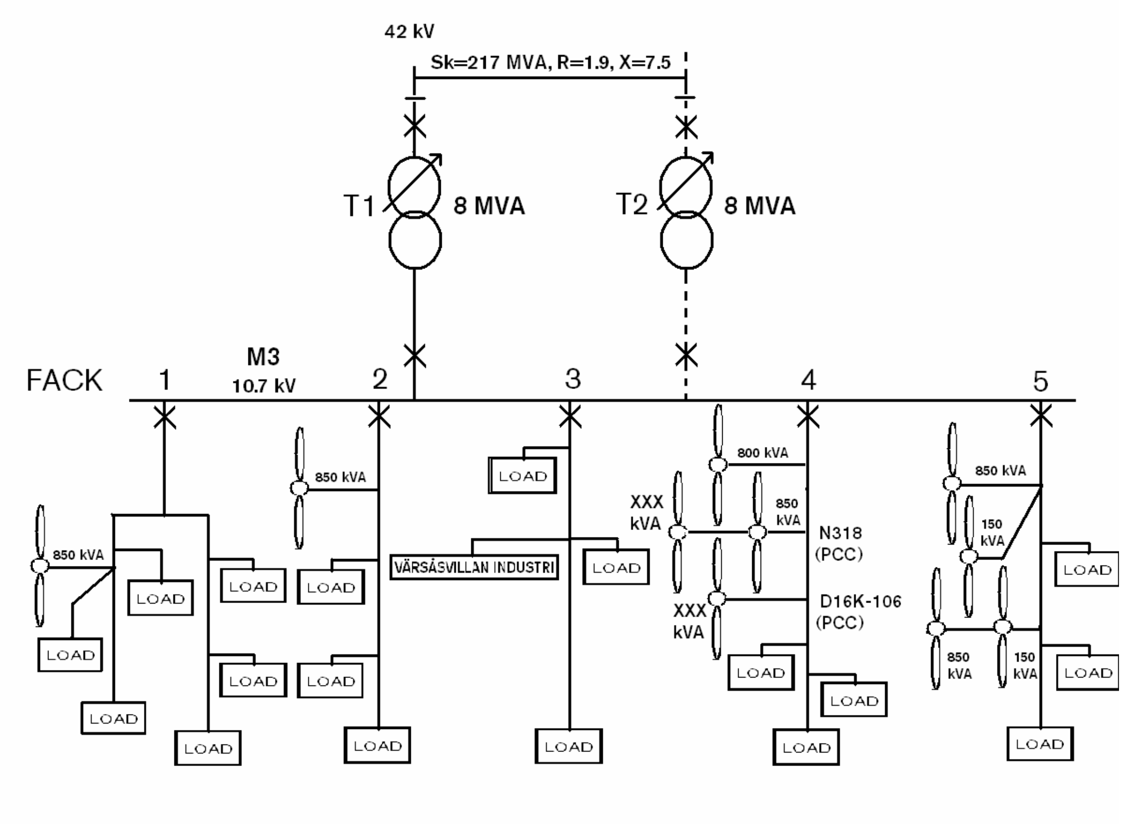


**Figure 4.2 Layout of the Lundsbrunn distribution network.**

## *4.3 Network Modeling and Assumptions*

1. In Sweden, to a large extent, the residential loads are considered as heating loads with thermostatic control devices. For a short duration of time, these loads behave as constant impedance loads [5]. For fault analysis, the residential loads are assumed as constant impedance loads. The residential loads are therefore modeled as constant impedance loads with a power factor of 0.9. The residential load in the feeders of the Lundsbrunn network is distributed along the feeder. It is divided into three equal parts and placed at three locations in the feeder.
2. Industrial loads are modelled as constant power loads with a power factor of 0.85 because the industries comprises mainly of induction motors [6] which are supplied with constant power during the fault by compensating the voltage at the bus connecting the industrial load with reactive power.
3. The wind turbines are assumed as constant current loads. These are considered as constant current loads to limit the current from the turbine during the fault. The wind turbines are considered as negative power loads with unity power factor.
4. It is assumed that the wind turbines possess fault ride-through capability and thus are not disconnected from the network during a fault.
5. The short circuit power at the point of connection of Lundsbrunn network with the utility is considered as the power generated by a generator connected at the high-voltage side of the transformer. In other words, the high voltage side of the

transformer is assumed as a slack bus whose maximum generating capacity equals the short circuit capacity of the utility to which the Lundsbrunn network is connected.

6. The transformer magnetizing losses are neglected.
7. In the fault analysis, for single phase-ground faults, the transformer is assumed as Y grounded - Y grounded.
8. The zero-sequence impedance of the over-head lines and the cables is three times the positive-sequence impedance. The negative sequence impedance of the over-headlines and the cables is equal to the positive-sequence impedance.
9. The zero-sequence, negative sequence and positive-sequence impedances of the transformer are the same.
10. The zero-sequence, negative sequence and positive-sequence impedances of the generator (short circuit power producing generator) are the same.
11. Since the industrial load is modeled as a constant power load (no induction motor), the simulation is run for about one or two seconds after clearing the fault because the voltage will recover instantly.
12. Throughout the thesis, all the faults are applied at the end of the feeders downstream from the substation busbar to maintain uniformity in fault location. Also, all the faults applied in the simulations are solidly grounded (zero impedance faults).

A model is built in the PSS/E® for the short circuit analysis. This distribution system at Lundsbrunn is maintained by the company *Gotene elforening*. The input data like system impedance and short circuit level, short circuit impedance of the transformers, the on-load tap changer settings, resistance, inductive reactance and charging of lines are given by the company.

To observe the variations in the voltage level at the substation and at the various loads caused by the disconnection of a certain amount of power produced by the wind turbines due to symmetrical and unsymmetrical faults and to observe the variations in the post fault voltages for different load operation conditions (combination of different mixes of loads and wind power), the Lundsbrunn network is modeled assuming full generation from the turbines and a low load consumption of around 10% in the feeder subjected to a fault and in the rest of the feeders it is assumed that the wind turbines do not inject power while the load demand is 100%.

To observe the over currents caused by applying symmetrical and unsymmetrical faults in the network, the following combinations of generation and load are considered.

1. No generation and Low load
2. No generation and Full load
3. Full generation and low load
4. Full generation and Full load

All the above cases are simulated and the worst case among them is considered for analysis. Here, the combination of full generation and low load is the worst case observed and hence this case is extensively investigated.

The short circuit fault analysis is carried out with the single transformer operation and parallel operation of the two transformers at the substation by applying the following three types of faults in the network.

1. Three phase short circuit fault
2. Two phase fault
3. Single phase-to-ground fault

## *4.4 Three Phase Short Circuit Faults*

### 4.4.1 Voltage Dip Analysis

#### 4.4.1.1 Methodology used in Analysis

The following is the method described for voltage sag analysis carried out in the thesis work using the PSS/E® software [1]

1. Choose a network for voltage sag analysis.
2. Create a model for each network component.
3. Solve the load flow. Save the voltage magnitude at each bus node. The saved values are the pre-fault values of the voltage magnitude for the respective bus nodes.
4. Create three phase faults at the end of each feeder and note the values of voltage magnitudes at all the load buses.
5. Create two-phase faults at the end of each feeder and note the values of voltage magnitudes at all the load buses.
6. Create single phase-to-ground faults at the end of each feeder and note the values of voltage magnitudes at all the load buses.

Voltage dips are short duration reductions in rms voltage caused by short circuits, overloads and starting of large motors, they last from one cycle to second or tens of milliseconds to hundreds of milliseconds [3]. Voltage sags are the most commonly occurring power system disturbances. They can arrive from the utility, in most cases they are generated due to disturbance inside the building (load). A short circuit at the end of radially operated distribution feeder causes voltage sag on substation busbar and loads in the other feeders [2]. Voltage sag can be calculated by modeling the network as a voltage divider.

$$U_{dip} = \left[ \frac{Z_f}{Z_s + Z_f} \right] * 1.0\,pu$$

Where $U_{dip}$ is the remaining voltage, $Z_f$ is the impedance of the feeder from the low voltage side of the transformer (substation) to the fault on the feeder, $Z_s$ is the source impedance. Throughout this thesis, the voltage dip refers to the fall in the voltage level but wherever a value is mentioned for the voltage dip, it refers to the remaining voltage. Therefore, a high voltage dip means less remaining voltage and a low voltage dip means more remaining voltage.

Voltage dip is high at the substation if the fault is near to it. The more the length of the feeder, the lower is the magnitude of the voltage dip at the substation if the fault is at the end of the feeder [3]. But longer the length of the feeder, more are the number of faults it is exposed to. The networks that are investigated in the thesis also have underground cables which experience larger voltage dips during the fault because of its larger cross section i.e., lesser line impedance. But underground cables experience less number of faults.

The duration of the voltage dip depends on the fault clearing time from the protection system [2]. The circuit breaker tripping time will depend on the magnitude of the fault current; larger the fault current, shorter the breaker tripping time.

In this section, voltage dips caused by applying three phase short circuit faults in the Lundsbrunn network are observed. The variations in the magnitude of the voltage dip on the low voltage side of the transformer (busbar M3) and the loads that occur due to three phase short circuit faults at the end of each feeder are observed. The same process is again carried out by connecting another transformer in parallel to the existing transformer to check the variations in the voltage dip magnitude at the low voltage side of the transformer and the loads.

To observe the variations in the voltage dip caused by disconnecting a certain amount of power produced by the wind turbines due to a fault and to observe the variations in the post fault voltage for different load operating conditions (combination of different mixes of loads and wind power), the feeder to which the fault is applied is assumed to have full wind power generation and 10 percent load connected to it and the other feeders have zero wind generation and 100 percent load. No fault is applied in the feeder L3 for voltage dip analysis as there are no wind turbines in this feeder to disconnect.

Circuit breaker tripping time for all the feeders in Lundsbrunn network is shown in Table (4.1). In the Lundsbrunn network data, it is given that the relays are of constant time overcurrent type. The relay will operate for two different values of current. The value of time depends on the value of the current. Higher the fault current, lower is the tripping time.

| | STEP1(200A) | STEP1 (120A) | STEP2(1200A) | STEP2(600A) |
|---|---|---|---|---|
| TIME(SEC) FOR | 1 | -- | 0.07 | -- |
| TIME(SEC) FOR L2 | 1 | -- | 0.06 | -- |
| TIME(SEC) FOR L3 | 1 | -- | 0.08 | -- |
| TIME(SEC) FOR L4 | -- | 1 | -- | 0.07 |
| TIME(SEC) FOR L5 | -- | 1 | -- | 0.06 |

**Table 4.1 Circuit breaker tripping time for feeders in Lundsbrunn network**

## 4.4.1.2 One transformer in operation

In order to see the variations in the magnitude of the voltage at the medium voltage busbar M3 and at the loads in the feeders, the following cases are considered for analysis.

1. Only Existing Turbines
2. New Turbine of 1.5MW
3. New Turbine of 3.0MW

Pre-fault, during fault, post fault conditions are analyzed for above three cases.

## 4.4.1.2.1 Only Existing Turbines

In this case, it is assumed that the faulted feeder has 100 percent generation from wind turbines, 10 percent of full load for the loads and the remaining feeders have 100 percent load and no generation. This is done in order to investigate the variation in the magnitude of the voltage at the substation (M3) and at the loads in different feeders associated with a large power disconnection due to a fault at the end of the feeder. The voltage dip depends on the magnitude of the fault current due to the fault and the impedance between the substation and the location where the fault occurs. When the fault is applied at the end of all the feeders, the voltage dip at M3 is observed to be severe for a fault at the end of the feeder L2. From the fault current analysis to be discussed later, we observed that the fault current is the highest when the fault is at the end of the feeder L3, but here this case is not considered because there is no wind generation in feeder L3.

**(A) Fault at the end of the feeder L1**

The layout of the feeder L1 is shown in Figure (4.3). Feeder L1 is divided into two at the bus EF-714. In this case, we study the voltage level at M3 and at the loads in the other feeders by applying the fault at both ends of this bifurcated feeder. The feeder with the load at bus EF-291 at the end is considered as L1 (1) and the feeder with the load at bus

EF-700 at its end is considered as L1 (2). It is observed that there is no change in the tap changer during the simulation. The rating of the wind turbine connected to feeder L1 (2) is 850KVA.

### (A-1) Fault at the end of the feeder L1 (1)

It is observed that the voltages at the load buses in the feeder L3 for pre fault, during fault and post fault conditions decreases from substation busbar M3 downstream towards the load at the end of the feeder because the impedance increases as we move down along the feeder. The above behavior is shown in Figure (4.4) for pre fault, during fault and post fault conditions.

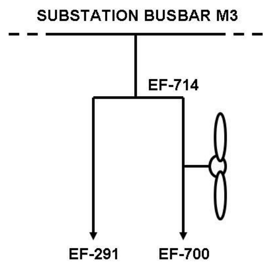


**Figure 4.3 Layout of the feeder L1**

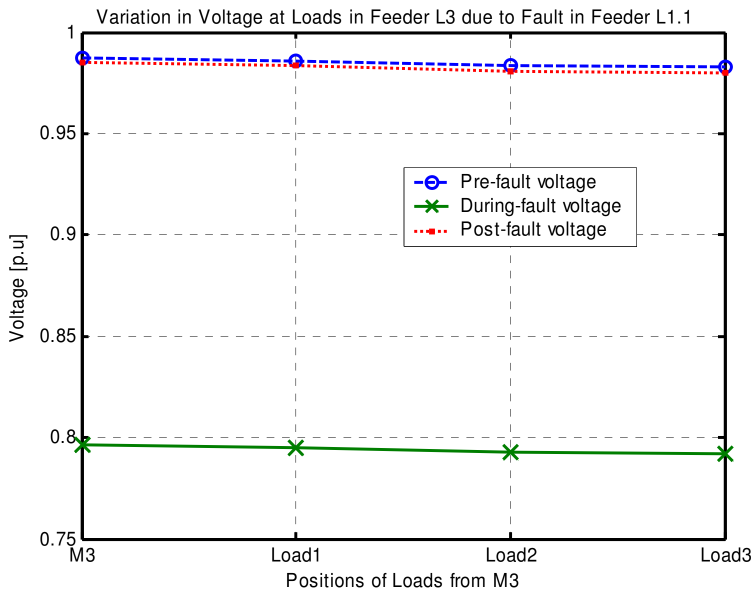


**Figure 4.4 Variation in the voltage at the load buses in Feeder L3 due to a three-phase short circuit fault at the end of the feeder L1 (1)**

Load2 in feeder L3 is an industrial load. The voltages for pre-fault, during-fault, post-fault conditions at M3 and at the industrial load are shown in Table (4.2). The network is simulated for 35 seconds after the fault clearance.

From Table (4.2), it is observed that when the feeder L1 is tripped due to a fault at the end of the feeder L1 (1), the change in the pre-fault and post-fault voltages is approximately 0.25% at M3 and all other loads. For all the cases observed, the voltage dip on M3 is high compared to the dip at the load at the end of the non-faulted feeder.

| | Voltage at M3 (p.u) | Voltage at Industrial Load (p.u) |
|---|---|---|
| Pre-fault | 0.9873 | 0.9833 |
| During-fault | 0.7963 | 0.7927 |
| Post-fault | 0.9848 | 0.9809 |

**Table 4.2 Voltage at M3 and at the industrial load for pre-fault, during-fault and post-fault conditions when the fault is applied at the end of the feeder L1 (1)**

To protect the network from the fault at the end of the feeder L1 (1), the magnitude of the fault current and the tripping time of the circuit breaker are to be considered. When the fault is at the end of L1 (1), the magnitude of the fault current is approximately 1055A. From Table (4.1), it is observed that the circuit breaker takes 1 second to trip the faulted feeder from the network. The pre-fault, during-fault and post-fault voltages are shown in Figure (4.5).

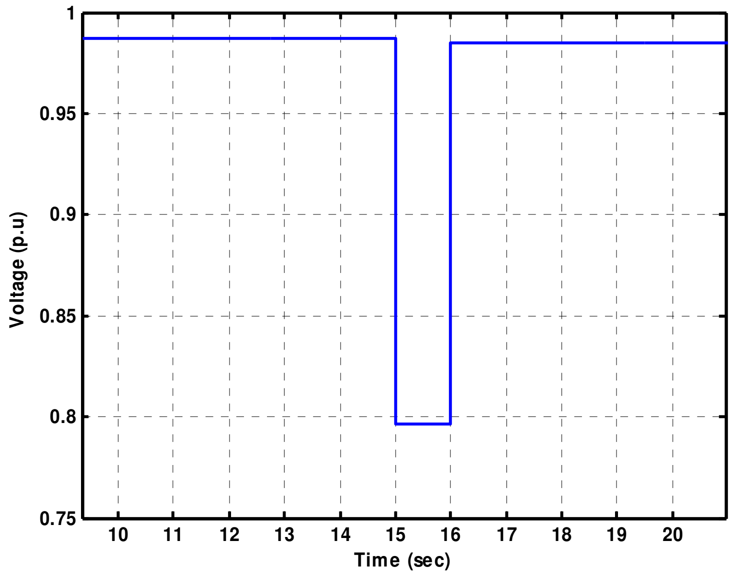


**Figure 4.5 Voltage dip at M3 when a three-phase fault is applied at the end of the feeder L1 (1)**

### (A-2) Fault at the end of the feeder L1 (2)

In Table (4.3), it is shown that the pre-fault and post-fault voltages on M3 are the same because there is no change in the power generation in feeder L1 and the same amount of power will be disconnected from the network when the feeder L1 is tripped. The value of the voltage level during the fault is different because it depends on the location of the fault from substation (M3). Since the location of the fault in the feeder L1 (2) is nearer to M3 as compared to that in feeder L1 (1), the voltage dip on M3 is more for a fault at the end of L1 (2) as compared to that due to a fault on the feeder L1 (1).

| | VOLTAGE AT M3 | VOLTAGE AT INDUSTRIAL LOAD |
|---|---|---|
| PRE-FAULT | 0.9873 | 0.9833 |
| DURING-FAULT | 0.6397 | 0.6363 |
| POST-FAULT | 0.9848 | 0.9809 |

**Table 4.3 Voltage at M3 and industrial load for pre-fault, during-fault and post-fault conditions when the fault is applied at the end of the feeder L1 (2)**

The duration of the voltage depends on the fault current and circuit breaker tripping time. In this case the magnitude of the fault current is approximately 1700A. From Table (4.1), it is observed that the circuit breaker will trip 70ms after the fault occurs. Here, the duration of the voltage dip is less compared to the above case, so the effect of the voltage dip will be less on the equipment in the network. The magnitude of the voltage decreases by 35% on M3 during the fault.

**(B) Fault at the end of the feeder L2**

The total length of the feeder L2 is 2.9 km. This is the shortest feeder in the Lundsbrunn network after feeder L3. In this case, the fault is applied at the bus EF-540 which is the end of the feeder. We observe that in this case the tap changer doesn't change. The installed wind power generation in this feeder is 850kVA. It is observed that the pre-fault voltage at the load buses in the feeders where the wind power generation is installed is more than the voltage at M3 because this generation has enough power to cater the load demand in its feeder and sends the remaining power to the grid or to other loads in the network. Since the fault occurs near to the substation, the voltage dip is around 50% of the nominal voltage.

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|
| PRE-FAULT | 0.9873 | 0.9833 |
| DURING-FAULT | 0.5262 | 0.5232 |
| POST-FAULT | 0.9848 | 0.9809 |

**Table 4.4 Voltage at M3 and at the industrial load for pre-fault, during-fault and post-fault conditions when the fault is applied at the end of the feeder L2**

As seen in the section (A-1) earlier, the voltage decreases slightly along the feeder from the substation busbar M3 to the load at the end of the feeder downstream from M3.

The purpose of this investigation as mentioned earlier is to study the network regarding voltage dips when a large part of power produced by the wind turbines is disconnected. Keeping this in mind, the network will experience the worst situation when the fault is in the feeder L2. In this case the fault current is above 2500A, the circuit breaker trips 60ms after fault occurs. The magnitude of the voltage on the substation busbar M3 decreases by 46.7% during the fault.

**(C) Fault at the end of the feeder L5**

The length of the feeder L5 is 8.866km in which a wind power generation of 2MVA exists. In the existing network at Lundsbrunn, feeder L5 has the maximum wind power integration. The voltage profile at the loads in this feeder is above 1 p.u. The tap changer does not change during the simulation.

| | LOAD AT BUS EF-740 | LOAD AT BUS D17N-101 | LOAD AT BUS EF-640 |
|---|---|---|---|
| PRE-FAULT CASE | 1.002 | 1.0086 | 1.0083 |

**Table 4.5 Voltage at the load buses in the feeder L5**

From Table (4.5), it is observed that the voltage level on the load buses in feeder L5 is not decreasing along the feeder from M3 downstream to the end of the feeder since the power flow at the load bus D17N-101, near which a wind turbine is also located, is high because of the active power injection into this bus from the turbine. So the voltage level at D17N-101 is higher than that at the other load buses in the feeder L5.

From Table (4.4) and Table (4.6), it is observed that the post-fault voltage depends on the amount of wind power generation that is disconnected from network after tripping the faulted feeder.

| | VOLTAGE AT M3 | VOLTAGE AT INDUSTRIAL LOAD |
|---|---|---|
| PRE-FAULT | 0.9878 | 0.9839 |
| DURING-FAULT | 0.7695 | 0.7659 |
| POST-FAULT | 0.9845 | 0.9807 |

**Table 4.6 Voltage at M3 and at the industrial load for pre-fault, during-fault and post-fault conditions when the fault is applied at the end of the feeder L5**

The pre-fault voltage at M3 is reduced by an amount 0.33% after tripping the feeder L5. From Table (4.4), it is observed that the pre-fault voltage at M3, when the fault occurs at the end of the feeder L2, is reduced by 0.25%. All the other loads connected to the network experience similar variations in the voltage at their respective buses. The magnitude of the voltage sag at a point depends on the location of the fault from the point.

It is seen from the simulation that the duration of the voltage dip is 60ms .It means that the circuit breaker trips 60ms after the fault occurs as per the relay settings shown in Table (4.1). The effect of voltage dip will be less on the equipment in the network. The magnitude of the voltage decreases by 22% on the substation busbar M3 during the fault.

**(D) Fault at the end of the feeder L4**

The wind power generation in the feeder L4 is 1.7MVA. The length of this feeder is 12.601km. From the above observations it can be concluded that if the fault is at the end of this feeder, the voltage dip on M3 is the least since the feeder L4 is the longest. In this case, the tap changer changes by one step.

In the PSS\E® software, the decimals in the number will be rounded up. As per the given data of Lundsbrunn network, the voltage at the substation busbar (M3) should be within 1.4% of the nominal voltage. In this case the voltage at M3 violates the limit because of the tap changer change. In order to verify the voltage at M3 without the tap change, it is fixed at 1.0 p.u. The voltages at M3 with and without tap change are mentioned in Table (4.7).

| TAP CHANGER POSITION | VOLTAGE AT SUB STATION(M3) |
|---|---|

| | |
|---|---|
| FIXED AT 1.00 P.U | 0.986 |
| FIXED AT 0.984 P.U | 1.002 |

**Table 4.7 Changes in the voltage at the sub station (M3) with a change in the tap changer**

Since the value of the voltage at M3 when the tap changer is fixed at 1 p.u is 0.986 p.u which could mean the PSS\E® software has rounded up the decimal number. It may be either 0.9859 p.u or 0.9861 p.u. The voltage level of the network increases because of the tap change.

| | VOLTAGE AT M3 | VOLTAGE AT INDUSTRIAL LOAD |
|---|---|---|
| PRE-FAULT | 1.002 | 0.9981 |
| DURING-FAULT | 0.8254 | 0.8218 |
| POST-FAULT | 1.0013 | 0.9974 |

**Table 4.8 Voltage at M3 and industrial load for pre-fault, during-fault and post-fault conditions when the fault is at the end of the feeder L4**

The pre-fault voltage both at the substation busbar M3 and the industrial load is reduced by an amount 0.07% after tripping the feeder L4. It is observed that the network does not experience much voltage instability in this case. Duration of the dip in this case is 70ms from Table (4.1). The magnitude of the voltage decreases by 17.6% at M3 during the fault.

## 4.4.1.2.2 New Turbine of 1.5MW

The new turbine is proposed to be installed at Västermark in Lundsbrunn. If the thermal limit of the cable connecting the turbine is considered, the maximum power injection into the grid from the new turbine is 1.5MW feeder (Reference "*Integration of Wind Energy Converters into an Existing Distribution Grid*"). The new turbine is connected at a distance of 500m from the existing turbine at Västermark which again is at a distance of 500m from the point of common coupling to the grid. The layout is shown in Figure (4.6).

In this case, the fault is applied at the end of the feeder L4 since Västermark is in feeder L4. The tap changer is fixed at 0.984 because the voltage at the Substation busbar (M3) behaves in the same manner as was presented in the section 4.4.1.2.1. The voltage level of the network increases when the tap is fixed at 0.984 p.u. When the tap changer is fixed at 0.984 p.u, the level of the voltage both at M3 and at the industrial load is shown in Table (4.9).

| TAP CHANGER POSITION | VOLTAGE AT SUB STATION(M3) |
|---|---|
| FIXED AT 1.00 P.U | 0.986 |
| FIXED AT 0.984 P.U | 1.003 |

**Table 4.9 Changes in the voltage at the sub station (M3) with an observed tap change**

The pre-fault voltage at M3 is reduced by 0.32% after tripping the feeder L4 as shown in Table (4.10). All the other loads connected to the network experience similar variations in the voltage. The magnitude of the voltage sag at a point depends on the location of the fault from the point.

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|
| PRE-FAULT | 1.003 | 0.9991 |
| DURING-FAULT | 0.830 | 0.8265 |
| POST-FAULT | 0.9998 | 0.996 |

**Table 4.10 Voltage at M3 and industrial load for pre-fault, during-fault and post- fault conditions when fault is at end of Feeder L4 with New turbine of 1.5MW**

It is seen from the simulation and Table (4.1) that the duration of the voltage dip is 60ms as per the fault current observed. It means that the circuit breaker trips 60ms after fault occurs. The magnitude of the voltage decreases by 17.24% at M3 during the fault.

## 4.4.1.2.3 New Turbine of 3.0MW

If a wind turbine injecting an active power of 3.0MW is installed in feeder L4 with the existing conditions, the cable ACJJ 70 of 3.1MVA capacity will be overloaded. Hence this cable has to be replaced by a cable of at least 5.2MVA capacity. The network is then simulated for three phase short circuit faults after introducing this new value of power injection (3MW). The layout of the feeder L4 can be seen in Figure (4.6)

As in the above case, the tap changer is fixed at 0.984 p.u. The voltage level of the network increases when the tap is fixed at 0.984 p.u. When the tap changer is fixed at 0.984, the level of voltage at M3 is given in Table (4.11).

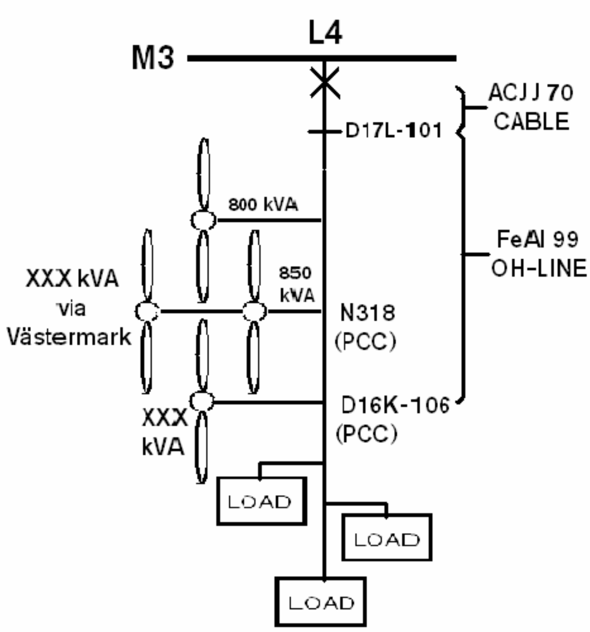


**Figure 4.6 Layout of feeder L4 showing the new turbine at Västermark**

| TAP CHANGER POSITION | VOLTAGE AT SUB STATION(M3) |
|---|---|
| FIXED AT 1.00 P.U | 0.986 |
| FIXED AT 0.984 P.U | 1.003 |

**Table 4.11 Changes in the voltage at the sub station (M3) with the tap Changer**

It is seen from the simulation that the duration of voltage dip is 60ms from Table (4.1). The pre-fault voltage at M3 is reduced by an amount 0.45% after tripping the feeder L4. All the other loads connected to the network experience similar variations in the voltage. The magnitude of the voltage sag at a point depends on the location of the fault from the point. Since large amount of wind power is disconnected from the feeder, the post fault voltage at Substation (M3) is less when compared to case 4.4.1.2.2. Because the power generation in this feeder is more, the voltage dip in this case is less as compared with the case in section (4.4.1.2.2). The magnitude of the voltage decreases by 16.7% at M3 during the fault as shown in Table (4.12).

| | VOLTAGE AT M3 | VOLTAGE AT INDUSTRIAL LOAD |
|---|---|---|
| PRE-FAULT | 1.003 | 0.9995 |
| DURING-FAULT | 0.8345 | 0.8307 |
| POST-FAULT | 0.9985 | 0.9946 |

**Table 4.12 Voltage at M3 and industrial load for pre-fault, during-fault and post-fault conditions when the fault is applied at the end of the feeder L4 with a new turbine of 3.0MW in the same feeder**

### 4.4.1.2.4 Comparison of the cases

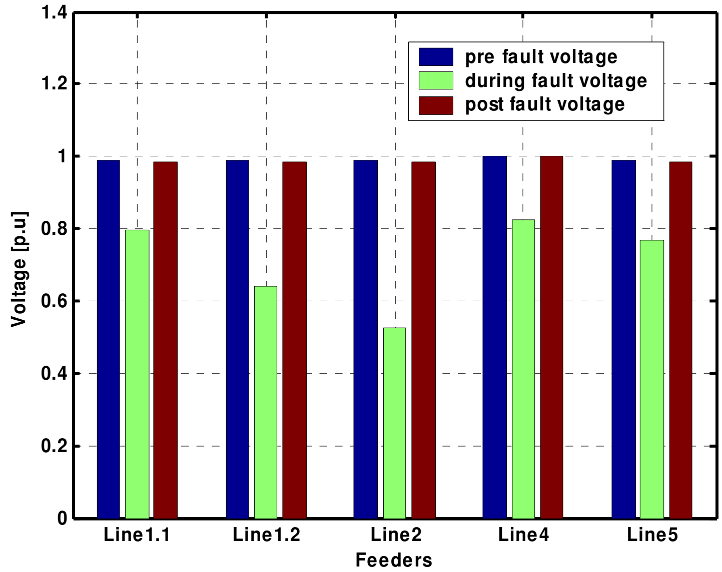


**Figure 4.7 Change in the voltage levels (Pre-fault, During-fault, Post-fault) due to a three phase short circuit fault in the respective feeders for existing network.**

From Figure (4.7) it is observed that the worst case is when the fault occurs at end of the feeder L2. This is when the network experiences the worst voltage dip. This happens because the fault occurs near to the substation.

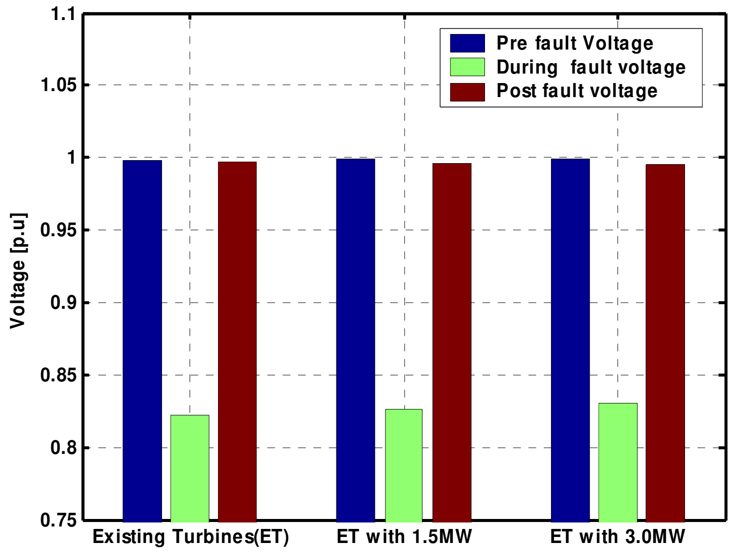


**Figure 4.8 Variation in the voltage at the industrial load for different combinations of wind generation when the fault is applied at the end of the feederL4**

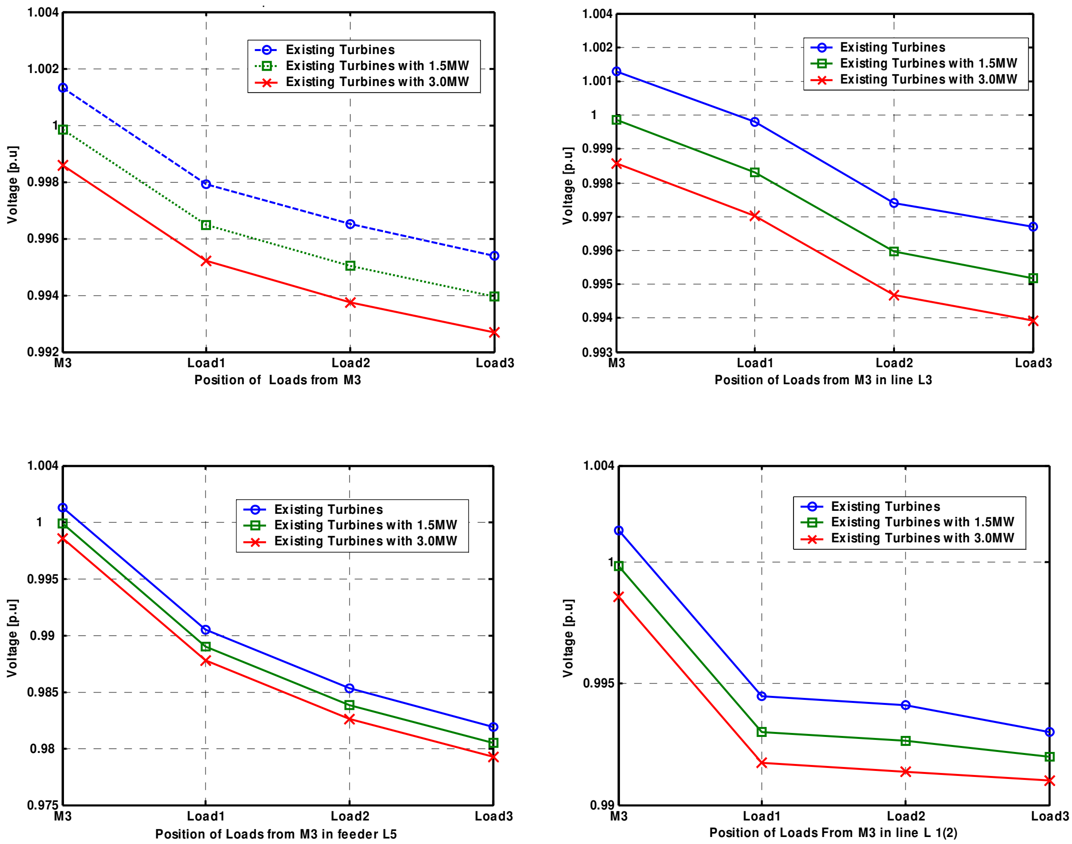


**Figure 4.9 Variation in post-fault voltage at the loads in Feeders L2, L3, L5, L1(2) for different combinations of wind generation with fix tap at 0.984 p.u when fault is applied at end of feederL4**

The voltage dip is less in the case of existing network with 3.0MW wind power generation from the new turbine to be installed, but in this case the post fault voltage is reduced more when compared to the other cases. From Figure (4.9), it is observed that the post fault voltages at the load buses along the feeder L2 from substation (M3) decreases downstream and the post fault voltages at the load buses in the feeder L2 for the existing network with 3.0MW new generation will be even less compared to the other two cases in the Figure (4.8).

## 4.4.1.3 Parallel operation of two transformers

In the Lundsbrunn network, only one of the transformers is being operated at a time. Operation of two transformers in parallel is considered to investigate the effect of the voltage dip on the substation and the loads in the network. The transformers are rated at 8MVA each but since their reactances are different, their will be in accordance with these reactances. Transformer T1 has a relative short circuit resistance and reactance of 4.9% and 7.75% respectively. Transformer T2 has a relative short circuit impedance of 0.49% and 6.35% respectively. At full load, the voltage drop over T1 will be larger than that over T2.

The conditions for the parallel operation of two transformers are as follows [7]

1) Same voltages on both sides of the transformers.
2) Same voltage shift meaning identical clock numbers.
3) Same relative short circuit impedance.

It is observed in the simulations carried out that connecting a transformer in parallel with the existing transformer will increase the voltage level of the network. All the three cases that were investigated for one transformer will be discussed here for the parallel operation of two transformers.

## 4.4.1.3.1 Only Existing Turbines

**(A) Fault at the end of the feeder L1**

**(A-1) Fault at the end of the feeder L1 (1)**

When compared to one transformer operation, it is observed here that there is an increase in the voltage level in the network and also voltage dip is less during the fault (more remaining voltage). The pre-fault voltage at M3 is reduced by an amount 0.17% after tripping the feeder L1 (1) as shown in Table (4.13). The post fault voltage at M3 for one transformer operation is more than that for the parallel operation of two transformers. The magnitude of the voltage decreases by 12.8% on M3 during the fault. Circuit breaker takes one second to disconnect the feeder from the network referring to the Table (4.1). There is no change in the tap changer for both the transformers.

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|
| PRE-FAULT | 0.9928 | 0.9888 |
| DURING-FAULT | 0.8649 | 0.8612 |
| POST-FAULT | 0.9911 | 0.9871 |

**Table 4.13 Voltage at M3 and industrial load for the parallel operation of two transformers when the fault is at the end of the feeder L1 (1)**

**(A-2) Fault at the end of the feeder L1 (2)**

Compared to the operation with one transformer, the voltage dip during the fault is lower (more remaining voltage) in the parallel operation of two transformers. The tap changer does not change in both the transformers as was the case with one transformer operation. The duration of the voltage sag is 70ms referring to the Table (4.1). The magnitude of the voltage decreases from the pre-fault voltage by 24.7% on M3 during the fault as shown in Table (4.14).

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|

| | | |
|---|---|---|
| PRE-FAULT | 0.9928 | 0.9888 |
| DURING-FAULT | 0.7468 | 0.7433 |
| POST-FAULT | 0.9911 | 0.9871 |

**Table 4.14 Voltage at M3 and industrial load for the parallel operation of two transformers when the fault is applied at the end of the feeder L1 (2)**

### (B) Fault at the end of the feeder L2

Among all the cases, this is the worst case with the most severe voltage dip (least remaining voltage) during the fault at end of the feeder L2. The pre-fault voltage at M3 is reduced by 33% during the fault as shown in Table (4.15). Both the transformers do not change the tap changer position. Duration of voltage dip is 60ms referring to the Table (4.1).

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|
| PRE-FAULT | 0.9928 | 0.9888 |
| DURING-FAULT | 0.6585 | 0.6552 |
| POST-FAULT | 0.9914 | 0.9875 |

**Table 4.15 Voltage at M3 and industrial load for the parallel operation of two transformers when the fault is applied at the end of the feeder L2**

### (C) Fault at the end of the feeder L5

The difference in the pre-fault and the post-fault voltages at M3 is more when compared to the voltages in cases (A) and (B) because large amount of wind power energy is disconnected after the fault.

Voltage dip also increases along the feeder from M3 downstream towards the load at end of the feeder. The pre-fault voltage at M3 is reduced by 15% during the fault as shown in Table (4.16). The tap changer of the transformer does not change. The duration of the voltage dip remains the same as was in the case of one transformer operation.

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|
| PRE-FAULT | 0.993 | 0.9891 |
| DURING-FAULT | 0.8437 | 0.8401 |
| POST-FAULT | 0.9905 | 0.9866 |

**Table 4.16 Voltage at M3 and industrial load for the parallel operation of two transformers when the fault is at end of the Feeder L5**

### (D) Fault at the end of the feeder L4

It is observed that the tap changer does not change in the parallel operation of two transformers. The pre-fault voltage is reduced by 12% during the fault as shown in Table (4.17). The duration of the dip in this case is 60ms referring to the Table (4.1). When the feeder L4 is disconnected from the network, the pre-fault and post-fault voltages at M3 will almost be the same because the two transformers will share the extra load burden in proportion of their impedance after the fault. Although the difference between the pre-fault and post-fault voltages is almost the same with the single and parallel operation of the transformers for the existing network when the fault occurs at the end of the feeder L4, it is to be noted that in the former case, a change in the tap position is observed whereas no tap change occurs in the latter.

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|
| PRE-FAULT | 0.992 | 0.9881 |
| DURING-FAULT | 0.8773 | 0.8736 |
| POST-FAULT | 0.9913 | 0.9874 |

**Table 4.17 Voltage at M3 and industrial Load for the parallel operation of two transformers when the fault is at end of Feeder L4**

## 4.4.1.3.2 New Turbine of 1.5MW

As mentioned earlier in the single transformer case, the post-fault voltage at M3 depends on the amount of load that is disconnected from the network. Here, the post-fault voltage is decreased substantially from the pre-fault voltage when compared to the case in section 4.4.1.3.1 since large amount of power is being disconnected from the network after the fault. The tap changer does not change. The pre-fault voltage at M3 is reduced by 0.22% during the fault as shown in Table (4.18). Referring to the Table (4.1), the duration of the fault is 60ms.

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|
| PRE-FAULT | 0.992 | 0.9885 |
| DURING-FAULT | 0.8795 | 0.8758 |

| | | |
|---|---|---|
| POST-FAULT | 0.9898 | 0.9858 |

**Table 4.18 Voltage at M3 and at the industrial Load for the parallel operation of two transformers when the fault is at end of Feeder L4 with New turbine of 1.5MW**

#### 4.4.1.3.2 New Turbine of 3.0MW

In this case, the post-fault voltage is decreased substantially compared to the above case since large amount of wind power is isolated from the feeder. The tap changer does not change. The pre-fault voltage at M3 is reduced by 11% during the fault as shown in Table (4.19). Referring to the Table (4.1), the duration of fault is 6ms.

| | VOLTAGE AT M3 (P.U) | VOLTAGE AT INDUSTRIAL LOAD (P.U) |
|---|---|---|
| PRE-FAULT | 0.992 | 0.9888 |
| DURING-FAULT | 0.8816 | 0.8779 |
| POST-FAULT | 0.9884 | 0.9845 |

**Table 4.19 Voltage at M3 and industrial load for the parallel operation of two transformers when the fault is at the end of the feeder L4 with a new turbine of 3.0MW installed in the feeder**

## 4.4.2 Short Circuit Fault current Analysis

In this section, fault currents caused by applying a three-phase short circuit fault to the feeders in the Lundsbrunn network are observed. At the same time, currents through the other feeders and on the low voltage side of the transformer are monitored to check the status of the relays and hence of the circuit breakers associated with the transformer and the feeders. This procedure is also carried out by including a second transformer in parallel to the first to see the change in the fault currents, the currents on the low voltage side of the transformers and eventually in the protection settings. The following combinations of generation and load are considered for the simulations.

1. No generation and Low load
2. No generation and Full load
3. Full generation and Low load
4. Full generation and Full load

Among these, the case with full generation from the turbines and low load condition is investigated for the short circuit faults in the following sections. A three-phase short circuit fault is applied on each feeder and it was observed that the case with a high generation from turbines and low load presents the highest fault current. Therefore, all the cases are simulated for this condition so that the protection system can be configured for the worst case.

### 4.4.2.1 One transformer in operation

Fault currents are observed by applying a three phase short circuit fault at the ends of the feeders. The purpose of choosing this location is to maintain uniformity in regarding the fault application in the network. Four cases are considered for analyzing this part which is discussed separately. These cases are

1. No Turbines
2. Only Existing Turbines
3. New Turbine of 1.5MW
4. New Turbine of 3MW

#### 4.4.2.1.1 No Turbines

**(A) Fault Currents**

In this case, the Lundsbrunn network is simulated without including any turbines so that the entire fault current will be contributed only through the transformer. This gives an idea concerning the change in the current through the transformer when the turbines are included and the power infeed is increased in the latter sections.

| Faulted Feeder | Fault Current (A) | Current at Transformer LV (A) |
|---|---|---|
| L1 (1) | 1062.08 | 1064.85 |
| L1 (2) | 1730.41 | 1727.26 |
| L2 | 2495.76 | 2501.39 |
| L3 | 2755.21 | 2765.96 |
| L4 | 1038.4 | 1047.87 |
| L5 | 1056.2 | 1061.33 |

**Table 4.20 Fault currents and the currents observed on the low voltage side of the transformer when a three-phase short circuit fault applied at the ends of all the feeders**

Table (4.20) shows that the case when a three-phase short circuit fault is applied at the end of the feeder L3 presents the highest fault current because of the lower impedance between the bus M3 (substation busbar) and the location where the fault is applied. It can be seen that the transformer provides the entire fault current in the absence of the turbines. The remaining current from the transformer feeds the loads. Since the residential loads are modelled as constant impedance loads due to the fact that most of the residential loads consist of local heating devices which can be thought of as a simple resistance for a very short time period, the current consumed by the loads varies with the varying voltage dip at the load buses. This can be seen in the form of varying differences between the current supplied by the transformer and the fault current. It is seen that this difference is the highest (around 10A) for the case when the fault is applied at the end of the feeder L3. This is due to the fact that the industrial load on feeder L3 is modelled as a constant power load and due to this a voltage dip at this node results in an increased current consumption. Since this load experiences the deepest dip (least remaining voltage) when the fault is applied on this feeder itself, the current consumed by this load will be the highest in this case which results in the transformer supplying more current than the fault current.

**(B) Overcurrent Protection settings**

To check if the overcurrent relays are setup appropriately to trip the faulted feeder and isolate the fault from the network, the current flow is monitored at the beginning of the feeders where they emerge from the substation busbar. Only one circuit breaker is assumed at the substation for each feeder that disconnects the entire feeder after detecting an overcurrent. Similarly, the high voltage and low voltage sides of the transformer are also provided with breakers to provide backup protection in case the primary protection for the feeders fails. The following is observed.

| | Relay status on the feeders and the transformer | | | | | | |
|---|---|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 | T/F $1^0$ | T/F $2^0$ |
| L1 (1) | **O** | C | C | C | C | C | C |
| L1 (2) | **O** | C | C | C | C | C | C |
| L2 | C | **O** | C | C | C | C | C |
| L3 | C | C | **O** | C | C | C | C |
| L4 | C | C | C | **O** | C | C | C |
| L5 | C | C | C | C | **O** | C | C |

**Table 4.21 Status of the relays on each feeder. O=Open, C=Close. T/F $1^0$ = High voltage side of the transformer, T/F $2^0$ = Low voltage side of the transformer.**

Table (4.21) shows the status of the overcurrent relays that are used to trip the circuit breakers at the beginning of each feeder. The relays considered here are of the type constant time provided with two steps as shown in Figure (4.10).

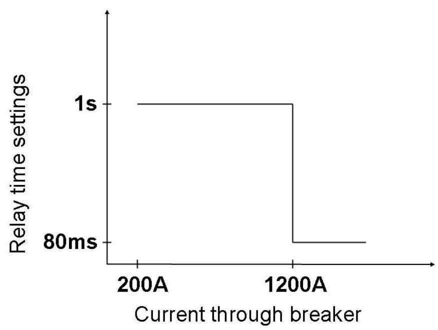


**Figure 4.10 Current - Time settings for the overcurrent relay of the feeder L3**

Figure (4.10) shows the typical relay settings for the feeder L3. When the current through the feeder exceeds 200A, the relay takes its first step and trips the feeder after 1 second. This current-time setting continues till the current reaches 1200A. When the current exceeds 1200A, the relay takes the second step and trips the feeder much faster i.e., after 80ms. By taking these settings into account, the current flowing through the feeders is monitored and the status of the corresponding relays is summarized in Table (4.21). Since no wind turbines are considered, the current through the non faulted feeders, when a fault is applied a feeder, stays well below the trip current and hence for all the cases, as can be seen in Table (4.21), only the faulted feeders are tripped. It is observed that in all the cases except when the fault is applied on the feeder L1 (1), the relay acts on the second time step and the feeders are tripped quickly (in a matter of milliseconds) whereas the relay takes 1 second to trip when the fault is applied on the feeder L1 (1). The fault current in this case is around 1062A. This particular case is checked again in the sections to be followed to see the frequency of its occurrence.

Also, the circuit breaker on the low voltage side of the transformer is set to trip after 1.3 seconds when the fault current exceeds 600A. This takes the role of backup protection in case the breakers on the feeders fail due to some reason and the faulted feeders do not get tripped. Current-time settings for the relays of other feeders are shown in Figure (4.11) and that for the relay on the low voltage side of the transformer in Figure (4.12).

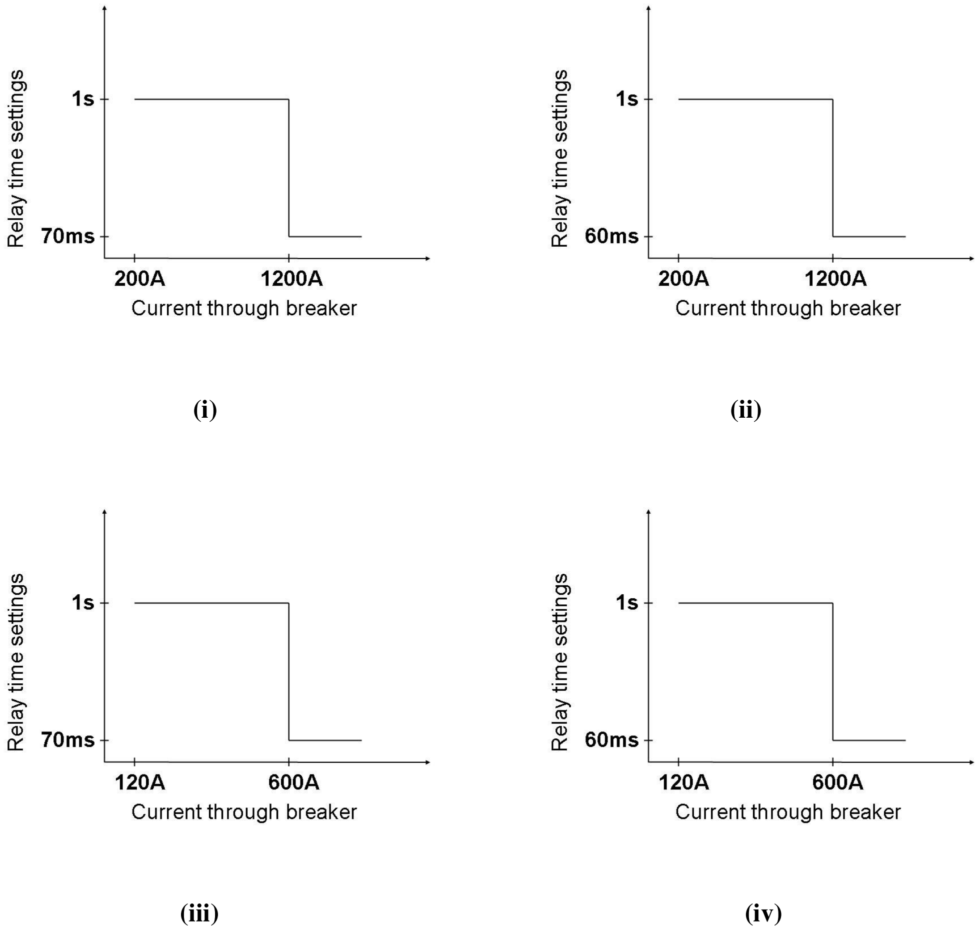


**Figure 4.11 Current-Time settings for the overcurrent relays of the feeders L1 (i), L2 (ii), L4 (iii) and L5 (iv**

## 4.4.2.1.2 Only Existing Turbines

### (A) Fault Currents

In this case, the Lundsbrunn network is investigated by including all the existing turbines that are up and running. Following are the fault currents observed along with the currents through the transformer when a three phase short circuit fault is applied at the ends of the feeders.

| Faulted Feeder | Fault Current (A) | Current at Transformer LV (A) |
|---|---|---|
| L1 (1) | 1088.11 | 864.18 |
| L1 (2) | 1786.17 | 1575.56 |
| L2 | 2610.91 | 2352.87 |
| L3 | 2900.93 | 2632.09 |
| L4 | 1063.72 | 829.39 |
| L5 | 1096.96 | 906.55 |

**Table 4.22 Fault currents and currents on the low voltage side of the transformer when a three phase short circuit fault is applied at the ends of the feeders**

Table (4.22) shows that the case when a three phase short circuit fault is applied at the end of the feeder L3 still presents the highest fault current. The current observed at the low voltage side of the transformer has been reduced now due to the current contributed by the wind turbines. The current injected by the turbine flows through the feeder and after arriving at the substation it is divided into two paths; one towards the short circuit fault and the other towards the utility through the transformer depending on the network impedance and the transformer impedance provided.

### (B) Overcurrent protection settings

Table (4.23) shows the currents observed at the beginning of the feeders where the overcurrent relays that signal the circuit breakers are located. The negative sign for the current through feeder L3 indicates that the current flows into the feeder because of the absence of integrated generation (wind turbine). Also shown is the status of the relays at the beginning of the feeders which follow the current-time settings shown in Figure (4.9) and Figure (4.10). Feeder L1 takes 1 second to trip because the current is still below 1200A.

Also shown is the status of the relays at the high voltage and low voltage sides of the transformer. As can be seen from the current-time settings for the relay on the low voltage side of the transformer in Figure (4.11), it trips the circuit breaker on detecting a current of 600A after a time delay of 1.3 seconds. If, within this time, the breaker provided for the faulted feeder trips the feeder, the transformer still remains online. It is for this reason that the trip time for the transformer breaker is set at a higher value than that for the feeder. It can be seen in this case that both the breakers of the transformer (at high and low voltage sides) remain closed assuming that the fault is successfully cleared by the breakers at the beginning of the feeders. If, due to some reason, the breaker provided for the feeder at the substation does not trip, the transformer relays act and protect the transformer from overloading due to the fault.

| | Current though the feeders (A) | | | | |
|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 |
| L1 (1) | **1050.31** | 42.5 | -3.92 | 85.52 | 103.1 |
| L1 (2) | **1763.81** | 43.09 | -4.07 | 86.05 | 103.54 |
| L2 | 43.17 | **2569.39** | -4.06 | 86.43 | 104.01 |
| L3 | 43.26 | 43.6 | **2903.79** | 86.53 | 104.11 |
| L4 | 42.18 | 42.44 | -3.92 | **985.04** | 103.04 |
| L5 | 42.3 | 42.6 | -3.94 | 85.62 | **1024** |

| | Relay status on the feeders and the transformer | | | | | | |
|---|---|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 | T/F $1^0$ | T/F $2^0$ |
| L1 (1) | **O** | C | C | C | C | C | C |
| L1 (2) | **O** | C | C | C | C | C | C |
| L2 | C | **O** | C | C | C | C | C |
| L3 | C | C | **O** | C | C | C | C |
| L4 | C | C | C | **O** | C | C | C |
| L5 | C | C | C | C | **O** | C | C |

**Table 4.23 Current through the feeders and the relay status corresponding to the feeders and the transformer during a three phase short circuit fault applied at the feeder ends. O=Open, C=Close, T/F $1^0$=High voltage side of the transformer, T/F $2^0$=Low voltage side of the transformer**

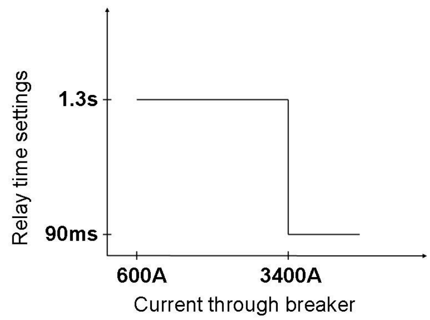


**Figure 4.12 Current-Time settings of the relay at low voltage side of the transformer T1**

## 4.4.2.1.3 New Turbine of 1.5MW

### (A) Fault Currents

A new turbine is proposed to be setup at the place called Västermark in the present distribution network. Several cases of input power injection from this new turbine into the grid are investigated and among those, one of the suitable solution, if the thermal limit of the cable connecting the turbine is to be considered as a limit, is to inject 1.5MW into the grid from this new turbine which is to be connected at a distance of 500m from the already installed turbine at Västermark which is again at a distance of 500m from the point of common coupling to the grid. Following are the fault currents along with the currents through the transformer that are observed after introducing the new turbine and running the simulations related to the short circuit faults for the entire network.

| Faulted Feeder | Fault Current (A) | Current at Transformer LV(A) |
|---|---|---|
| L1 (1) | 1092.86 | 810.07 |
| L1 (2) | 1798.59 | 1529.01 |
| L2 | 2641.18 | 2309.89 |
| L3 | 2939.59 | 2594.38 |
| L4 | 1077.05 | 776.92 |
| L5 | 1101.01 | 863.73 |

**Table 4.24 Fault currents and the currents on the low voltage side of the transformer for when a three phase short circuit fault applied at the feeder ends after introducing a new turbine that injects an active power of 1.5MW at Västermark**

Table (4.24) shows that the fault currents for all the cases have increased but at the same time the currents observed at the low voltage side of the transformer have decreased because the current from the newly installed turbine, after arriving at the substation, gets divided and the part that flows towards the transformer reduces the current through the transformer.

**(B) Overcurrent protection settings**

| | Current though the feeders (A) | | | | |
|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 |
| L1 (1) | **1055.08** | 42.4 | -3.92 | 164.52 | 103.09 |
| L1 (2) | **1776.17** | 43.08 | -4.07 | 165.05 | 103.63 |
| L2 | 43.15 | **2599.41** | -4.07 | 165.43 | 104.0 |
| L3 | 43.24 | 43.58 | **2942.2** | 165.51 | 104.08 |
| L4 | 42.16 | 42.43 | -3.92 | **928.69** | 103.03 |
| L5 | 42.34 | 42.62 | -3.94 | 164.63 | **1028.04** |

| | Relay status on the feeders and the transformer | | | | | |
|---|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 | T/F $1^0$ | T/F $2^0$ |
| L1 (1) | **O** | C | C | **O** | C | C | C |
| L1 (2) | **O** | C | C | **O** | C | C | C |
| L2 | C | **O** | C | **O** | C | C | C |
| L3 | C | C | **O** | **O** | C | C | C |
| L4 | C | C | C | **O** | C | C | C |
| L5 | C | C | C | **O** | **O** | C | C |

**Table 4.25 Current through the feeders and the status of the relays associated with the feeders and the transformer during a three phase short circuit fault applied at the feeder ends. O=Open, C=Close, $1^0$=High voltage side of the transformer, $2^0$=Low voltage side of the transformer**

Table (4.25) shows the currents observed at the beginning of each feeder during a three phase short circuit fault applied at the feeder ends. It can be seen that the feeder L1 still trips after 1 second because the fault current is high but below 1200A.

An interesting point to be observed here is that the feeder L4 will trip irrespective of which feeder is faulted. Due to the integration of a new turbine injecting an active power of 1.5MW into the grid, the normal current injection from feeder L4 has now increased to around 164A. The overcurrent relay for the feeder L4 has been set to trip for a current of 120A. So, this relay will trip no matter where the fault is applied because we have assumed the turbines as constant current injecting loads that will inject their rated current irrespective of the fault conditions. If the power infeed from the new turbine to be installed at Västermark is planned to be taken as 1.5MW, then a change in the setting of the overcurrent relay for the feeder L4 at the substation may be suggested. Otherwise, each time a fault occurs on any feeder, or for that matter even for the normal operation of the network with the new turbine, feeder L4 will also trip. The current-time settings with the suggested new values for the relay of feeder L4 is shown in Figure (4.13). The current for the first step of the relay could then be set to that of the relay for the feeders L1, L2 and L3.

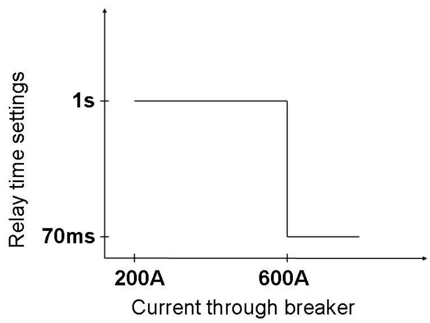


**Figure 4.13 Suggested new settings for the relay of the feeder L4 upon integrating new turbine of 1.5MW at Västermark**

The breakers on the high and low voltage side of the transformer remain closed assuming that the circuit breakers provided for the feeders at the substation will trip them during a fault on the corresponding feeders. The current-time setting for the relay on the low voltage side of the transformer is shown in Figure (4.12).

### 4.4.2.1.4 New Turbine of 3MW

#### (A) Fault Currents

One more possible case of power injection at the same place as discussed in the previous section is 3MW from the new turbine. It is assumed that the current cable, ACJJ 70 of 3.1MVA capacity, connecting the substation busbar M3 with the bus D17L-101 as shown in Figure (4.14), is replaced by a cable of atleast 5.2MVA capacity. D17L-101 is the bus to which the new turbine is to be connected. This figure is reached by running the simulation and noting the value at which the thermal limit of the transformer is exceeded. The network is then simulated for short circuit faults after introducing this new value of power injection (3MW).

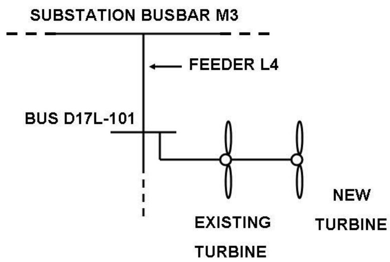


**Figure 4.14 Layout of feeder L4 with the new turbine**

| Faulted Feeder | Fault Current (A) | Current at Transformer LV(A) |
|---|---|---|
| L1 (1) | 1097.07 | 760.96 |
| L1 (2) | 1810.10 | 1483.4 |
| L2 | 2669.86 | 2267.79 |
| L3 | 2976.73 | 2557.20 |
| L4 | 1089.86 | 727.55 |
| L5 | 1104.58 | 827.09 |

**Table 4.26 Fault currents and the currents on the low voltage side of the transformer when a three phase short circuit fault is applied at the feeder ends after introducing a new turbine of 3MW at Västermark**

Three phase short circuit faults are applied at the end of the feeders and the fault currents along with the currents on the low voltage side of the transformer are observed and tabulated as shown in Table (4.26). As for the cases discussed in the previous sections, the case when the fault is applied on the feeder L3 gives the highest fault current. The current through the feeder L1 does not cross 1200A and for this reason the relay takes 1 second to trip the feeder.

**(B) Overcurrent protection settings**

It can be seen in Table (4.27), which shows the currents through the feeders and the status of the relays associated with the tripping of these feeders, that the current through the feeder L4 has still increased to around 243A and this feeder, as was in the previous case, is tripped along with the faulted feeder. It is tripped even under normal operation. Therefore, in case the existing link between the substation busbar M3 and the bus

| | Current though the feeders (A) | | | | |
|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 |
| L1 (1) | **1059.27** | 42.5 | -3.92 | 242.14 | 103.13 |
| L1 (2) | **1787.55** | 43.08 | -4.07 | 242.67 | 103.66 |
| L2 | 43.14 | **2628.15** | -4.08 | 243.04 | 104.03 |
| L3 | 43.23 | 43.57 | **2979.53** | 243.12 | 104.11 |
| L4 | 42.17 | 42.40 | -3.92 | **874.66** | 103.06 |
| L5 | 42.35 | 42.63 | -3.94 | 242.26 | **1031.5** |

| | Relay status on the feeders and the transformer | | | | | | |
|---|---|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 | T/F $1^0$ | T/F $2^0$ |
| L1 (1) | **O** | C | C | **O** | C | C | C |
| L1 (2) | **O** | C | C | **O** | C | C | C |
| L2 | C | **O** | C | **O** | C | C | C |
| L3 | C | C | **O** | **O** | C | C | C |
| L4 | C | C | C | **O** | C | C | C |
| L5 | C | C | C | **O** | **O** | C | C |

**Table 4.27 Current through the feeders and Relay status corresponding to the feeders and the transformer during a 3 phase short circuit fault applied at the feeder ends. O=Open, C=Close, $1^0$=Low voltage side of the transformer, $2^0$=High voltage side of the transformer**

D17L-101 is replaced with a 5.2MVA link and the thermal limit of the transformer considered as the limit thereby achieving a 3MW power infeed from the new turbine into the grid, it could be suggested that the current relay setting of the relay associated with the feeder L4 at the substation be reconfigured to a minimum of 250A to avoid its tripping unnecessarily.

Similar to the above cases, the breaker on the low voltage side of the transformer remains closed as long as the breaker on the faulted feeder trips the feeder and clears the fault. The current-time setting of the relay on the low voltage side of the transformer is shown in Figure (4.12). The suggested new values for the relay of the feeder L4 after integrating a new turbine of 3 MW at Västermark is shown in Figure (4.15).

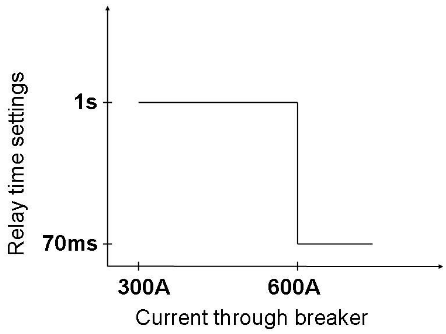


**Figure 4.15 Suggested new current-time settings for the relay of the feeder L4 upon integrating a new turbine of 3MW at Västermark**

A summary of the four cases investigated so far is presented in the form of a plot showing the fault currents for faults on all the feeders. This can be seen in Figure (4.16)

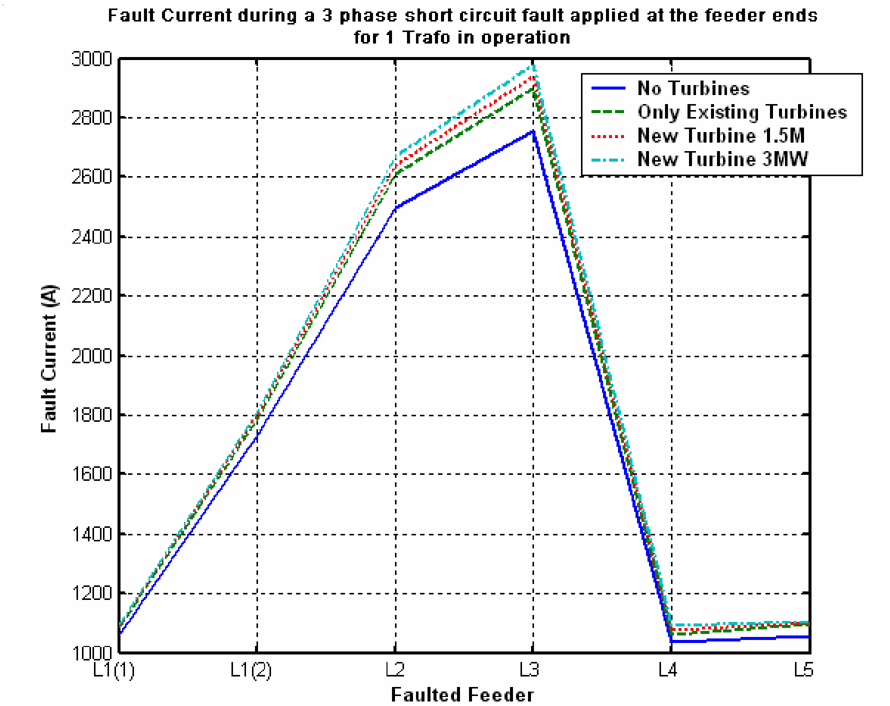


**Figure 4.16 Fault Current during a three phase short circuit fault applied at the feeder ends for one transformer in operation**

### 4.4.2.2 Parallel operation of two transformers

Another point to be investigated in the Lundsbrunn network is the parallel operation of two transformers. In the Lundsbrunn substation, only one of the transformers is operated at any time, but the behavior of the network is investigated by placing both the transformers in parallel and running the simulations to see the change in the parameters affecting the fault current, the current contributions through each of the transformers and the corresponding protection settings.

All the four cases that were investigated when one transformer was in operation are investigated.

## 4.4.2.2.1 No Turbines

**(A) Fault Currents**

The case when the turbines are not included in the network, when simulated with two transformers in parallel, yield the following results

| Faulted Feeder | Fault Current (A) | I (T1) | I (T2) |
|---|---|---|---|
| L1 (1) | 1145.58 | **528.21** | 627.24 |
| L1 (2) | 2006.01 | 914.7 | 1099.78 |
| L2 | 3111.92 | 1410.04 | 1710.65 |
| L3 | 3531.3 | 1598.23 | 1942.72 |
| L4 | 1113.82 | **514.0** | 611.01 |
| L5 | 1152.10 | **531.34** | 627.22 |

**Table 4.28 Fault currents and the currents on the low voltage side of both the transformers during a three phase short circuit fault applied at the feeder end. I (T1) = Current on the low voltage side of the transformer T1, I (T2) = Current on the low voltage side of the transformer T2.**

From Table (4.28), it can be seen that the fault current is shared by both the transformers. Transformer T2 contributes more current as compared to T1 since its impedance is lower compared to that of T1. Feeder L1 still takes 1 second to trip because the current did not exceed 1200A.

**(B) Overcurrent protection settings**

For the cases in Table (4.29), when the fault is applied at the end of the feeders L1 (1), L4 and L5, the current observed on the low voltage side of the transformer T1 is less than 600A (which is the trip current for the relay as shown in Figure (4.12)) which leads to that the overcurrent relay located here may not detect the fault current.

In this case, since the current through the transformer T2 is over 600A (the threshold current for the relay to trip), it will trip after 1.3 seconds in Figure (4.17), but the transformer T1 will still be in operation because the current at its low voltage side did not exceed 600A and was not detected by the relay. Due to this, if the breaker associated with the faulted feeder did not trip, transformer T2 will trip in 1.3 seconds as shown in Figure

(4.17) and all the fault current will suddenly be transferred to transformer T1 and it will take 1.3 seconds from this point until the transformer is tripped. The suggested values of current-time settings for this relay may be as shown in Figure (4.18).

| | Relay status on the feeders and the transformer | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 | 1 T/F $1^0$ | 1 T/F $2^0$ | 2 T/F $1^0$ | 2 T/F $2^0$ |
| L1 (1) | **O** | C | C | C | C | C | **C** | C | C |
| L1 (2) | **O** | C | C | C | C | C | C | C | C |
| L2 | C | **O** | C | C | C | C | C | C | C |
| L3 | C | C | **O** | C | C | C | C | C | C |
| L4 | C | C | C | **O** | C | C | **C** | C | C |
| L5 | C | C | C | C | **O** | C | **C** | C | C |

**Table 4.29 Status of the relays associated with the feeders during a three phase fault applied at the ends of feeders. 1 T/F=Transformer T1, 2 T/F=Transformer T2, $1^0$=Low voltage side, $2^0$=High voltage side.**

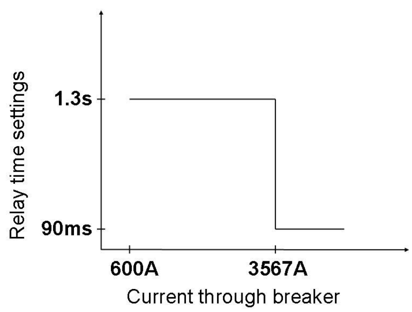


**Figure 4.17 Current-Time settings for the relay on the low voltage side of the transformer T2**

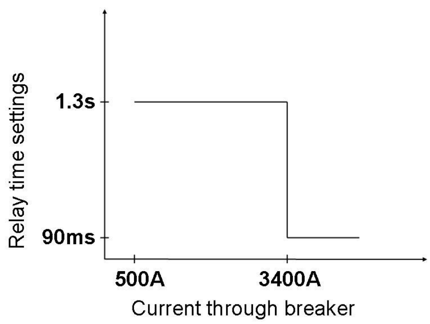


**Figure 4.18 Suggested current-time settings for the relay on the low voltage side of the transformer T1 when no turbines are considered in Lundsbrunn while the transformers are operated in parallel**

## 3.4.2.2.2 Only Existing Turbines

**(A) Fault Currents**

In this case, the Lundsbrunn network is simulated by including only the existing turbines with the two transformers operating in parallel. The following results are recorded.

| Faulted Feeder | Fault Current (A) | I (T1) | I (T2) |
|---|---|---|---|
| L1 (1) | 1162.04 | **431.48** | **505.57** |
| L1 (2) | 2043.77 | 833.15 | 998.62 |
| L2 | 3184.29 | 1321.94 | 1602.41 |
| L3 | 3618.88 | 1512.38 | 1837.58 |
| L4 | 1128.84 | **411.47** | **482.36** |
| L5 | 1186.18 | **458.18** | **534.82** |

**Table 4.30 Fault currents and the currents on the low voltage side of both the transformers during a three phase short circuit fault applied at the feeder ends. I (T1) =Current on the low voltage side of the transformer T1, I (T2) =Current on the low voltage side of the transformer T2.**

Table (4.30) shows that the case when a 3 phase short circuit fault is applied at the end of feeder L3 gives the highest fault current, it being around 718A more as compared with the same case under one transformer operation. This current is shared by both the transformers with transformer T2 supplying majority of the share due to its lower impedance. As compared to its counterpart in one transformer operation, the load on the transformer T1 has reduced by around 1120A.

**(B) Overcurrent protection settings**

Table (4.31) shows that the current through the feeders for a three phase short circuit fault has increased considerably from the case with one transformer in operation due to the addition of the new transformer which also contributes to the fault current. When the fault is applied at the ends of the feeders L1 (1), L4 and L5, the current, as seen by the overcurrent relays on the low voltage side of both the transformers is less than 600A which is the threshold setting of these relays. Due to this, the transformers may not trip if the faulted feeder is not tripped by its breaker, for instance, due to a malfunction of the feeder breaker. Therefore, if the Lundsbrunn is to be run on two transformers for the existing network, it may be suggested to reconfigure the relay settings of the overcurrent relays on the low voltage side of both the transformers as shown in Figure (4.19).

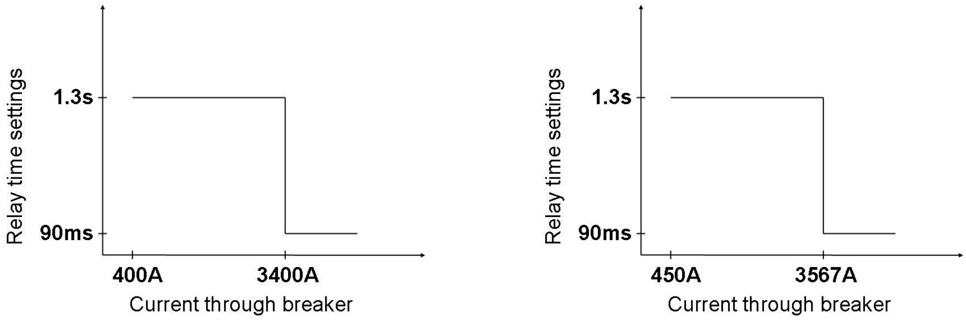


**Figure 4.19 Suggested current-time settings for the relays on the low voltage side of the transformers T1 (left) and T2 (right) for the existing network with the parallel operation of the two transformers in Lundsbrunn**

| | Current though the feeders (A) | | | | |
|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 |
| L1 (1) | **1124.14** | 42.36 | -3.92 | 85.45 | 103.06 |
| L1 (2) | **2019.54** | 42.8 | -3.97 | 85.86 | 103.46 |
| L2 | 42.8 | **3141.95** | -4.07 | 86.15 | 103.76 |
| L3 | 43.86 | 43.18 | **3621.89** | 86.21 | 103.82 |
| L4 | 42.06 | 42.31 | -3.92 | **1050** | 103.02 |
| L5 | 42.18 | 42.45 | -3.92 | 85.53 | **1111.9** |

| | Relay status on the feeders and the transformer | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 | 1 T/F $1^0$ | 1 T/F $2^0$ | 2 T/F $1^0$ | 2 T/F $2^0$ |
| L1 (1) | **O** | C | C | C | C | C | **C** | C | **C** |
| L1 (2) | **O** | C | C | C | C | C | C | C | C |
| L2 | C | **O** | C | C | C | C | C | C | C |
| L3 | C | C | **O** | C | C | C | C | C | C |
| L4 | C | C | C | **O** | C | C | **C** | C | **C** |
| L5 | C | C | C | C | **O** | C | **C** | C | **C** |

**Table 4.31 Current through the feeders and the status of the relays associated with the feeders during a three phase fault applied at the ends of feeders. 1 T/F=Transformer T1, 2 T/F=Transformer T2, $1^0$=Low voltage side, $2^0$=High voltage side.**

## 3.4.2.2.3 New Turbine of 1.5MW

### (A) Fault Currents

In this case, the new turbine to be setup at the place called Västermark is assumed to inject a power of 1.5MW by investigating the maximum power infeed that can be achieved considering the thermal limit of the cable link between bus M3 at the substation and D17L-101 and the simulations are run by applying a 3 phase short circuit fault at the end of the feeders by placing two transformers in parallel at the substation. The following results are observed.

| Faulted Feeder | Fault Current | I (T1) | I (T2) |
|---|---|---|---|
| L1 (1) | 1164.33 | **406.21** | **473.48** |
| L1 (2) | 2050.34 | 808.61 | 968.11 |
| L2 | 3202.33 | 1297.01 | 1571.77 |
| L3 | 3643.23 | 1488.78 | 1808.66 |
| L4 | 1139.48 | **386.85** | **451.31** |
| L5 | 1188.21 | **437.93** | **509.01** |

**Table 4.32 Fault currents and the currents through both the transformers during a three phase short circuit fault applied at feeder ends. I (T1) =Current on the low voltage side of the transformer T1, I (T2) =Current on the low voltage side of the transformer T2.**

It can be seen from Table (4.32) that the fault current in all the cases has increased but it is not a prominent increase because the current injected from the new turbine, after arriving at the PCC, sees the impedance of all the paths and since there is an addition of one more impedance path in the form of a second transformer, this current now has 3 paths to get divided into; 2 transformers and the short circuit fault. The impedance of both the transformers, individually, is less than the impedance from the PCC to the fault location. This could be the reason why the fault current has not increased much inspite of integrating 1.5MW into the network from the new turbine.

### (B) Overcurrent protection settings

Table (4.33) shows the load on the transformers decreases because of the current injection by the new turbine upstream to the utility through the transformer. It can also be seen that the feeder L4 trips no matter which feeder is faulted. This can be prevented by configuring the threshold setting of the relay to the maximum among all the cases (165.29A). The settings shown in Figure (4.13) also hold good for this case. The condition where the overcurrent relays at the low voltage side of both the transformers do not trip in case the breaker associated with the faulted feeder malfunctions, repeats itself even in this case. Hence, if the new turbine to be installed is a 1.5MW one as suggested, the overcurrent relays on the low voltage side of the both the transformers may be reconfigured to a current threshold which is the minimum in both the cases so that the relays detect this current as shown in Figure (4.20).

| | Current though the feeders (A) | | | | |
|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 |
| L1 (1) | **1126.46** | 42.34 | -3.92 | 164.54 | 103.03 |
| L1 (2) | **2026.12** | 42.78 | -3.96 | 164.94 | 103.43 |
| L2 | 42.78 | **3159.89** | -4.07 | 165.23 | 103.72 |
| L3 | 42.84 | 43.15 | **3646.12** | 165.29 | 103.78 |
| L4 | 42.05 | 42.3 | -3.92 | **990.75** | 102.99 |
| L5 | 42.17 | 42.43 | -3.92 | 164.62 | **1113.97** |

| | Relay status on the feeders and the transformer | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 | 1 T/F $1^0$ | 1 T/F $2^0$ | 2 T/F $1^0$ | 2 T/F $2^0$ |
| L1 (1) | **O** | C | C | **O** | C | C | **C** | C | **C** |
| L1 (2) | **O** | C | C | **O** | C | C | C | C | C |
| L2 | C | **O** | C | **O** | C | C | C | C | C |
| L3 | C | C | **O** | **O** | C | C | C | C | C |
| L4 | C | C | C | **O** | C | C | **C** | C | **C** |
| L5 | C | C | C | **O** | **O** | C | **C** | C | **C** |

**Table 4.33 Current through the feeders and the status of the relays associated with the feeders during a three phase short circuit fault applied at the end of feeders. 1 T/F=Transformer T1, 2 T/F=Transformer T2, $1^0$=High voltage side, $2^0$=Low voltage side.**

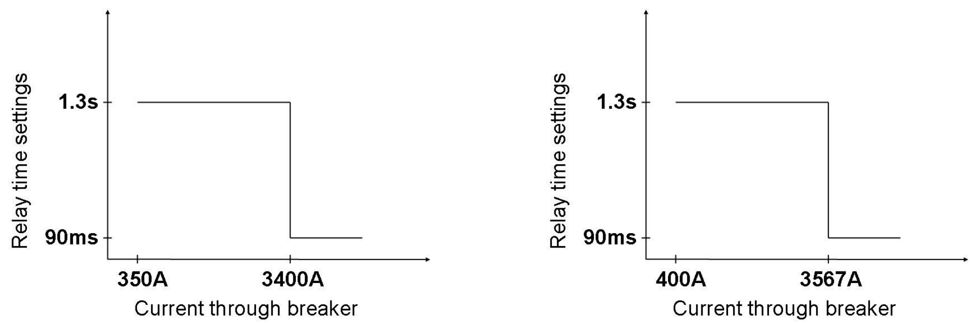


**Figure 4.20 Suggested current-time settings of the relays on the low voltage side of the transformers T1 (left) and T2 (right) for the parallel operation of two transformers when a new turbine injecting an active power of 1.5MW installed in Lundsbrunn at Västermark**

## 4.4.2.2.4 New Turbine of 3MW

### (A) Fault Currents

One more possibility of power injection from the new turbine is 3MW after investigating the maximum power infeed that can be achieved until the thermal limit of the transformer is exceeded assuming that the existing 3.1MVA link between M3 and D17L-101 is replaced by atleast a 5MVA cable. The Lundsbrunn network is then analyzed for short circuit faults when the two transformers are operating in parallel.

It can be seen in Table (4.34) that the fault current increased by a very small margin of around 22A in the worst case of a three phase short circuit fault on feeder L3. This holds the same explanation as was discussed earlier in section (4.4.2.2.3) regarding the addition of the new impedance as seen by the injected current from the new turbine at the PCC so that only a minor part of it is contributed towards the fault.

| Faulted Feeder | Fault Current | I (T1) | I (T2) |
|---|---|---|---|
| L1 (1) | 1166.44 | **406.01** | **470.5** |
| L1 (2) | 2056.51 | 785.42 | 939.26 |
| L2 | 3219.44 | 1272.85 | 1541.9 |
| L3 | 3666.52 | 1465.75 | 1780.41 |
| L4 | 1149.78 | **363.74** | **421.99** |
| L5 | 1190.04 | **420.36** | **486.51** |

**Table 4.34 Fault currents and the currents through both the transformers during a three phase short circuit fault applied at feeder ends. I (T1) =Current on the low voltage side of the transformer T1, I (T2) =Current on the low voltage side of the transformer T2.**

It is observed that the parallel operation of two transformers, as compared to operation with single transformer, prevents large increase of fault currents after integrating new turbines to the existing network at Lundsbrunn.

### (B) Overcurrent protection settings

The currents through the feeders in this case as shown in Table (4.35) have also increased only by a small margin following the same pattern as was in the case with 1.5MW integration into the network. The feeder L4 still trips for three phase short circuit fault in any of the feeders because the current through the feeder is more than the existing threshold current setting of the overcurrent relays associated with the feeder breakers. Should the network be operated with the transformers connected in parallel with a 3MW power infeed from the new turbine, the relay settings for the feeder L4 may be reconfigured to a value that is more than the maximum current of all the cases of faulted feeders (in this case 242.88A) as shown in Figure (4.15), which holds good even for this case, along with the reconfiguration of the overcurrent relays on the low voltage side of both the transformers for the cases of three phase short circuit fault application at the end of feeders L1 (1), L4 and L5 to a value that is minimum of the currents observed for these cases so as to ensure emergency backup for the transformers. The suggested values of the current-time settings when a 3MW turbine is integrated while operating the network with two transformers in parallel is shown in Figure (4.18).

| | Current though the feeders (A) |
|---|---|

| Faulted Feeder | L1 | L2 | L3 | L4 | L5 |
|---|---|---|---|---|---|
| L1 (1) | **1128.55** | 42.33 | -3.92 | 242.14 | 103.02 |
| L1 (2) | **2032.22** | 42.77 | -3.96 | 242.54 | 103.42 |
| L2 | 42.76 | **3177.17** | -4.06 | 242.82 | 103.7 |
| L3 | 42.82 | 43.13 | **3669.47** | 242.88 | 103.76 |
| L4 | 42.04 | 42.29 | -3.92 | **934.06** | 102.98 |
| L5 | 42.16 | 42.42 | -3.92 | 242.22 | **1115.75** |

| | Relay status on the feeders and the transformer | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Faulted Feeder | L1 | L2 | L3 | L4 | L5 | 1 T/F $1^0$ | 1 T/F $2^0$ | 2 T/F $1^0$ | 2 T/F $2^0$ |
| L1 (1) | **O** | C | C | **O** | C | C | **C** | C | **C** |
| L1 (2) | **O** | C | C | **O** | C | C | C | C | C |
| L2 | C | **O** | C | **O** | C | C | C | C | C |
| L3 | C | C | **O** | **O** | C | C | C | C | C |
| L4 | C | C | C | **O** | C | C | **C** | C | **C** |
| L5 | C | C | C | **O** | **O** | C | **C** | C | **C** |

**Table 4.35 Current through the feeders and the status of the relays associated with the feeders during a 3 phase fault applied at the ends of the feeders. 1 T/F=Transformer T1, 2 T/F=Transformer T2, $1^0$=High voltage side, $2^0$=Low voltage side.**

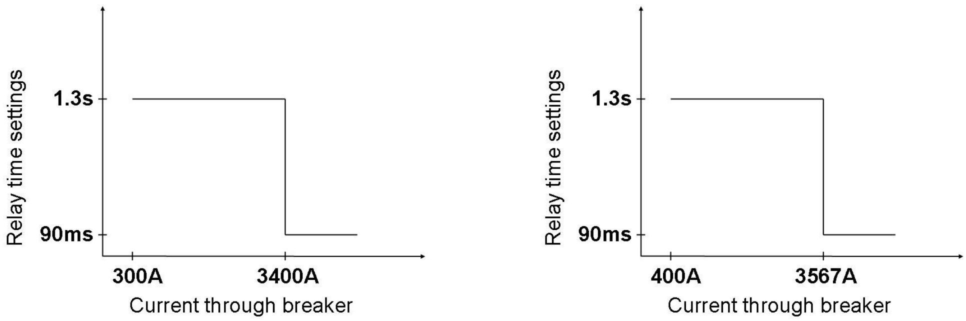


**Figure 4.21 Suggested current-time settings of the relays on the low voltage side of the transformers T1 (left) and T2 (right) for the parallel operation of two transformers when a new turbine injecting an active power of 3MW is installed in Lundsbrunn at Västermark**

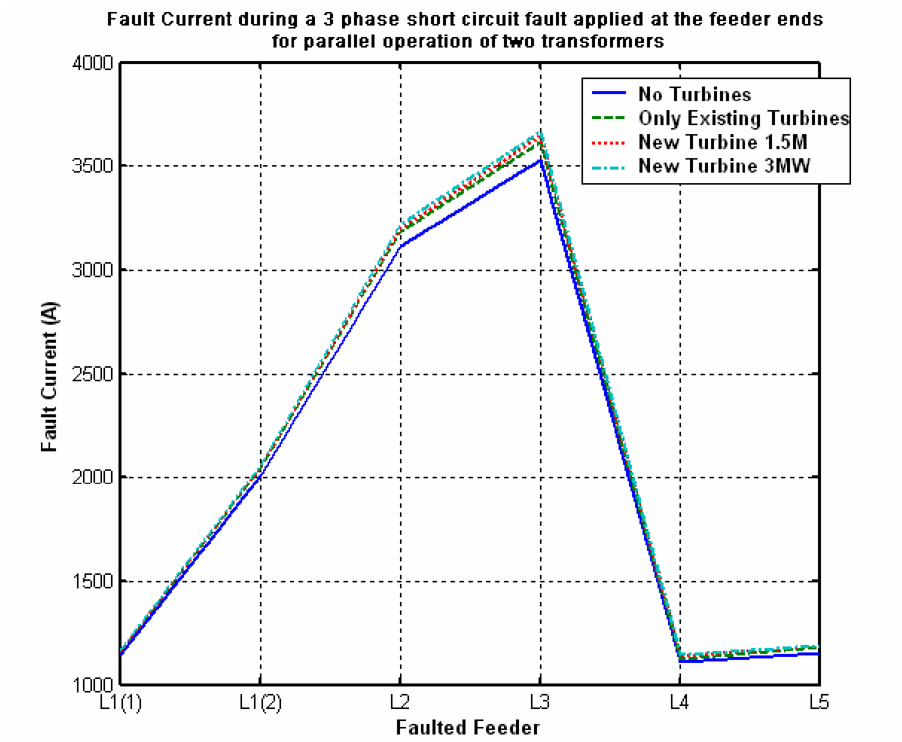


**Figure 4.22 Fault Current during a three phase short circuit fault applied at the feeder ends for parallel operation of two transformers**

A summary of all the four cases investigated for the parallel operation of two transformers is shown in the form of a plot of fault currents observed by applying a three phase short circuit fault at the end of all the feeders. This is shown in Figure (4.22)

## *4.5 Two Phase Short Circuit Faults*

### 4.5.1 Voltage dip Analysis

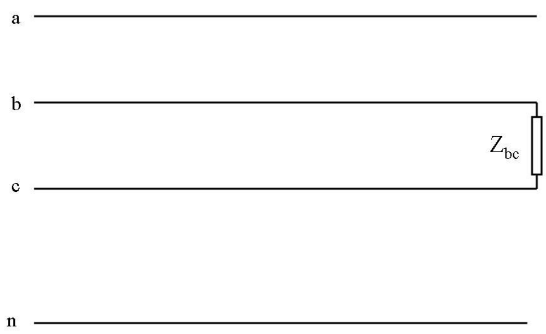


**Figure 4.23 A phase-phase fault between the phases b and c**

When a two-phase fault occurs between the two phases with the fault impedance as shown in Figure (4.23), the fault can be described in the phase domain through the following equations.

$$\left.\begin{array}{l} I_a = 0 \\ I_b + I_c = 0 \\ U_b - U_c = Z_{bc} * I_b \end{array}\right\} \qquad \text{Equation (1)}$$

Simplification of equation (1) results in the following equation

$$\left.\begin{array}{l} I_0 = 0 \\ I_1 + I_2 = 0 \\ U_1 - U_2 = Z_{bc} * I_1 \end{array}\right\} \qquad \text{Equation (2)}$$

From Equation (2) it can be concluded that [1]

1) From $I_0 = 0$ it can be said that the zero-sequence network forms an open network.
2) The positive sequence network and the negative sequence network are anti-parallel.
3) The positive sequence network, the negative sequence network and the fault impedance form a loop.

The fault current is limited by the impedance of positive sequence network impedance, the negative sequence network impedance and the fault impedance. The zero sequence impedance of the network does not affect the fault current when a two-phase fault occurs in the network [1]. It is assumed that the two-phase faults applied in the network have zero fault impedance.

In this case, a two-phase fault is applied at the end of the feeder to observe the voltage dip or the remaining voltage at busbar M3 and at the loads connected to the feeders. It is assumed that the feeder to which a fault is applied has full wind power generation and 10% load connected to it while the other feeders are assumed to have no wind power generation and a 100% load demand.

#### 4.5.1.1 One transformer in operation

All the three conditions that were considered for three phase fault analysis are investigated in this case.

1. Only Existing Turbines
2. New Turbine of 1.5MW
3. New Turbine of 3.0MW

When a two phase fault is applied at the end of each feeder, the remaining voltage at M3 and the industrial load during the fault are listed in Table (4.36). It is observed that the tap changer behaves in a similar way as was observed in the three phase short circuit analysis.

**(A) Fault at the end of feeder the L2**

When a two-phase fault is applied at end of the feeder L2, the voltage dip is less (more remaining voltage) compared to the voltage dip when a three-phase fault is applied at the same location. The remaining voltage at M3 during the fault is 0.725 p.u. The duration of the voltage dip depends on the tripping time of the circuit breaker. In this case, the fault current is 1240A, so the circuit breaker trips after 60ms. Therefore, the duration of the voltage dip is 0.06 sec referring to the Table (4.1).

When the fault occurs in the feeders L1 {both L1 (1) & L1 (2)}, L4, L4 with a new turbine of 1.5MW, L4 with a new turbine of 3.0MW and L5, the duration of the voltage dip in all these cases is one second because the fault current is less than 1200A. The circuit breaker tripping time is one second from Table (4.1).

The pre-fault voltage and the post-fault voltage for the cases that are presented in the Table (4.36) are similar to those observed in the three-phase fault analysis because the network topology has not changed.

| | Voltage at M3 during two phase fault | Voltage at Industrial load during two phase fault |
|---|---|---|
| Faulted feeder L1 (1) | 0.8861 | 0.8823 |
| Faulted feeder L1 (2) | 0.8015 | 0.7979 |

| | | |
|---|---|---|
| Faulted feeder L2 | 0.7244 | 0.7209 |
| Faulted feeder L5 | 0.8740 | 0.8703 |
| Faulted feeder L4 (existing system) | 0.9078 | 0.9041 |
| Faulted feeder L4 (New Turbine of 1.5MW) | 0.9099 | 0.9062 |
| Faulted feeder L4 (New Turbine of 3MW) | 0.9115 | 0.9078 |

**Table 4.36 Voltage at M3 and at the industrial load during two phase faults applied at the end of each feeder**

From Figure (4.24) it is observed that the voltage dip at M3 is severe when a two-phase fault is applied at the end of the feeder L2. It is observed that the voltage dip in the two-phase fault analysis is less (more remaining voltage) when compared to its counterpart in the three-phase fault analysis.

From Figure (4.25) it is observed that when a two-phase fault is applied at the end of the feeder L4 and the simulations are run for the existing system, a new turbine of 1.5MW and a new turbine of 3MW in the feeder L4, it is observed that the voltage dip with a new turbine of 3MW is the least i.e., the remaining voltage is more compared to the voltage dip for existing system and for the feeder L4 with a new turbine of 1.5MW. The voltage dip for the two-phase faults compared to the three-phase faults is less because the fault current is limited by the impedance of the positive sequence network, the negative sequence network and the fault impedance. The fault impedance is assumed to be zero in these investigations.

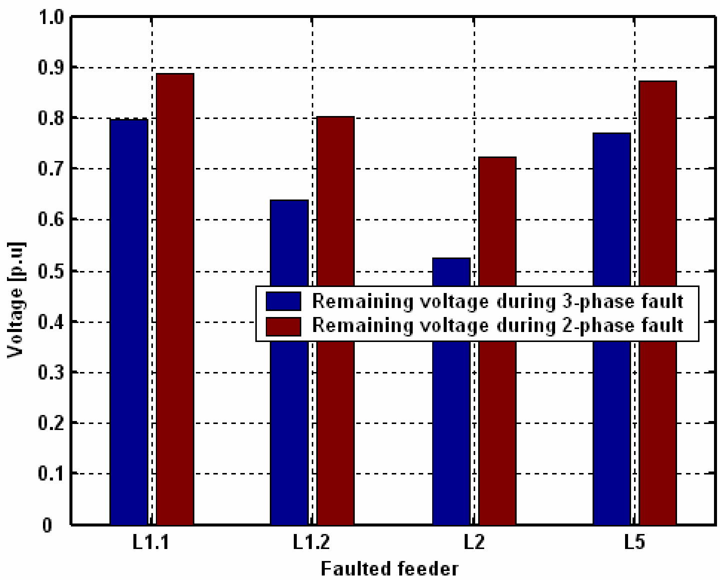


**Figure 4.24 Comparison of the remaining voltages at M3 during three phase fault and two phase fault conditions when the fault is at the end of each feeder**

In Figure (4.26) & Figure (4.27), the variations in the remaining voltage at the industrial load during three phase and two phase faults are observed.

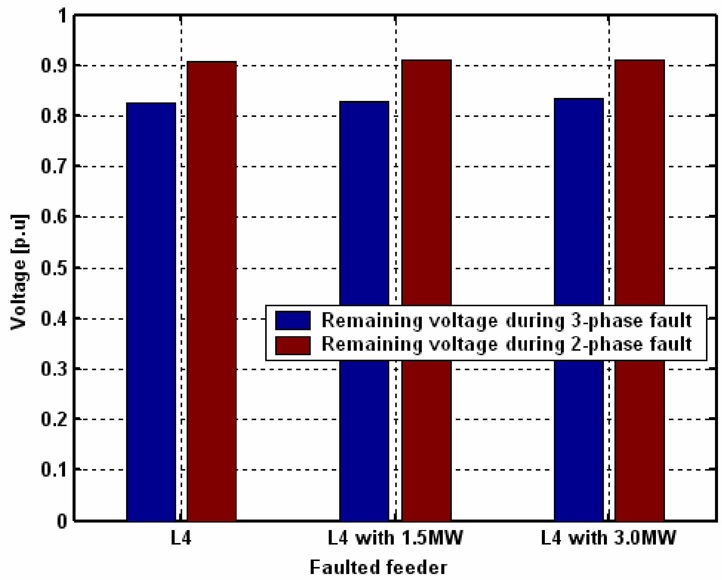


**Figure 4.25 Comparison of remaining voltages at M3 during 3-phase and 2-phase fault conditions when fault is at end of the feeder L4. Feeder L4 is considered with different denominations of wind power generation units**

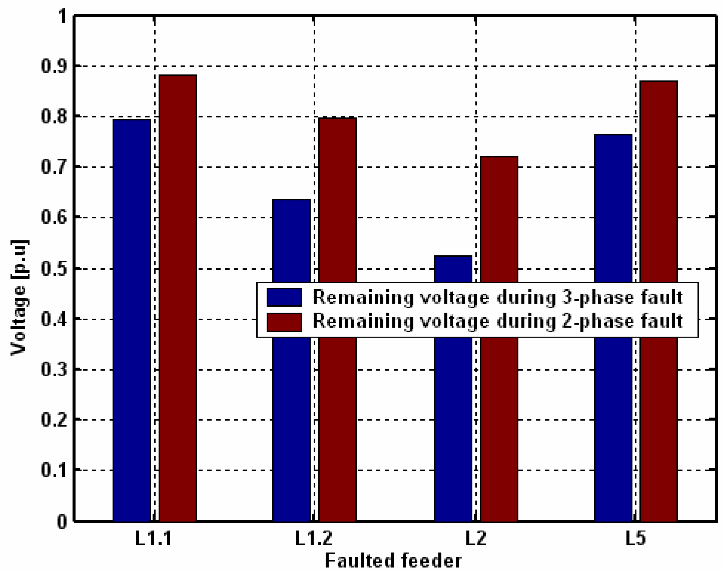


**Figure 4.26 Comparison of the remaining voltages at the industrial load during three-phase and two-phase fault conditions when the fault is at the end of each feeder**

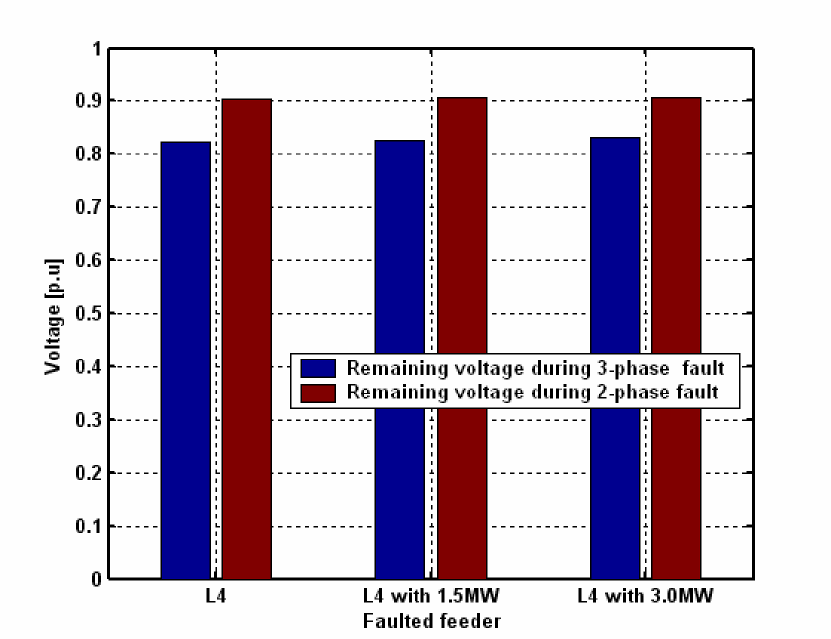


**Figure 4.27 Comparison of the remaining voltages at industrial load during three-phase and two-phase fault conditions when the fault is applied at the end of the feeder L4. Feeder L4 is considered with different denominations of wind power generation units**

## 4.5.1.2 Parallel operation of two transformers

It is observed in the simulations carried out that connecting a transformer in parallel with the existing transformer will increase the voltage level of the network. All the three cases that were investigated for one transformer in the two phase fault analysis will be discussed here for the parallel operation of two transformers.

| | Voltage at M3 during two phase fault | Voltage at Industrial load during two phase fault |
|---|---|---|
| Faulted feeder L1 (1) | 0.9256 | 0.9218 |
| Faulted feeder L1 (2) | 0.8627 | 0.8590 |
| Faulted feeder L2 | 0.8043 | 0.8007 |
| Faulted feeder L5 | 0.9156 | 0.9119 |
| Faulted feeder L4 (existing system) | 0.9314 | 0.9276 |
| Faulted feeder L4 (New Turbine of 1.5MW) | 0.9331 | 0.9293 |
| Faulted feeder L4 (New Turbine of 3MW) | 0.9334 | 0.9296 |

**Table 4.37 Voltage at M3 and at the industrial load for the parallel operation of two transformers during the two phase faults that are applied at the end of each feeder**

When a two phase fault is applied at the end of each feeder, the remaining voltage at the medium voltage busbar M3 and the industrial load during the fault are listed in Table (4.37). It is observed that the tap changer behaves in a similar way as was observed in the three phase short circuit analysis for parallel operation. The pre-fault voltage and the post-fault voltage for the cases that are presented in the Table (4.37) are similar to those observed in the three-phase fault analysis because the network topology has not changed.

**(A) Fault at the end of feeder the L2**

When a two-phase fault is applied at the end of the feeder L2, the voltage dip is less (more remaining voltage) compared to the voltage dip when a three-phase fault is applied at the same location for the parallel operation of transformers. The remaining voltage at medium voltage busbar M3 during the fault is 0.8043 p.u. The duration of the voltage dip depends on the tripping time of the circuit breaker. In this case, the fault current is 1555.62A, so the circuit breaker trips after 60ms. Therefore, the duration of the voltage dip is 0.06 sec referring to the Table (4.1).

When the fault occurs in the feeders L1 {both L1 (1) & L1 (2)}, L4, L4 with a new turbine of 1.5MW, L4 with a new turbine of 3.0MW and L5, the duration of the voltage dip in all these cases is one second because the fault current is less than 1200A. The circuit breaker tripping time is one second from Table (4.1).

## 4.5.2 Short Circuit Fault current Analysis

In this section, the fault currents caused by applying two phase short circuit faults to the feeders in the Lundsbrunn network are observed. At the same time, the current through the transformer along with the currents at the beginning of the feeders are observed to check if the relay settings need to be reconfigured. As was done in the three phase fault cases, the fault is applied at the end of the feeders. The turbines are assumed to inject a constant rated current in order to limit the fault current contribution from the turbines during the fault. The following four cases are investigated for one transformer operation and the parallel operation of two transformers.

### 4.5.2.1 One Transformer Operation

All the above cases are simulated assuming full generation from the existing and new turbines and a low demand from the loads to present the worst case condition.

4. No Turbines
5. Only Existing Turbines
6. New Turbine of 1.5MW

7. New Turbine of 3MW

All the fault currents for the four cases above are summarized and shown in Table (4.38).

| | Fault Current (A) | | | |
|---|---|---|---|---|
| Faulted Feeder | No Turbines | Existing Turbines | New Turbine of 1.5MW | New Turbine of 3MW |
| L1 (1) | 532.85 | 543.76 | 545.84 | 547.68 |
| L1 (2) | 866.75 | 886.99 | 891.5 | 895.83 |
| L2 | 1241.48 | 1284.71 | 1294.34 | 1303.57 |
| L3 | 1381.04 | 1423.58 | 1435.4 | 1446.98 |
| L4 | 520.07 | 530.86 | 536.39 | 541.77 |
| L5 | 530.12 | 544.71 | 546.46 | 547.97 |

**Table 4.38 Fault currents during a two phase-phase fault at the end of the feeders**

Table (4.38) shows the fault currents observed during a two phase fault applied at the end of the feeders. Phase B and phase C and shorted for these cases. As explained in the section for three phase short circuit fault analysis, the Lundsbrunn network is first investigated assuming that there is no wind generation in the network. It is then simulated for the existing turbines and then with a new turbine at Västermark injecting an active power of 1.5MW and 3MW respectively. Similar to the three phase faults, a two phase fault on feeder L3 presents the highest fault current and that on feeder L4 presents the least due to the differences in the fault impedances.

The faulted feeders are tripped in a time according to the current-time settings of the relays associated with those feeders. The current-time settings for the feeders are shown in Figure (4.10) and Figure (4.11). Currents through the faulted feeders are shown in Table (4.39). Time taken to trip the feeders is summarized in Table (4.39).

Table (4.40) shows the currents on the low voltage side of the transformer and the currents at the beginning of each faulted feeder observed by the relays at the substation during two phase faults applied at the end of the feeders. Since the wind turbines are modelled as constant current injecting loads, the currents through the remaining feeders when a fault is applied in one feeder will be the same irrespective of the type of the fault applied (three-phase or two-phase fault).

| | Time taken to trip the feeders (seconds) | | | |
|---|---|---|---|---|
| Faulted Feeder | No Turbines | Existing Turbines | New Turbine of 1.5MW | New Turbine of 3MW |
| L1 (1) | 1 | 1 | 1 | 1 |
| L1 (2) | 1 | 1 | 1 | 1 |
| L2 | 0.06 | 0.06 | 0.06 | 0.06 |
| L3 | 0.08 | 0.08 | 0.08 | 0.08 |
| L4 | 1 | 1 | 1 | 1 |
| L5 | 1 | 1 | 1 | 1 |

**Table 4.39 Time taken to trip the feeders when a two phase fault is applied at the end of the feeders**

| | Current on the low voltage side of the transformer (A) | | | |
|---|---|---|---|---|
| Faulted Feeder | No Turbines | Existing Turbines | New Turbine of 1.5MW | New Turbine of 3MW |
| L1 (1) | 541.86 | **367.95** | **344.93** | **339.74** |
| L1 (2) | 873.79 | 732.21 | 701.82 | 684.49 |
| L2 | 1256.18 | 1103.41 | 1070.86 | 1044.89 |
| L3 | 1388.91 | 1234.73 | 1201.36 | 1174.20 |
| L4 | 529.94 | **342.07** | **315.94** | **307.12** |
| L5 | 536.01 | **410.71** | **402.56** | **410.61** |
| | Current through the faulted feeder (A) | | | |
| L1 (1) | 532.42 | 509.36 | 511.5 | 513.39 |
| L1 (2) | 866.25 | 860.33 | 865.06 | 869.58 |
| L2 | 1249.75 | 1253.98 | 1263.86 | 1273.32 |
| L3 | 1384.27 | 1426.72 | 1438.55 | 1450.11 |
| L4 | 519.72 | 460.17 | 409.23 | 367.93 |
| L5 | 531.46 | 484.01 | 486.01 | 487.77 |

**Table 4.40 Currents on the low voltage side of the transformer and the currents observed by the relays of the faulted feeders during a two phase fault applied at the end of the feeders**

The current-time settings for the relay on the low voltage side of the transformer T1 is shown in Figure (4.12). It can be seen from Table (4.40) that for the cases of existing turbines, new turbine of 1.5MW and new turbine of 3MW, when the fault is applied at the end of the feeders L1 (1), L4, L5, the relay on the low voltage side of the transformer T1 does not detect the current because its first step is configured for a current threshold of 600A. Therefore, for these cases, if the primary protection for the feeders at the substation fails, the backup protection does not activate since the relays on the low voltage side of the transformer will not detect the current as it is less than 600A. Hence, a reconfiguration of the current-time settings for this relay may be suggested as shown in Figure (4.28).

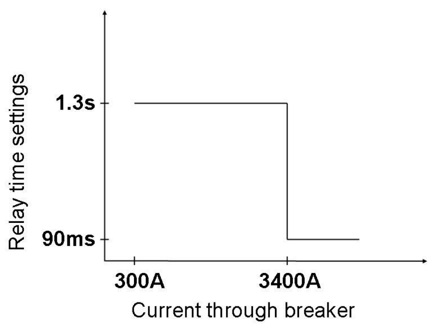


**Figure 4.28 Suggested current-time settings of the relay on the low voltage side of the transformers T1**

#### 4.5.2.2 Parallel operation of two transformers

The Lundsbrunn network is operated by placing two transformers in parallel at the substation and then investigated for two phase faults applied to the feeders. In this section, the fault currents pertaining to the two phase faults are observed along with the current through the transformers and the protection settings for all the four cases mentioned in the previous section.

| | Fault Current (A) | | | |
|---|---|---|---|---|
| Faulted Feeder | No Turbines | Existing Turbines | New Turbine of 1.5MW | New Turbine of 3MW |
| L1 (1) | 577.21 | 584.34 | 585.37 | 586.41 |
| L1 (2) | 1007.63 | 1022.35 | 1024.98 | 1027.47 |
| L2 | 1560.62 | 1586.21 | 1592.95 | 1599.40 |
| L3 | 1769.71 | 1801.31 | 1810.23 | 1818.76 |
| L4 | 560.36 | 566.99 | 571.65 | 576.15 |
| L5 | 581.11 | 593.58 | 594.54 | 595.32 |

**Table 4.41 Fault currents during a two phase fault at the end of the feeders when operating two transformers in parallel**

Table (4.41) shows the fault currents when a two phase-phase fault is applied at the end of the feeders. An increase in the fault currents for all the four cases as compared to the operation with a single transformer can be observed because the net impedance of the parallel transformers is less than that of the single transformer T1.

Table (4.42) shows the currents observed by the relay on the low voltage side of the transformers T1 and T2 when a two phase fault is applied at the end of the feeders. Since the threshold current value of these transformers is 600A, for all the cases where the current on the low voltage side of the transformer is less than 600A, this overcurrent is not detected by the relay and hence the backup protection for the transformer in case the primary protection for the feeder fails may not be achieved. To achieve this, the current-time settings for these relays may be reconfigured to a value less than the least in Table (4.42). These suggested new settings are shown in Figure (4.29).

| | Current on the low voltage side of the transformer T1 (A) | | | |
|---|---|---|---|---|
| Faulted Feeder | No Turbines | Existing Turbines | New Turbine of 1.5MW | New Turbine of 3MW |
| L1 (1) | 273.61 | 190.32 | 176.43 | 169.57 |
| L1 (2) | 467.19 | 389.83 | 372.32 | 358.18 |
| L2 | 714.68 | 627.02 | 605.01 | 584.95 |
| L3 | 808.92 | 718.57 | 695.67 | 674.41 |
| L4 | 265.91 | 176.84 | 161.76 | 153.24 |
| L5 | 275.54 | 213.10 | 205.43 | 204.26 |
| | Current on the low voltage side of the transformer T2 (A) | | | |

| | | | | |
|---|---|---|---|---|
| L1 (1) | 313.77 | 203.41 | 184.14 | 174.47 |
| L1 (2) | 548.65 | 449.84 | 427.22 | 408.82 |
| L2 | 854.16 | 744.42 | 716.75 | 691.38 |
| L3 | 970.62 | 858.06 | 829.33 | 802.68 |
| L4 | 305.57 | 187.73 | 166.78 | 154.53 |
| L5 | 312.33 | 229.10 | 218.67 | 217.16 |

**Table 4.42 Current on the low voltage side of the transformers T1 and T2 during two phase fault at the end of the feeders**

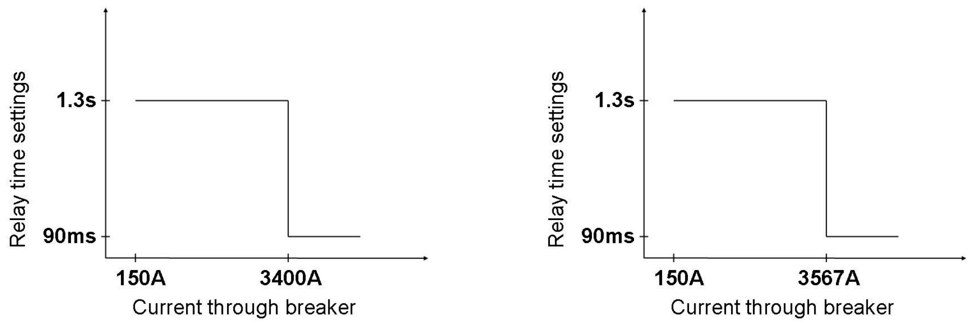


**Figure 4.29 Suggested current-time settings for the relays on the low voltage side of the transformers T1 (left) and T2 (right) when they are operated in parallel during a two phase fault applied at the end of the feeders**

Table (4.43) shows the currents through the faulted feeders observed at the substation during a two phase fault applied at the ends of the feeders while the transformers are operated in parallel. The breakers trip according to the current-time settings of the relays associated with each feeder; the current is as shown in Table (4.43) and the time to trip is as shown in Table (4.39). Since the wind turbines are modelled as constant current injecting loads, the currents through the remaining feeders with wind turbines when a fault is applied in any feeder will be the same irrespective of the type of the fault applied (three-phase or two-phase fault).

| | Current through the faulted feeder (A) | | | |
|---|---|---|---|---|
| Faulted Feeder | No Turbines | Existing Turbines | New Turbine of 1.5MW | New Turbine of 3MW |
| L1 (1) | 576.92 | 548.51 | 549.58 | 550.65 |
| L1 (2) | 1007.45 | 1184.19 | 994.82 | 997.41 |
| L2 | 1561.22 | 1550.82 | 1557.69 | 1564.17 |
| L3 | 1773.16 | 1804.71 | 1813.58 | 1822.21 |
| L4 | 560.20 | 493.56 | 437.65 | 389.69 |
| L5 | 583.52 | 527.73 | 528.79 | 529.69 |

**Table 4.43 Currents through the faulted feeders during a two phase fault applied at the end of the feeders for the parallel operation of two transformers**

## *4.6 Single Phase Short Circuit Faults*

The single phase-to-ground faults are the most common faults in the distribution networks [8]. In this section, single phase-to-ground faults are investigated to have an overview of the existing earth protection system. New turbines are then introduced and the network is again analyzed to check if the protection system for the earth faults needs to be reconfigured. Resonant grounding method (also called arc suppression coil or Petersen coil) is employed to compensate the single phase-to-ground faults. The theoretical background for the resonant grounding system is provided in section (3.5). The steps carried out in investigating the single phase-to-ground faults using the Petersen coil are described along with the observed results. A typical resonant grounding system used for compensating single phase-to-ground faults is shown in Figure (4.30).

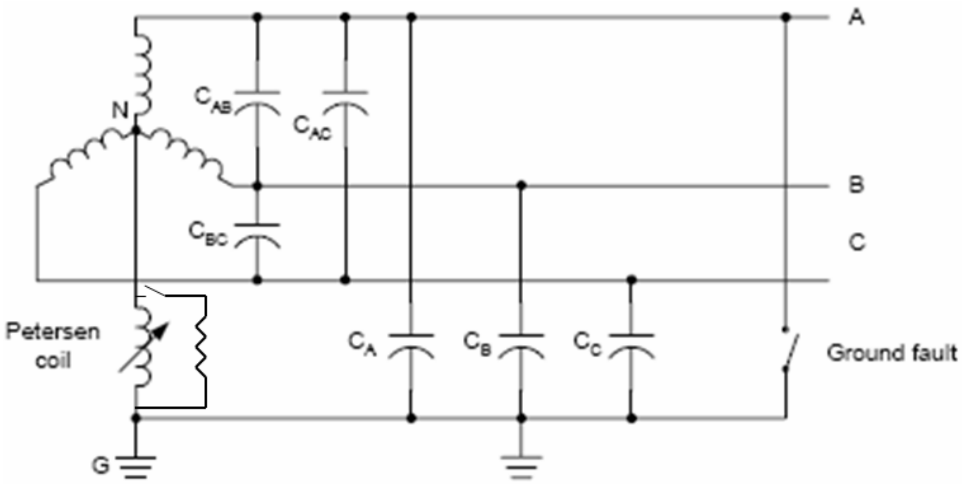


**Figure 4.30 Resonant grounding system for compensating single phase-to-ground faults in distribution networks**

The following are the steps carried out to investigate the single phase-to-ground faults.

1) It is assumed that the neutral point-to-ground voltage of the transformer during the single phase-to-ground fault is always equal to the phase-to-neutral voltage during the simulations i.e., the affects of the harmonics and the transients during the fault on the neutral point voltage are neglected. It is also assumed that the parallel resistor is always connected to the coil.
2) The transformers through which the turbines are connected to the grid are of the type delta-wye grounded with delta on the grid side, the ratings of which are provided in Table (4.44). The turbines, therefore, do not contribute towards the earth fault. Since the fault current in a single phase-to-ground fault is the total earth capacitive current of the network [10], the total per phase capacitive ground current of the network is calculated ($I_c$). It is to be noted that in the calculations,
3) The purpose of the Petersen coil is to compensate this earth capacitive current with a reactor that is connected between the transformer neutral point and the ground by forming a resonance between the capacitive reactance and the inductive reactance [8]. This leads to the condition that the current through this coil ($I_L$) should equal the total earth capacitive current of the network ($I_c$).

4) Now that we know the current through the reactor from the above condition, the value of this reactor is obtained. This reactor is placed between the transformer neutral point and the ground and it is observed that the earth capacitive current is compensated after running the simulations.
5) In well tuned compensation systems, the fault current is usually so small that they cause the self extinction of the faults for most of the cases (less than 40A) [8]. Thus, in a well tuned system, the fault current is so little that selective tripping of the faulted feeder is not possible. A resistor is placed in parallel to the Petersen coil and a "zero point voltage measuring" protection system is employed so that the substation will be tripped after a preset time if none of the line protections are able to detect the faulted line. The data provided in this thesis specifies a zero point protection threshold of 15% of the nominal voltage for a time of 10 seconds.
6) The active part of the zero sequence current in the faulted feeder is the residual current due to the single phase-to-ground fault. This zero sequence current and the zero sequence voltage are used by the earth fault directional overcurrent relay to decide whether the fault is a forward or a reverse fault. This helps in selectively tripping only the faulted feeder because due to the single phase-to-ground fault, the capacitive current also flows in the remaining feeders in a direction towards the medium voltage busbar at the substation.

| Turbine Rating | T/F Rating | Reactance (X) | T/F $1^0$ Voltage | T/F $2^0$ Voltage |
|---|---|---|---|---|
| 150 kVA | 150 kVA | 6% | 690V | 10.7 KV |
| 800 kVA | 150 kVA | 6% | 690V | 10.7 KV |
| 850 kVA | 150 kVA | 6% | 690V | 10.7 KV |
| 1.5 MVA | 1.6 MVA | 6% | 690V | 10.7 KV |
| 3 MVA | 3 MVA | 6% | 690V | 10.7 KV |

**Table 4.44 Ratings of the step-up transformer that connects the turbines to the grid**

| Network Topology | Faulted Feeder | Total earth capacitive Current (A) | Residual Current (A) | Zero-point Voltage (V) |
|---|---|---|---|---|
| Existing | Any | 28.03 | 3.12 | 1982.89 |
| 1.5MW | Any | 28.23 | 3.12 | 1982.89 |
| 3MW | Any | 28.23 | 3.12 | 1982.89 |

**Table 4.45 The residual currents and the zero-point voltages during a single phase-to-ground fault applied at the end of the feeders for a coil current obtained by compensating the total earth capacitive current of the network**

Table (4.44) shows the coil current during a single phase-to-ground fault applied at the end of all the feeders. It is seen that the residual current, which is the active part of the zero-sequence current, is the same irrespective of the faulted feeder. The coil current has increased when a new turbine is installed in the network since the earth capacitive current has also increased with the new line connecting the turbine to the grid. The zero-point voltage protection setting for the Lundsbrunn network is specified as 15% of nominal voltage which is 6350*0.15 = 952.5V. If the voltage across the resistor placed parallel to the Petersen coil exceeds this voltage, then the zero-point protection system will trip the substation in case none of the relays trip the faulted feeder. The value of this resistor is given as 635Ω. Only the residual current, which is the active current, will flow through this resistor. As shown in Table (4.45), the zero-point voltages for all the cases are around 1982V (3.12*635 = 1982.89V) which is greater than the threshold value. Therefore, it is seen that the backup protection for the transformer is active.

As far as the earth fault directional overcurrent relay for the feeders are concerned, they use the zero-sequence voltage and zero-sequence current observed at the beginning of the feeder as the input quantities to trip the feeder. The decision element measures the phase angle between the zero-sequence voltage and the zero-sequence current and if it lies between +/- 90 degrees then the power flow is in the forward direction and the protection settings related to a forward fault are applied. If the phase angle is outside this area then the power flow is in the reverse direction and the protection settings related to the backward fault are applied.

## *4.7 Turbines added via dedicated line*

The dedicated feeder is connected to the busbar M3. It was found that a total wind power of 6MW can be connected to this feeder (Reference "*Integration of Wind Energy Converters into an Existing Distribution Grid*"). When operated with a single transformer, it becomes fully loaded at about 3MW. Therefore, in order to add more wind power into the network, parallel operation of the transformers is necessary.

A wind turbine of 2MW capacity is connected at a distance of 2km from the busbar M3 and two turbines of 2MW capacity each are connected at a distance of 5km from the medium voltage busbar M3. All the three turbines are connected on the same feeder which is 5km long.

### 4.7.1 Voltage sag analysis

**Assumptions**

1) The new line connected to busbar M3 is a cable of the model AXCEL240 and its rating is 7.3 MVA.
2) The network is assumed as 100% loaded. A 100% power generation is assumed from the new turbine at Västermark and a100% power generation from the turbines in the dedicated line and no wind power generation from the remaining turbines in the network is assumed.

**Analysis procedure**

1) Symmetrical and unsymmetrical faults are applied at two locations in the new line. The first location is at a distance of 2km from busbar M3 and the second is at a distance of 5km from busbar M3.
2) Simulations are carried out for two different cases of wind power generations from the new turbine at Västermark (1.5MW and 3MW).

From Table (4.46), it is observed that the pre-fault voltage at busbar M3 is the same when the new line is added to the busbar M3 and the new turbine at Västermark is simulated for two different cases of power generation. The post-fault voltage will differ because it depends on the amount of wind power generation disconnected from the network after the fault. The tap changer of both the transformers does not change during the simulation for both the cases i.e., the new turbine at Västermark injecting 1.5MW and 3MW.

| | 3.0MW at the Västermark | | 1.5 MW at the Västermark | |
|---|---|---|---|---|
| | Pre-fault voltage | Post-fault voltage | Pre-fault voltage | Post-fault voltage |
| M3 | 0.994 | 0.987 | 0.994 | 0.986 |
| Industrial load | 0.990 | 0.983 | 0.990 | 0.982 |

**Table 4.46 Pre-fault voltage and post-fault voltage at M3 and industrial load when symmetrical and unsymmetrical faults are applied at two different positions in the new line**

The voltage dip depends on the impedance of the line. When the fault is applied at a distance of 5km from the busbar M3 the voltage dip is less (more remaining voltage) than that when the fault is at a distance of 2km from the busbar M3 as shown Table (4.47).

The voltage dip is almost the same when the new turbine at the Västermark is assumed to generate 3.0MW of power. The voltage dip depends on the tripping time of the circuit breaker.

| 1.5MW at västermark | 3-phase fault | | 2-phase fault | |
|---|---|---|---|---|
| | 2km from busbar M3 | 5km from busbar M3 | 2km from busbar M3 | 5km from busbar M3 |
| Voltage dip at M3 | 0.333 | 0.463 | 0.639 | 0.707 |
| Voltage dip at industrial load | 0.329 | 0.459 | 0.635 | 0.703 |

**Table 4.47 Voltage dip at M3 and at the industrial load when a three-phase fault and a two-phase fault are applied at two different positions in the new line assuming a generation of 1.5MW at Västermark**

## 4.7.2 Overcurrent protection settings

The network is simulated for three-phase and two-phase faults after adding a new line to the medium voltage busbar M3. The power injection from the new turbine at Västermark is taken to be 3MW. Table (4.48) shows the fault currents when three-phase and two-phase faults are applied at the end of the feeders.

| | Three-phase fault | Two-phase fault |
|---|---|---|

| Faulted Feeder | Fault Current (A) | Current through faulted feeder (A) | Fault Current (A) | Current through faulted feeder (A) |
|---|---|---|---|---|
| L1 (1) | 1175.35 | 1137.46 | 590.01 | 554.3 |
| L1 (2) | 2082.42 | 2057.98 | 1037.65 | 1007.94 |
| L2 | 3291.64 | 3249.47 | 1626.53 | 1591.63 |
| L3 | 3764.18 | 3767.25 | 1855.17 | 1858.63 |
| L4 | 1158.76 | 943.07 | 579.87 | 393.51 |
| L5 | 1197.87 | 1123.52 | 598.13 | 532.79 |

**Table 4.48 Fault currents and the currents through the faulted feeders when three-phase and two-phase faults are applied at the end of the feeders after adding a new line to the Lundsbrunn network**

As shown in Table (4.48), it is observed that there is no substantial increase in the fault currents with and without the new line in Lundsbrunn network. A very high fault current of around 4700A is observed when a three-phase fault is applied at the turbine which is at a distance of 2km from M3 on the new line and around 3981A when the fault is applied at the turbine which is at a distance of 5km from M3 on the same new line. During normal operation, the current through the feeder L4 is around 243A assuming that the turbines inject a constant current equal to their rated full current. The relay settings of feeder L4 could be configured to the settings as shown in Figure (4.15).

Observing the currents on the low voltage side of the transformers T1 and T2 during three-phase and two-phase faults, it can be seen that the for some cases the relays located on the low voltage side of both these transformers do not detect the fault current as the threshold is not exceeded. The current-time settings of these relays are shown in Figure (4.12) and Figure (4.17). These could be reconfigured so that the relay detects the fault current even for the least severe case.

| | Three-phase fault | | Two-phase fault | |
|---|---|---|---|---|
| Faulted Feeder | T1 | T2 | T1 | T2 |
| L1 (1) | 308.35 | 347.24 | 205.93 | 226.52 |
| L1 (2) | 696.72 | 828.47 | 329.38 | 371.29 |
| L2 | 1175.36 | 1421.94 | 515.53 | 603.27 |
| L3 | 1372.96 | 1666.51 | 597.11 | 705.2 |
| L4 | 278.59 | 311.67 | 188.62 | 206.06 |
| L5 | 370.38 | 1657.07 | 251.08 | 281.82 |

**Table 4.49 Currents on the low voltage side of the transformers T1 and T2 when three-phase and two-phase faults are applied at the end of the feeders in Lundsbrunn network**

From Table (4.49), for the transformer T1, the least fault current can be seen when a two-phase fault is applied at the end of the feeder L4 (around 188.62A) and that for the transformer T2 it is around 206A. The new current-relay settings can be configured as shown in Figure (4.31).

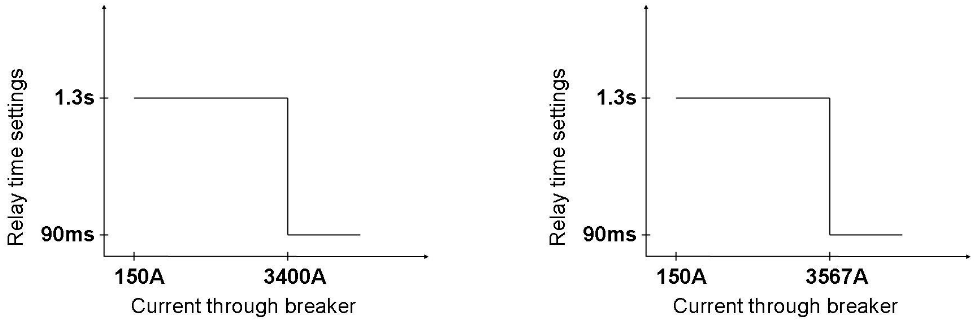


**Figure 4.31. Suggested current-time settings for the relays on the low voltage side of the transformers T1 (left) and T2 (right) when a new feeder is added to the existing network at Lundsbrunn and a wind power of 6MW is fed into the grid**

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# Chapter 5

# Analysis of Hällekis Network

## *5.1 Brief Description of the Network*

The Hällekis network has two transformers which are connected to the same high voltage busbar (HKS) shown in Figure (5.1).The two transformers have different MVA ratings; the transformer T3 is rated for 13MVA and the transformer T4 is rated for10MVA as shown in Figure (5.1). The short circuit power of the grid to which the Hällekis network is connected is 279MVA. The supply voltage source of 42kV and the short circuit impedance R=0.9Ω and X = 6.3Ω represents the Thevenin's equivalent of the grid at the point of connection.

Both the transformers are in operation and feed two different medium voltage busbars A10 and B10. The transformer T3 is connected to busbar A10 and the transformer T4 is connected to B10. The nominal voltages at high voltage side and low voltage side of both transformers are 42KV and 10.7KV respectively. The busbars A10 and B10 are connected through a circuit breaker which is not connected during the normal operation of the network and is connected during maintenance in the network. The layout of the Hällekis network is shown in Figure (5.1).

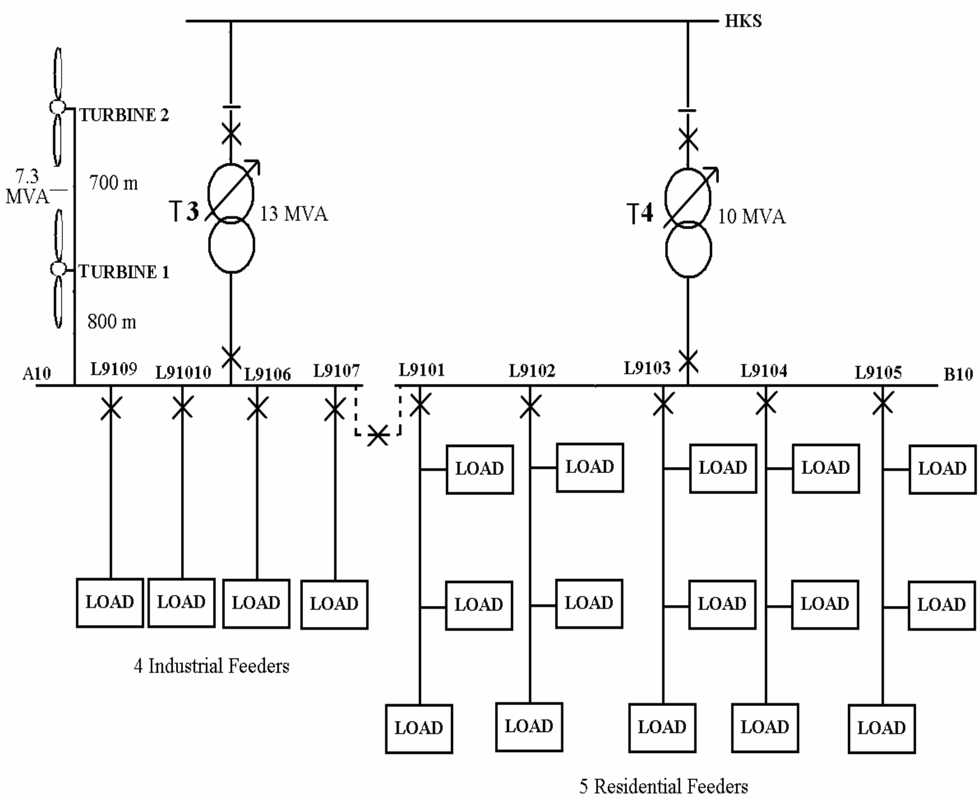


**Figure 5.1 Layout of the Hällekis distribution network.**

The Hällekis network is assumed to be a radial network. The circuit breakers are connected at the beginning of each feeder on the 10.7KV side of transformers. The relays in the network are constant time over current relays. The earth fault relays are directional over current relays and trips for earth faults on the outgoing line which means that they also need the zero sequence voltage to trip

Four feeders are connected to the busbar A10 and feed the industrial loads. The feeders connected to A10 are L9109, L91010, L9106 and L9107. Five feeders are connected to the busbar B10 and feed the residential loads. Residential loads are distributed along each feeder in the network. The feeders connected to B10 are L9101, L9102, L9103, L9104 and L9105. The load is calculated from the current measured at the beginning of the feeder at the substation. For the existing Hällekis network, there is no wind power generation. Two new turbines are going to be installed on a feeder connected to the busbar A10.

## *5.2 Objectives*

The main objectives of this study is to observe

4. The variations in the voltage level at different locations by disconnecting certain amount of power produced by the wind turbines due to symmetrical and unsymmetrical faults in the network.
5. The variation in the voltage level at different locations after symmetrical and unsymmetrical faults are cleared in the network with different load combinations.
6. How the line and transformer protection systems are affected because of over currents in the feeders due to symmetrical and unsymmetrical faults.

## *5.3 Network Modelling and Assumptions*

The assumptions considered for modelling the Hällekis network are same as those considered for Lundsbrunn network. These assumptions can be found in section (4.3).

Since the entire wind turbine power is integrated in one feeder, investigation of the following two cases of different combinations of load and wind generation would suffice the analysis.

1. High Generation and Low Load
2. High Generation and High Load

Here, the generation refers to the power infeed from the new turbines to be installed in the network. Since the new turbines are connected by a feeder dedicated only to these turbines, the maximum power injection from these turbines is determined by continuously injecting power from these turbines until the thermal limit of the cable connecting the turbines to the grid is hit which is 7.3MVA. It was found that a maximum of 3.6MW can be injected from each turbine. Therefore, a total active power of 7.2MW can be injected from the turbines into the grid without exceeding the thermal limit of the cable connecting these turbines to the grid. High generation implies full power injection by the wind turbines into the grid and low load implies 10% of the full load.

Short circuit fault analysis is carried out by applying the following three types of faults in the network.

1. Three phase short circuit fault
2. Two phase fault
3. Single phase-to-ground fault

## *5.4 Three Phase Short Circuit Faults*

### 5.4.1 Voltage Dip Analysis

The methodology followed for the voltage dip analysis is as mentioned in section (4.4.1.1.) of Lundsbrunn analysis.

To observe the variations in the voltage level caused by the disconnection of certain amount of power produced by the wind turbines due to symmetrical and unsymmetrical faults and to observe the variations in the post-fault voltage for different load operation conditions (combination of different mixes of loads and wind power), the Hällekis network is modelled for the following combinations of wind generation and load.

1. High Generation and Low Load
2. High Generation and High Load

High generation implies full power injection from the wind turbines into the grid and low load implies 10% of the full load.

#### 5.4.1.1 High Generation and Low Load

In this case, a three-phase short circuit fault is applied at the bus where the new turbine is going to be installed. Since there are two new turbines that are going to be installed in the new feeder, two instances of fault applications (one at each new turbine) are studied. Assuming a high power injection from the new turbines which was found to be 7.6MW connected to the existing system and a low load, the voltages observed at the other loads connected to the same medium voltage bus A10 are shown in Table (5.1)

| Buses | A10 | Paroc-1 | Paroc-2 | Svensk-Fo-1 | Svensk-Fo-2 |
|---|---|---|---|---|---|
| Voltage (p.u) | 0.9914 | 0.9912 | 0.9912 | 0.9914 | 0.9913 |

**Table 5.1Voltages at busbar A10 and at the industrial loads connected to this busbar**

Table (5.2) shows the voltages on the medium voltage busbar B10 along with the voltages at the load buses connected to this busbar.

| Buses | B10 | L9101 | L9102 | L9103 | L9104 | L9105 |
|---|---|---|---|---|---|---|
| Voltage(p.u) | 0.9912 | 0.9886 | 0.9889 | 0.9894 | 0.9907 | 0.9909 |

**Table 5.2 Voltages at busbar B10 and at the residential loads connected to this busbar**

When a three-phase short circuit fault is applied at the bus which is at a distance of 800m from the substation busbar A10 (where the first turbine is going to be installed), the remaining voltage at busbar A10 and on the industrial loads is around 0.09 p.u. The fault current due to this fault is above 4000A as mentioned in the section (5.4.2). Referring to section (5.4.2.1.2), for the new feeder, the relay settings existing for the feeder connecting the industry Svenska Foder AB can be used to configure its relay settings. Since the duration of the voltage dip depends on the tripping time of the circuit breaker, the duration of the dip in this case is 0.1 sec as shown in Figure (5.2).

The voltage level on the high voltage busbar HKS is reduced to 0.697 p.u during the fault. This voltage level influences the busbar B10 and the loads connected to it. The voltages at residential loads which are located at the end of each feeder along with the voltage on busbar B10 are shown in Table (5.3).

| Buses | B10 | L9101 | L9102 | L9103 | L9104 | L9105 |
|---|---|---|---|---|---|---|
| Voltage(p.u) During fault | 0.6907 | 0.6889 | 0.6891 | 0.6894 | 0.6904 | 0.6904 |
| Post fault | 0.9906 | 0.988 | 0.9884 | 0.9888 | 0.9902 | 0.9903 |

**Table 5.3 During fault and post fault voltages at busbar B10 and at the residential loads when the fault is applied at a distance of 800m from the busbar B10**

Now, the faulted feeder is removed from the network, that is, the wind power generation in the network is zero. The voltages at the Industrial loads which are at the end of each feeder connected to the busbar A10 after the fault is cleared are as shown in Table (5.4).

| Buses | A10 | Paroc-1 | Paroc-2 | Svensk-Fo-1 | Svensk-Fo-2 |
|---|---|---|---|---|---|
| Voltage (p.u) | 0.9887 | 0.9885 | 0.9885 | 0.9886 | 0.9885 |

**Table 5.4 Voltages at busbar A10 and the industrial loads for post fault condition, when the fault is applied at a distance of 800m from the busbar**

When a three-phase short circuit fault is applied on the bus where the second turbine is going to be installed (1500m from the medium voltage busbar A10), the remaining voltage at busbar A10 and on the industrial loads connected to it is around 0.16 p.u which is more than the remaining voltage at busbar A10 and the industrial loads when the fault is applied 800m from A10. The voltages at the residential loads which are at the end of the feeders connected to busbar B10 are as shown in Table (5.5). The voltage level at bus (HKS) which is the high voltage side of the transformers is reduced to 0.715 p.u during the fault.

| Buses | B10 | L9101 | L9102 | L9103 | L9104 | L9105 |
|---|---|---|---|---|---|---|
| Voltage(p.u) | 0.7086 | 0.7067 | 0.707 | 0.7073 | 0.7083 | 0.7084 |

**Table 5.5 Voltages at busbar B10 and at the residential loads connected to it during a three phase short circuit fault when the fault is applied at a distance of 1500m from the busbar A10**

### 5.4.1.2 High Generation and High Load

Three-phase short circuit faults are applied at the buses to which the two new turbines are connected in the new feeder assuming full generation from the new turbines and a high load demand. When a wind power of 7.6MW is connected to existing network of Hällekis with a high load demand, the voltage on the medium voltage busbar A10 and at the loads connected to it is as shown in Table (5.6). In this case the on load tap changers for both the transformers are in step up mode i.e., they increase the voltage on the medium voltage buses A10 and B10 by 1.6% of the nominal voltage.

| Buses | A10 | Paroc-1 | Paroc-2 | Svensk-Fo-1 | Svensk-Fo-2 |
|---|---|---|---|---|---|
| Voltage (p.u) | 0.9822 | 0.9795 | 0.9794 | 0.9815 | 0.9804 |

**Table 5.6 Voltages at busbar A10 and at the industrial loads connected to it**

Voltage on the medium voltage busbar B10 and at the loads connected to it is shown in Table (5.7).

| Buses | B10 | L9101 | L9102 | L9103 | L9104 | L9105 |
|---|---|---|---|---|---|---|
| Voltage(p.u) | 0.9909 | 0.9632 | 0.9646 | 0.9724 | 0.9857 | 0.987 |

**Table 5.7 Voltages at busbar B10 and at the residential loads connected to it**

When a three-phase short circuit fault is applied at the bus which is at a distance of 800m from the substation busbar A10 (where the first turbine is going to be installed), the remaining voltage at busbar A10 and at the industrial loads is around 0.087 p.u. Since the duration of voltage dip depends on tripping time of the circuit breaker, the duration of dip in this case is 0.1 sec assuming that the relay settings for this new feeder are configured to those for the industrial feeder Svenska Foder AB.

The voltage level on the high voltage busbar HKS is reduced to 0.698 p.u during the fault. This voltage level influences the busbar B10 and the loads connected to it. The voltages on the residential loads which are at the end of each feeder along with the voltage on busbar B10 are shown in Table (5.8).

| Buses | B10 | L9101 | L9102 | L9103 | L9104 | L9105 |
|---|---|---|---|---|---|---|
| Voltage(p.u) During fault | 0.6919 | 0.6726 | 0.6735 | 0.679 | 0.6883 | 0.6892 |
| Post fault | 0.9875 | 0.960 | 0.9613 | 0.9691 | 0.9824 | 0.9837 |

**Table 5.8 During fault and post fault voltages at busbar B10 and at the residential loads when the fault is applied at a distance of 800 m from the busbar A10**

Now, the faulted feeder is removed from the network, that is, the wind power generation in the network is zero. The voltages on the industrial loads which are at the end of each feeder connected to the busbar A10 after the fault are as shown in Table (5.9).

| Buses | A10 | Paroc-1 | Paroc-2 | Svensk-Fo-1 | Svensk-Fo-2 |
|---|---|---|---|---|---|
| Voltage (p.u) | 0.9743 | 0.9716 | 0.9715 | 0.9736 | 0.9725 |

**Table 5.9 Voltages at busbar A10 and at the industrial loads for post fault condition, when the fault is at a distance of 800m from the busbar A10**

When a three phase short circuit fault is applied at the bus where the second turbine is going to be installed (1500m from the medium voltage busbar A10), the remaining voltage at busbar A10 and at the industrial loads connected to it is around 0.153 p.u which is more than the remaining voltage at busbar A10 and at the industrial loads when the fault is at a distance of 800m from busbar A10. The voltages at the residential loads which are at the end of the feeders connected to busbar B10 are as shown in Table (5.10). The voltage level at bus (HKS) which is the high voltage side of the transformers is reduced to 0.714 p.u during the fault.

| Buses | B10 | L9101 | L9102 | L9103 | L9104 | L9105 |
|---|---|---|---|---|---|---|
| Voltage(p.u) | 0.7081 | 0.6884 | 0.6893 | 0.6949 | 0.7044 | 0.7054 |

**Table 5.10 Voltages at busbar B10 and at the residential loads during the fault condition, when the fault is at a distance of 1500m from the busbar A10**

## 5.4.2 Short circuit fault current analysis

In this section, the Hällekis network is investigated for fault currents by applying three-phase short circuit faults at the end of the feeders. Currents through the feeders are also observed to check if the current overcurrent protection system should be reconfigured.

### 5.4.2.1 High Generation and Low Load

### 5.4.2.1.1 Fault Currents

In this case, the Hällekis network is simulated for short circuit faults by assuming that the new turbines inject full power into the grid while the load requirement is low. The following are the fault currents observed along with the currents on the high voltage side of the transformers T3 and T4.

Table (5.11) shows the fault currents and the current through the high voltage side of the transformers T3 and T4 in the Hällekis network during a three phase short circuit fault on the feeders. The faults are simulated at the end of feeders. It can be seen that if a three-phase fault occurs on the feeders connected to the transformer T3, that is, at the industrial feeders, a very high fault current flows through the transformer to the fault location. This is because all these feeders are dedicated entirely to the industries with the impedance from the substation to the industries being very small compared to the other residential loads connected to the transformer T4 since the industries are very near to the transformer substation.

| Faulted Feeder | Fault Current (A) | I (T3) | I (T4) |
|---|---|---|---|
| 9105 Hönsätersvägen | 3074.29 | 88.61 | 778.73 |
| 9103 Österäng | 1049.95 | 89.91 | 268.23 |
| 9104 Stenbacksvägen | 2708.46 | 89.88 | 693.41 |
| 9102 Kestad | 835.38 | 90.04 | 214.39 |
| 9101 Blomberg | 873.29 | 89.98 | 223.48 |
| 9106 PAROC | 4680.45 | 1149.44 | 3.4 |
| 9107 PAROC | 4680.84 | 1149.42 | 3.4 |
| 9109 Svenska Foder AB | 4832.97 | 1192.1 | 3.34 |
| 91010 Svenska Foder AB | 4837.18 | 1192.06 | 3.34 |

**Table 5.11 Fault currents and currents at the high voltage side of the transformers T3 and T4 during a three phase short circuit fault applied at the feeder ends. I (T3) = current at the high voltage side of the transformer T3, I (T4) = current at the high voltage side of the transformer T4**

The case when the fault is applied at the end of the feeder 9102 presents the lowest fault current because the impedance from the substation busbar to the fault location is the highest in this case as compared to the others. Since the impedance between the substation busbar to the fault location is the lowest for the feeders 9109 and 91010, the fault current is the highest when the fault is applied at the end of this feeder.

## 5.4.2.1.2 Overcurrent Protection Settings

In Hällekis, two new turbines to be installed are connected to the grid through a separate feeder entirely dedicated to the turbines. Throughout the network, no other feeder houses any wind turbine. Therefore, in this network, when a fault is applied on a feeder, only that feeder gets tripped. The relay settings for the feeders are provided below.

Figure (5.2) shows the current-time settings for the relays associated with the feeders in Hällekis. These relays will trip the faulted feeders in a time that depends on the fault current as shown in Table (5.11).

There is a backup protection on the high voltage side for both the transformers T3 and T4 which will trip the transformer in case the faulted feeder is not tripped by its associated feeder. The current-time settings for the relays on the high voltage side of these transformers show that the breaker will trip in 1.2 seconds when the current exceeds 192A for the transformer T3 and in 1.2 seconds when the current exceeds 200A for the transformer T4. This means that when the current through the transformer exceeds the threshold value, the relay will check if the faulted feeder is tripped by its associated breaker or else it will trip the transformer in the time specified. There is no second step for these relays. The current-time settings for the relays of these transformers are shown in Table (5.12).

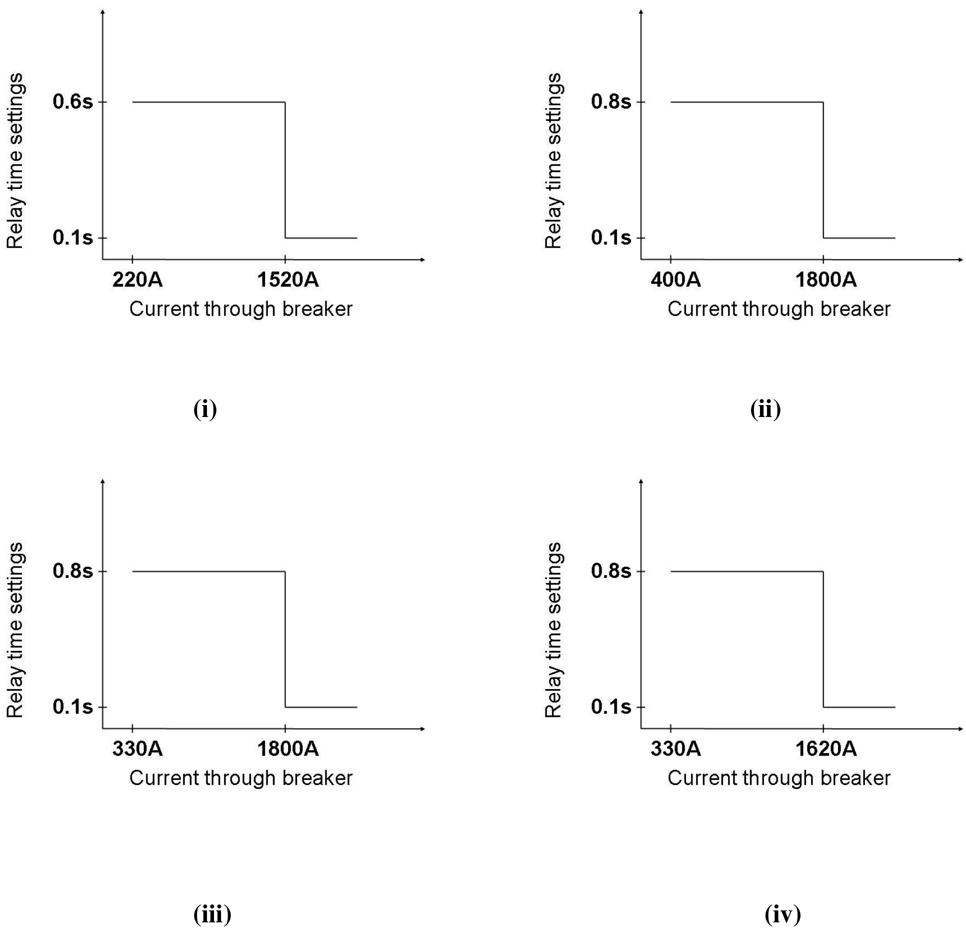


**Figure 5.2 Current-Time settings of the relays corresponding to the feeders in Hällekis. (i) Shows the relay settings for the feeders L9101, L9102, L9103, L9104 and L9105. (ii) Shows the relay settings for the feeders L9109 and L91010. (iii) Shows the relay settings for the feeder L9106. (iv) Shows the relay settings for the feeder L9107**

| | T3 High Voltage Side | T4 High Voltage Side |
|---|---|---|
| Over Current (A) | 192 | 200 |
| Time (S) | 1.2 | 1.2 |

**Table 5.12 Current-time settings for the relays at the high voltage side of the transformers T3 and T4 in Hällekis**

Since we are adding a new feeder to the medium voltage bus A10 at the transformer substation T3, in order to facilitate the integration of new turbines into the grid we need to place a relay and a circuit breaker for this feeder. By looking at the currents that flow in or out of this feeder, we can configure the relay settings.

Table (5.13) shows the current through the feeder connecting the new turbines to the medium voltage busbar A10. Since the turbines are modelled as constant current loads, it can be seen that for the faults on feeders connected to the medium voltage busbar B10, a constant current of around 389A flows through the feeder. The direction of this flow is towards the utility. When the faults occur on the feeders connected to the medium voltage busbar A10, a maximum current flow of around 190A can be observed. When the fault occurs in the feeder containing the two new wind turbines, a very high fault current (above 4500A) flows through the feeder.

A suggested value of the current threshold for the relay to be associated with this feeder should be more than 389A so that this breaker does not trip when a fault occurs somewhere else since this is the total current which is always injected by the turbines. The relay settings for the feeder connecting Svenska Foder AB could be used as the relay settings for this new feeder.

| Faulted Feeder | Current through the new feeder (A) |
|---|---|
| 9105 Hönsätersvägen | 388.83 |
| 9103 Österäng | 388.83 |
| 9104 Stenbacksvägen | 388.83 |
| 9102 Kestad | 388.83 |
| 9101 Blomberg | 388.83 |
| 9106 PAROC | 190.46 |
| 9107 PAROC | 190.47 |
| 9109 Svenska Foder AB | 151.43 |
| 91010 Svenska Foder AB | 151.53 |
| Nu Turbine1 | 4602.32 |
| Nu Turbine2 | 4402.01 |

**Table 5.13 Current through the feeder connecting the new turbines when faults are applied at the end of all the feeders**

## 5.4.2.2 High Generation and High Load

### 5.4.2.2.1 Fault Currents

This case assumes that the new turbines inject full power into the grid while there is a 100% load requirement, that is, full load condition. Three-phase short circuit faults are applied at the end of the feeders and the fault currents and currents on the high voltage side of the transformers T3 and T4 are observed during the fault.

As shown in Table (5.14), the case when a three-phase short circuit fault occurs at the end of the feeder 9102 still presents the least fault current because of lowest impedance from the substation busbar to the fault location while the case when the same fault is applied at the end of the feeder connecting the industry Svenska Foder AB presents the highest. The fault currents are comparatively lower in this case because of an increase in the load current.

| Faulted Feeder | Fault Current (A) | I (T3) | I (T4) |
|---|---|---|---|
| 9105 Hönsätersvägen | 3061.38 | 64.06 | 807.03 |
| 9103 Österäng | 1045.03 | 55.78 | 305.68 |
| 9104 Stenbacksvägen | 2690.54 | 61.20 | 717.30 |
| 9102 Kestad | 829.93 | 55.18 | 575.37 |
| 9101 Blomberg | 869.24 | 55.43 | 260.16 |
| 9106 PAROC | 4599.47 | 1197.11 | 37.99 |
| 9107 PAROC | 4603.46 | 1197.00 | 37.99 |
| 9109 Svenska Foder AB | 4743.26 | 1238.68 | 37.39 |
| 91010 Svenska Foder AB | 4783.80 | 1238.31 | 37.39 |

**Table 5.14 Fault currents and the current through the transformers during a three phase short circuit fault applied at the feeder ends. I (T3) = current on the high voltage side of the transformer T3, I (T4) = current on the high voltage side of the transformer T4**

### 5.4.2.2.2 Overcurrent protection settings

As seen in the previous case, since there are no wind turbines in the network except for the new ones that are to be installed, the breakers associated with the feeders will trip them whenever the fault occurs in the same feeder. The current-time settings for these relays are shown in Figure (5.2) and those for the relays at the high voltage side of the transformers T3 and T4 are shown in Table (5.12). The relay settings for the feeders need not be reconfigured because the new turbines are not going to be installed on the existing feeders but they are going to be installed on a feeder entirely dedicated to the wind turbines.

As was done in the previous case, the current through the feeder which is supposed to house the incoming new turbines is observed to configure the feeder's relay settings.

| Faulted Feeder | Current through the new feeder (A) |
|---|---|
| 9105 Hönsätersvägen | 392.34 |
| 9103 Österäng | 392.34 |
| 9104 Stenbacksvägen | 392.34 |
| 9102 Kestad | 392.34 |
| 9101 Blomberg | 392.34 |
| 9106 PAROC | 189.81 |
| 9107 PAROC | 189.93 |
| 9109 Svenska Foder AB | 150.63 |
| 91010 Svenska Foder AB | 151.62 |
| Nu Turbine1 | 4480.97 |
| Nu Turbine2 | 4140.76 |

**Table 5.15 Current through the feeder connecting the new turbines when faults are applied on all the feeders**

As seen in Table (5), the current through the feeder which will house the incoming turbines is almost the same as compared to the previous case of high generation and low load. Therefore, the settings for the relay to be associated with this feeder can be similar to those suggested for the previous case, that is, use of the relay settings for the feeder connecting the industry Svenska Foder AB with the medium voltage bus A10 may be suggested for the new feeder.

## *5.5 Two phase short circuit faults*

### 5.5.1 Voltage dip analysis

In this case, a two phase short circuit fault is applied at the bus where the new turbine is going to be installed. Since there are two new turbines that are going to be installed in the new feeder, two instances of fault applications (one at each new turbine) are studied. Two combinations of generation and load that were considered in the three phase short circuit analysis are also studied here. The pre-fault and post-fault voltages are similar to those obtained in the three-phase short circuit analysis because the network topology remains same in this case. With a high generation and low load, the on load tap changer for both the transformers does not change. With a high generation and high load, the on load tap changer for both the transformers are in step up mode i.e., they increase the voltage on the medium voltage busbars A10 and B10 by 1.6% of the nominal voltage. When a fault is applied at each turbine in both the cases, the fault current is above 2000A. It is assumed that the relay settings for this new feeder are configured to those for the industrial feeder Svenska Foder AB. The duration of the voltage dip depends on the tripping time of the circuit breaker; the duration of the voltage dip is 0.1 sec.

The voltage dip in two-phase short circuit analysis is less than that observed in three-phase short circuit analysis. From Table (5.16) ,(5.17),(5.18) and (5.19) it is observed that the voltage dip is more (less remaining voltage) when the fault is applied at a distance of 800m from the substation than the voltage dip when the fault is applied at a distance of 1500m from substation. From Table (5.16) and (5.17), it is observed that the voltage dip, when the fault is applied on the new feeder, is more (less remaining voltage) for the case of high generation and high load than the voltage dip for the high generation and low load case.

| Buses | A10 | Paroc-1 | Paroc-2 | Svensk-Fo-1 | Svensk-Fo-2 |
|---|---|---|---|---|---|
| During fault Voltage(p.u) (high gen.& low load) | 0.5202 | 0.5198 | 0.5197 | 0.5199 | 0.5201 |
| During fault Voltage(p.u) (high gen. & high load) | 0.4948 | 0.4905 | 0.4903 | 0.4936 | 0.4919 |

**Table 5.16 Voltages at the busbar A10 and at the industrial loads during a two-phase fault, when the fault is applied at a distance of 800m from the busbar for the two combinations of generation and load considered**

| Buses | B10 | L9101 | L9102 | L9103 | L9104 | L9105 |
|---|---|---|---|---|---|---|
| During fault Voltage(p.u) (high gen.& low load) | 0.8392 | 0.8369 | 0.8372 | 0.8376 | 0.8388 | 0.8389 |
| During fault Voltage(p.u) (high gen. & high load) | 0.8324 | 0.8093 | 0.8104 | 0.8169 | 0.8281 | 0.8292 |

**Table 5.17 Voltages at the busbar B10 and at the residential loads during a two-phase fault, when the fault is applied at a distance of 800 m from the busbar A10 for the two combinations of generation and load considered**

| Buses | A10 | Paroc-1 | Paroc-2 | Svensk-Fo-1 | Svensk-Fo-2 |
|---|---|---|---|---|---|
| During fault Voltage(p.u) (high gen.& low load) | 0.5476 | 0.5471 | 0.5472 | 0.5475 | 0.5473 |
| During fault Voltage(p.u) (high gen. & high load) | 0.5215 | 0.5173 | 0.5171 | 0.5204 | 0.5187 |

**Table 5.18 Voltages at the busbar A10 and at the industrial loads during a two-phase fault, when the fault is applied at a distance of 1500m from the busbar for the two combinations of generation and load considered**

| Buses | B10 | L9101 | L9102 | L9103 | L9104 | L9105 |
|---|---|---|---|---|---|---|
| During fault Voltage(p.u) (high gen.& low load) | 0.8480 | 0.8458 | 0.8461 | 0.8465 | 0.8476 | 0.8477 |
| During fault Voltage(p.u) (high gen. & high load) | 0.8405 | 0.8171 | 0.8182 | 0.8248 | 0.8361 | 0.8372 |

**Table 5.19 Voltages at the busbar B10 and at the residential loads during a two-phase fault, when the fault is applied at a distance of 1500 m from the busbar A10 for the two combinations of generation and load considered**

## 5.5.2 Short circuit fault current analysis

In this section, two-phase faults are applied to the feeders in Hällekis network to simulate phase-to-phase fault currents in the network followed by an observation of the fault currents and currents on the high voltage side of the transformers T3 and T4. Since all the wind power in Hällekis is concentrated in only one feeder, an investigation of the faults for the following two cases is carried out.

1. High Generation and Low Load
2. High Generation and High Load

Table (5.20) shows the fault currents when a two-phase fault is applied at the end of all the feeders in Hällekis network. Both the cases of wind and load combination are shown. It can be seen that when the fault is applied at the industrial load, bus Svenska Foder AB, highest fault current is observed because of the lowest impedance from the medium voltage busbar A10 to the fault location. The least fault current is observed when the same fault is applied at the end of the feeder 9102. The feeders are tripped according to the current-time settings of the relays associated with the feeders as shown in Figure (5.2).

| | Fault Current (A) | |
|---|---|---|
| Faulted Feeder | High G Low L | High G High L |
| 9105 Hönsätersvägen | 1538.28 | 1542.18 |
| 9103 Österäng | 525.92 | 529.57 |
| 9104 Stenbacksvägen | 1354.96 | 1355.1 |
| 9102 Kestad | 418.64 | 422.29 |
| 9101 Blomberg | 437.62 | 442.25 |
| 9106 PAROC | 2310.69 | 2337.24 |
| 9107 PAROC | 2302.22 | 2342.9 |
| 9109 Svenska Foder AB | 2372.23 | 2337.86 |
| 91010 Svenska Foder AB | 2378.6 | 2409.03 |

**Table 5.20 Fault currents observed when a two phase fault is applied at the end of the feeders for the cases of high wind generation and low load, high wind generation and high load**

Table (5.20) shows the fault currents when a two-phase fault is applied at the end of all the feeders in Hällekis network. Both the cases of wind and load combination are shown. It can be seen that when the fault is applied at the industrial load, bus Svenska Foder AB, highest fault current is observed because of the lowest impedance from the medium voltage busbar A10 to the fault location. The least fault current is observed when the same fault is applied at the end of the feeder 9102. The feeders are tripped according to the current-time settings of the relays associated with the feeders as shown in Figure (5.2).

Table (5.21) shows the currents observed by the relays at the high voltage side of the transformers T3 and T4 respectively when a two-phase fault is applied at the end of the feeders. It can be seen that the current through the transformer T3 for the high load condition decreases because of the increased current consumption by the load which is supplied by the turbines.

| | Current on transformer HV (A) | | | |
|---|---|---|---|---|
| | High G Low L | | High G High L | |
| Faulted Feeder | T3 | T4 | T3 | T4 |
| 9105 Hönsätersvägen | 89.58 | 390.96 | 57.44 | 426.95 |
| 9103 Österäng | 90.15 | **136.05** | 54.8 | **178.11** |
| 9104 Stenbacksvägen | 89.74 | 345.18 | 56.64 | 383.4 |
| 9102 Kestad | 90.21 | **109.37** | 54.56 | **153.21** |
| 9101 Blomberg | 90.18 | **113.65** | 54.66 | **155.31** |
| 9106 PAROC | 579.26 | 4.11 | 654.61 | 45.53 |
| 9107 PAROC | 579.24 | 4.11 | 654.51 | 45.54 |
| 9109 Svenska Foder AB | 601.03 | 4.09 | 676.18 | 45.22 |
| 91010 Svenska Foder AB | 600.9 | 4.09 | 675.08 | 45.24 |

**Table 5.21 Currents at the high voltage side of the transformers T3 and T4 for both conditions of high generation and low load, high generation and high load during a two phase fault applied at the end of the feeders**

From Table (5.21), which shows the current at the high voltage side of the transformers T3 and T4, it can be seen that when the fault is applied at the feeders 9103, 9102 and 9101, the relay at the transformer T4 does not detect the current as its current threshold is set at 200A. It could be reconfigured to a value of around 100A as shown in Table (5.22) to detect the fault current for all the cases in Table (5.21).

| | T4 High Voltage Side |
|---|---|
| Over Current (A) | 100 |
| Time (S) | 1.2 |

**Table 5.22 Suggested current-time settings for the relay at the high voltage side of the transformers T4 when a two phase fault is applied at the end of the feeders in Hällekis network**

| | Current through the new feeder (A) | |
|---|---|---|
| Faulted Feeder | High G Low L | High G High L |
| 9105 Hönsätersvägen | 388.83 | 392.33 |
| 9103 Österäng | 388.83 | 392.33 |
| 9104 Stenbacksvägen | 388.83 | 392.33 |
| 9102 Kestad | 388.83 | 392.33 |
| 9101 Blomberg | 388.83 | 392.33 |
| 9106 PAROC | 388.83 | 392.33 |
| 9107 PAROC | 388.83 | 392.33 |
| 9109 Svenska Foder AB | 388.83 | 392.33 |
| 91010 Svenska Foder AB | 388.83 | 392.33 |
| Nu Turbine1 | 388.83 | 392.33 |
| Nu Turbine2 | 388.83 | 392.33 |

**Table 5.23 Current through the feeder connecting the new turbines when faults are applied at all the feeders for both the cases of high generation and low load, high generation and high load**

For configuring the settings of the relay to be associated with the feeder connecting the wind turbines to the medium voltage busbar A10, the current injected by the turbines are observed as shown in Table (5.23). The relay can be set to a threshold value of around 400A so that the currents shown in Table (5.23) , which are the currents from both the turbines assuming that they inject constant rated current during the fault, do not cause a tripping of the feeder.

## *5.6 Single phase short circuit faults*

In this section, single phase-to-ground faults are simulated to check if the existing earth fault protection systems need to be changed when a new feeder in which two wind turbines are going to be installed. The theory related to the operation of the resonance grounding system used for the compensation of earth fault current is discussed in section (3.5). The steps followed in investigating single phase-to-ground faults are discussed in section (4.6). The results regarding the residual currents, the coil currents and the zero-point protection voltages are shown in this section.

| Network Topology | Faulted Feeder connected to A10 | Total earth capacitive Current (A) | Residual Current (A) | Zero-point Voltage (V) |
|---|---|---|---|---|
| Existing | Any | 2.05 | 3.24 | 2057.4 |
| New Feeder | Any | 3.22 | 3.24 | 2057.4 |

**Table 5.24 The residual currents and the zero-point voltages during a single phase-to-ground fault applied at the end of the feeders connected to the medium voltage busbar A10 for a coil current obtained by compensating the total earth capacitive current of the network**

Table (5.24) shows the coil currents, the residual currents and the zero-point voltages when a single phase-to-ground fault is applied at the end of the feeders connected to the medium voltage substation busbar A10.

| Network Topology | Faulted Feeder connected to B10 | Total earth capacitive Current (A) | Residual Current (A) | Zero-point Voltage (V) |
|---|---|---|---|---|
| Existing | Any | 5.98 | 3.24 | 2057.4 |
| New Feeder | Any | 5.98 | 3.24 | 2057.4 |

**Table 5.25 The residual currents and the zero-point voltages during a single phase-to-ground fault applied at the end of the feeders connected to the medium voltage busbar B10 for a coil current obtained by compensating the total earth capacitive current of the network**

Table (5.25) shows the coil currents, the residual currents and the zero-point voltages when a single phase-to-ground fault is applied at the end of the feeders connected to the medium voltage substation busbar B10. The coil current does not change even after the addition of the new feeder because additional earth capacitive current due to the new feeder is taken care of by the Petersen coil connected to the transformer T3 and hence has no effect on the settings of the coil connected to the transformer T4. In both the cases above, the residual current is the active part of the zero-sequence current observed at the beginning of the faulted feeder. The zero-point voltage is obtained as follows

Zero-point voltage = Residual current*Parallel resistor placed across the Petersen coil

## *5.7 Conclusions*

1. Voltage dip depends on the position of the fault; longer the distance, lower is the voltage dip.
2. The voltage level of the network is better in the case of high generation and low load.
3. For the case of high wind power generation and low load, the tap changer remains same. For the case of high generation and high load, the tap changer is at 0.983 p.u which means that it is in step up mode i.e., there will be an increase in voltage on the low voltage side of the transformers T3 and T4.
4. The voltage dip is less when a two-phase fault is applied in the new feeder connected to the network compare to three-phase fault in the feeder.

5. The case with a high generation and low load is the worst case with respect to the amount of fault current because the current demand from the loads is low and most of the current from all the generations goes to the fault.
6. The case when a three-phase short circuit fault is applied at the end of the feeder 9102 presents the highest fault current because of the lowest impedance from the medium voltage busbar to the fault location and the case when the fault is applied at the end of the feeders 9109 and 91010 presents the lowest fault current because the impedance from the medium voltage busbar to the fault location is the highest.
7. The current injected by the turbines into the grid, assuming it to be constant, is observed and it is seen that they inject a current of around 389A under normal operation and a current of around 4600A flows during a three phase fault in this feeder. Based on this, it may be suggested to configure the relay to be associated with this feeder to the settings held by the relay of the feeders 9109 and 91010.
8. The coil current when a new turbine of 7.2MW is installed in the network is within 15A which is the current coil setting for the transformer in Hällekis network. The residual current remains same. The zero-point voltage protection setting for the transformer is found to be correct which means that the substation will be tripped in case the faulted feeder is not isolated by the associated circuit breaker.

# Appendix

**Per unit calculations:**

Base impedance and base current can be calculated from three-phase values of base kilovolts and base kilovoltamperes

Base current in amperes = $\dfrac{basekVA_{3\phi}}{\sqrt{3} * basevoltage, kV_{LL}}$

$V_{LL}$ is line-line voltage, kVA is product of line current and phase to neutral voltage.

Base impedance in ohms = $\dfrac{(basevoltage, kV_{LL})^2}{baseMVA_{3\phi}}$

**Load calculations**

$P = \sqrt{3} * V_{LL} * I_{ph} * \cos\theta$

$Q = \sqrt{3} * V_{LL} * I_{ph} * \sin\theta$

$\theta$ is the angle between phase voltage and phase current.

**Coil impedance calculations:**

Charging current per phase = $B * V_{ph}$

B is the total network susceptance per phase.

The total earth capacitive current $= 3 * V_{ph} * \omega C$

If the grounding is through a reactance $X_L = 2\pi f * L$

To obtain satisfactory cancellation of arcing grounds, the inductance L should be related to the capacitance,

$I_L = I_C$,

$L = \dfrac{1}{3\omega^2 C}$

In PSS/E® the flow through the T/F is shown as the same either (i) from the high voltage to low voltage or (ii) from the low voltage to high voltage side. To Calculate the current on the low voltage side of the T/F, the following steps are carried out.

a. MVA flow through the T/F is observed.
b. Current on the High voltage side of the T/F is calculated as

$$I_{H3} = \frac{S}{\sqrt{3} * U_{H3}}$$

$U_{H3}$ is the Voltage on the high voltage side bus of transformer.

c. This current is transformed to the low voltage side as

$$I_{M3} = \frac{42}{10.7} * I_{H3}$$

Where 42kV and 10.7kV are the nominal voltages on the high voltage side and the low voltage side of the transformer.

| **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 |

**Table 6. 1 Values of resistance, inductive reactance and susceptance for different cables**