CHALMERS
UNIVERSITY OF TECHNOLOGY

Improved Lightning Performance for 132 kV OHL

Master's thesis in Electric Power Engineering

Tomas Ingmarson

Johan Stelin

Department of Materials and Manufacturing Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

Master's thesis 2017:195

Improved Lightning Performance for 132 kV OHL

TOMAS INGMARSON

JOHAN STELIN

Department of Materials and Manufacturing Technology

Division of High Voltage Engineering

Chalmers University of Technology

Gothenburg, Sweden 2017

Improved Lightning Performance for 132 kV OHL
TOMAS INGMARSON
JOHAN STELIN

Supervisor: Per Norberg, Vattenfall Eldistribution AB
Examiner: Jörgen Blennow, Department of Materials and Manufacturing Technology

Master's Thesis 2017:195
Department of Materials and Manufacturing Technology
Division of High Voltage Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: An old 132 kV wood portal tower without arcing horns and with two shield wires.

Typeset in LaTeX
Gothenburg, Sweden 2017

Improved Lighting Performance for 132 kV OHL
TOMAS INGMARSON
JOHAN STELIN
Department of Materials and Manufacturing Technology
Chalmers University of Technology

Abstract

Lightning strokes to transmission lines causes a majority of the power quality issues that are so severe that sensitive industrial loads are disturbed. Historically Vattenfall concluded that it is too expensive to use shield wires for the 132 kV grid due to the high soil resistivity in Sweden. Today the situation is different with sensitive industrial loads and the current Vattenfall standard is to build portal tower with one shield wire. The shield wire is however not used to reduce the amount of lightning faults, it is used to ground the cross arm and reduce the amount of short circuits.

In this project the lightning performance of different tower configurations used in the 132 kV grid is investigated using statistical insulation coordination in the softwares LPE and PSCAD. The optimal placement of the shield wires on towers located on flat ground is determined. Furthermore, the shield wire configuration of a new portal tower with two shield wires and typical Swedish conditions is proposed and compared to a portal tower with one shield wire. The demand is that the amount of lightning faults should be reduced by half compared to the case with a portal tower without shield wires. It is concluded that in order to achieve this decrease in the amount of faults a portal tower with one shield wire requires a tower foot resistance of 16.5 Ω while a portal tower with two shield wires requires a tower foot resistance of 35.1 Ω. The distribution between single line to ground faults and short circuits for both configurations is estimated, where a second shield wire proved to reduce the amount of short circuits. Furthermore, it is concluded that every cross arm needs to be grounded properly in order to achieve the desired lightning performance.

A cost estimation based on an average 132 kV line with average loading showed that a second shield wire could not cover its own costs. It is important to remember that the cost estimation is based on an average 132 kV line and it does not consider important industries or costs of groundings. If this would be included a second shield wire could be profitable in some cases. Therefore it is recommended to consider the local conditions when deciding if a new transmission line is built with one or two shield wires.

Keywords: Lightning performance, statistical insulation coordination, shield wire, portal tower, tower foot resistance, fault distribution, 132 kV.

Acknowledgements

A special thanks to our supervisor Per Norberg at Vattenfall Eldistribution who gave us the opportunity to carry out this master thesis and provided continuous support throughout the project. Furthermore, we would like to thank our examiner Jörgen Blennow at Chalmers for his helpful comments and discussions. Other people who contributed to the project and should be mentioned are Staffan Moss at Vattenfall Eldistribution who always provided necessary data. Jan Lundquist at STRI, who provided support regarding LPE and helpful discussions about lightning simulations. Tarik Abdulahovic and Ehsan Behrouzian at Chalmers gave us important advices regarding PSCAD modeling which was very useful.

Tomas Ingmarson & Johan Stelin, Gothenburg, May 2017

Contents

Nomenclature

BFR	Back flashover rate
BIL	Basic insulation level
CFO	Critical flashover voltage
CFO_{NS}	Non-standard critical flashover voltage
GFD	Ground flash density
LPE	Line performance estimator
LPM	Leader progression model
OHL	Overhead line
SEK	Swedish currency
$SFFOR$	Shielding failure flashover rate
SFR	Shielding failure rate

1

Introduction

This chapter gives a brief introduction to the history of shield wire usage at Vattenfall Eldistribution AB, henceforth referred to as Vattenfall, and explains the questions which are treated in the report.

1.1 Background

People have been fascinated by lightning flashes for decades. Historically it has caused thousands of deaths and destroyed buildings and ships. Much of the knowledge about lightning flashes today is based upon observations from the ground and satellites [1]. A lightning flash can consist of several lightning strokes. The strokes has a statistical nature, where the amplitude can range from a few kA to several hundreds of kA [1, 2].

Today lightning strokes to transmission lines is the source behind a majority of the power quality issues that are severe enough to disturb sensitive industrial loads [3]. If a transmission line is unshielded the lightning strokes may terminate on the phase conductors, resulting in a high overvoltage and usually flashovers across the insulator strings. By equipping the insulator strings with arc horns the flashover takes place in the air instead of on the insulator string and thereby the risk of total destruction of the string is reduced, or in other words, the insulation is self-recovering. Almost every stroke to an unshielded line with wood poles will cause short circuits between the phases [4]. This is a severe issue for heavy motor industries like paper mills, where a disturbance due to a lightning stroke to a transmission line may cause several hours of lost production and scrapping of the paper that is currently in the production line [3, 5].

One way to protect transmission lines against lightning strokes is by placing shield wires above the phase conductors. The purpose is to cover or shield the phase conductors from direct lightning strokes. A path to ground from the shield wires is required and thereby the shield wires needs to be grounded along the transmission line [1]. Two common ways of designing the grounding and shield wires is deterministic respectively statistical insulation coordination. In the deterministic approach no faults are tolerated and the worst case scenario is the design factor. The statistical approach can be used when failure is allowed due to self-restoring insulation and instead of a worst case design a certain risk of failure is allowed [6]. Usually the deterministic approach is impossible from an economical aspect, because in order to achieve a full protection the shield wires need to cover the phase conductors completely and a very low tower foot resistance is required to avoid back flashovers [1]. The tower foot resistance is the resistance between the grounding of tower and a point which is located so far away that the potential at this point is unaffected by a change in potential at the grounding of the tower [7]. The way shield wires are used in practice can vary a lot between different areas and different companies [8].

In the 1930:s Vattenfall concluded that it would be too expensive to achieve a proper grounding to use shield wires for the 132 kV grid due to high soil resistivity [8]. In the 1990:s Vattenfall re-introduced the shield wire again. The current Vattenfall standard is to build with one shield wire. A portal tower with two shield wires for 132 kV and typical Swedish conditions has not been investigated yet. It is unknown if it would have a lightning performance that can motivate the usage of an additional shield wire while also considering an economical aspect. The re-introduction of the shield wire was not done primarily to reduce the amount of flashovers. By grounding the cross arm the amount of short circuits between the phases is reduced and instead the chance of having a single line to ground fault is increased. Historically it was not important to distinguish between different kinds of faults for Vattenfall, since the line is tripped anyway. With sensitive industrial loads the situation is different today. If a fault is single line to ground there will still be some voltage left on all phases since the line passes one or several wye/delta transformers before the load, compared to the case with a short circuit where several phases could be without voltage at the load. From that perspective Vattenfall prefers single line to ground faults over short circuits [9]. In order to get single line to ground faults the tower foot resistance must be low to avoid back flashovers from the shield wires and the cross arm to the phase conductors [1].

The tower foot resistance is depending on the soil resistivity. Sweden has different soil resistivities, ranging from a few hundreds of $\Omega\,\mathrm{m}$ to several thousands $\Omega\,\mathrm{m}$ depending on the location [7]. The basic insulation level, BIL, for an overhead line with 132 kV is 550 kV [9]. BIL is defined as the crest value of the voltage of a standard lightning impulse which has a 10% chance of causing a failure [1]. Theoretically this means that if an average lightning stroke would be 20 kA (later in this thesis it is shown that the average lightning current is 33.3 kA) and it would meet a resistance of $550/20 = 27.5\,\Omega$, flashovers for roughly half of the lightning strokes could be prevented. A tower foot resistance of $27.5\,\Omega$ is a value that Vattenfall think is possible to reach in many different areas in Sweden. If the tower foot resistance would be higher than $27.5\,\Omega$ it could still be worth it to reduce it below $27.5\,\Omega$ by improving the grounding of the poles. Furthermore, an optimal placement and number of shield wires could reduce the amount of short circuits and instead increase the amount of single line to ground faults, which is preferred.

1.2 Aim

The overall aim of the project is to give Vattenfall a recommendation on shield wire configuration for new constructions based on a technical, economical and reliability perspective.

1.3 Research questions

The following research questions are treated in the project:

- What is the optimal placement of the shield wires for the different configurations?
- Which tower foot resistance is required for portal tower with one respectively two shield wires to reduce the lightning faults by half?
- What is the expected fault distribution with the proposed solutions for portal towers?
- How frequent should the cross arms of the portal towers be grounded?
- Is a portal tower with an additional shield wire better from an economical perspective than a portal tower with one shield wire?

In order to give a recommendation, the risk for flashover for typical line designs with shield wires must be calculated. Three different tower topologies are considered. These are concrete tower with one shield wire, steel tower with one shield wire and wood portal tower with one respectively two shield wires. For the steel and concrete tower it is not possible to add another shield wire with the current tower construction. Therefore only the optimal position of the shield wire should be determined. In this case the parameter which is determined is the height of the shield wire at the towers located on flat ground. The phase conductors are kept at their current positions, it is not allowed to move them closer to the shield wires.

For the portal towers with one respectively two shield wires the optimal positioning of the shield wires is determined. The demand is that the shield wires should be configured and grounded in order to avoid flashovers for half of the lightning strokes. The amount of short circuits for lightning strokes of higher amplitude should be as low as possible, instead single line to ground fault is preferred. Therefore the expected distribution between single line to ground faults and short circuits is estimated with one respectively two shield wires.

The tower foot resistance is an important parameter which is determined. For portal towers with one respectively two shield wires the tower foot resistance which is required in order to meet the demand of a reduction in lightning faults by half is determined. As mentioned earlier it is believed that it is required to be 27.5 Ω or lower. If this is true or not should be determined. Furthermore, how frequent the shield wires needs to be grounded is determined. This is important since it might be possible to save some money by for example only grounding every second or every third pole.

It is also important to determine if a new portal tower with two shield wires is better than a portal tower with one shield wire from an economic perspective. Therefore the cost for an additional shield wire and the cost for the reduction in the amount of faults is estimated.

There are several unknown parameters which needs to be determined to answer the questions above. The soil resistivity in different areas needs to be determined. Common grounding methods in general and which ones are typical in use for the 132 kV grid and typical resulting values of tower foot resistances needs to be determined. The lightning and its parameters needs to be characterized. The environmental gains with an improved lightning performance is also considered and discussed.

1.4 Scope

Typical pole designs provided by Vattenfall are used to test different shield wire configurations. Pole constructions without shield wires are not covered since it is not a Vattenfall standard anymore. The location of the phase conductors is fixed. For portal towers with shield wire the distance between the phase conductors is 4.5 m in order to provide a safety margin. No other positioning of the phases is covered. Only lightning studies are conducted, icing and pollution studies are not considered. Furthermore, high altitudes are not considered, the transmission lines are assumed to be located close to the sea level.

Only new constructions are considered for the towers since existing constructions will not be modified in order to change the location of the shield wire or be equipped with an additional shield wire.

The use of shield wires to protect against lightning strokes is an old method. One other method is to use line surge arresters. STRI, a Swedish power system consultant company, developed a 420 kV line that was built without shield wires in Norway. Instead of shield wires the phase conductors were placed in a vertical configuration and the top phase conductor acts as a shield wire. Line surge arresters are used on every tower and it has a lightning performance similar to a conventional portal tower with shield wires but it was a lot more expensive [10]. Line surge arresters also requires low tower foot resistance and Vattenfall considers them to be a complement and too expensive to be used in a standardized solution. Therefore the use of line surge arresters are not evaluated.

1.5 Method

Statistical insulation coordination is used since faults are tolerated and the insulation is self-restoring. A literature review is conducted with focus on lightning, grounding methods and shielding of transmission lines. The lightning needs to be characterized with respect to amplitude and front time [2]. It is also important to determine how the outcome of a lightning stroke is depending on the tower foot resistance and the wave impedances. The review of shielding is also including the difference between grounded and ungrounded cross arms. Ground flash density, GFD, data is retrieved from SMHI [11]. The Swedish soil resistivity in different areas was measured by a committee consisting of Vattenfall and some other companies [7].

In order to determine typical tower foot resistance values an interview is conducted with a Vattenfall employee who is working with field measurements on different pole constructions. Vattenfall is also providing data for towers, phase conductors, shield wires, insulator strings and distances between towers.

When the literature study is finished and all parameters are known the lightning performance of the different towers are evaluated in a software called Line Performance Estimator "LPE" provided by STRI. A detailed study of LPE is done in order to determine its limitations. It is also important to determine how the lightning is characterized in the software. LPE can calculate the amount of faults due to strokes to the phase conductors and faults due to back flashovers from strokes to the shield wires [12, 13]. It is used for both horizontal and vertical configurations with or without shield wires [13]. In order to judge the results from the simulations it is compared to fault statistics for a portal tower without shield wires from Vattenfall.

Initially it was unknown if LPE considered sag of lines and if it could distinguish between different types of faults. Sag of a line can be described as how much the line hangs down between two towers. LPE could not dinstiguish between single line to ground faults and short circuits. Therefore an additonal model is developed in PSCAD. The PSCAD model is based on the leader propagation model which is used in several different lightning studies from IEEE and CIGRE [1, 2]. CIGRE, International Council on Large Electric Systems, is a European organisation based in France which gathers members from all around the world. IEEE, Institute of Electrical and Electronics Engineers, is similar to CIGRE but it covers more fields than large power systems and it is based in the United States.

The PSCAD model is used to estimate the distribution between single line to ground faults and short ciruits and to determine if every pole needs to be grounded or not. In order to verify that the PSCAD model works as intended the potential at a tower during a linear increasing stroke is compared to theoretical wave shapes and values. Furthermore, STRI has estimated the fault distribution for a tower with different dimensions and parameters [14]. These parameters are also used in the PSCAD model in order to compare with the result STRI achieved.

The cost for an additional shield wire for the portal tower is estimated by looking at previous line constructions which are similar to the suggested configurations. In order to judge if it is profitable or not it is compared to the reduction in cost for faults. The cost for faults are estimated using a reference line model provided by Vattenfall. The reference line is a 132 kV line with average length and average loading in a meshed grid. The environmental impact of an additional shield wire is discussed based on the extra material required and some papers from IEEE regarding consequences of disruptions at paper mills due to lightning strokes.

2

Lightning and transmission lines

This chapter contains the literature review that was conducted. Several characterisations of the lightning has already been done. Models which describes if a lightning stroke terminates on a phase conductor or a shield wire and the soil breakdown around a ground rod are explained. Furthermore, the difference between grounded and ungrounded cross arms during lightning strokes is explained.

2.1 Lightning flashes

There are four different types of lightning flashes, they are determined by the polarity of the accumulated charges in the thunder cloud and the leader propagation direction [2]. These four types are known as:

- Negative Downward Flash
- Negative Upward Flash
- Positive Downward Flash
- Positive Upward Flash

For structures with heights less than 100 m, about 85-95% of the flashes are of negative downward type while upward strokes are more common at mountains and tall buildings [1]. A lightning flash can consist of more than one stroke. Strokes that takes place after the first stroke are known as subsequent strokes. The subsequent strokes are usually smaller in amplitude compared to the first stroke, but they can sometimes achieve a higher amplitude than the first stroke [1, 2].

2.1.1 Lightning characteristic

Three important quantities in lightning studies are amplitude, front time and tail time [1, 2]. Since the negative downward stroke is the most common to low structures such as transmission lines the CIGRE Working Group 01 (Lightning) of Study

Committee 33 studied it at seven different locations in the world [2]. In order to fit a curve to these measurements and get the first stroke amplitude distribution a log-normal probability density distribution is used, which can be described by the following equation [2]

$$f(I) = \frac{1}{\sqrt{2\pi}\beta I} e^{-}(\frac{z^2}{2}) \tag{2.1}$$

where z can be calculated from (2.2).

$$z = \frac{\ln(\frac{I}{M})}{\beta} \tag{2.2}$$

In (2.2) and (2.1) f(I) is the probability density, I is the current in kA, M is the median value and β is the standard deviation of the stroke current. Initially CIGRE used one curve to describe the amplitude distribution but it was later splitted up in two domains in order to get a better curve fitting. The first curve is called the shielding failure domain and is used for currents below 20 kA and the second curve is the backflash domain for currents larger than 20 kA. The values for M and β for the different domains can be seen below [2].

- Shielding failure domain (I < 20 kA) M = 61 and $\beta = 1.33$
- Backflash domain (I > 20 kA) M = 33.3 and $\beta = 0.605$

IEEE is using another method to describe the amplitude [1, 2]. Instead of using a log-normal distribution as (2.1) a more simplified equation is used, which was adopted in [15]. This simplified method can be expressed as

$$p(I) = \frac{1}{1 + (\frac{I}{31})^{2.6}} \tag{2.3}$$

where I is the current in kA [15]. Equation (2.3) is a cumulative distribution and directly gives the probability for a stroke below a certain amplitude while (2.1) is the probability density which needs to be integrated in order to find the cumulative distribution [2]. In Figure 2.1 the integrated version of (2.1) is the solid red line and (2.3) is the dashed blue line.

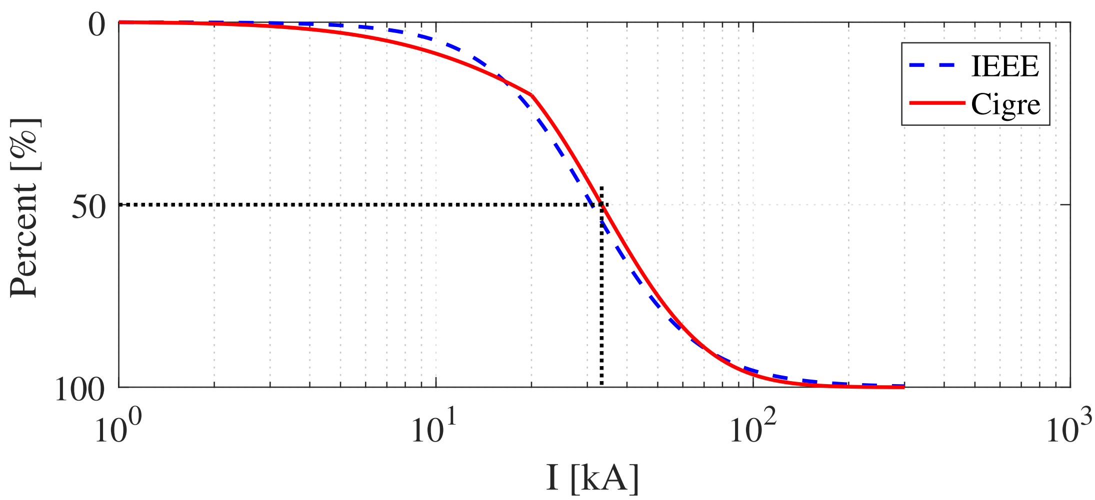


Figure 2.1: Probability that the lightning stroke amplitude is below a certain amplitude [1, 2].

The 50% value has been marked in Figure 2.1. For the CIGRE distribution 50% of the lightning strokes has an amplitude of about 33.3 kA or less [1, 2]. It can also be noted that IEEEs method deviates a bit from CIGRE's method but both characterizations are quite similar overall. However, the CIGRE distribution is based on newer data and more measurements than IEEE and is therefore considered to be more accurate [1, 2]. Table 2.1 shows the probability of a negative downward stroke with an amplitude equal to or less than a certain amplitude with steps of 5 kA according to the CIGRE distribution from Figure 2.1. Furthermore, in [2] it is also concluded that a negative downward stroke has a median front time of 2.2 µs and a median tail time of 77.5 µs.

Table 2.1: Probability that the lightning stroke amplitude is below a certain amplitude according to the CIGRE distribution [1, 2].

I [kA]	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
%	3	9	15	20	32	43	53	62	69	75	80	84	87	89	91	93	94	95	96	97

2.2 Wave impedance that lightning stroke meets

When a lightning stroke hits the transmission line it can be modeled as traveling waves of voltage and current propagating on the line. The impedance seen by a traveling wave is known as the characteristic impedance and can be expressed as the quotient of the voltage and current wave at any position and time on the line [1]

$$Z = \frac{V(t,z)}{I(t,z)}. \tag{2.4}$$

A distributed transmission line model consists of series elements of resistance and inductance and shunt elements of capacitance and resistance. By starting from the differential equations known as the general transmission line equations and assuming a lossless line, (2.4) can be rewritten as

$$Z = \sqrt{\frac{L}{C}} \quad [\Omega] \tag{2.5}$$

where L and C is the inductance respectively the capacitance per unit length of the line with respect to ground [1, 16]. One important property of the characteristic impedance, which can be seen in (2.5), is that the characteristic impedance is not dependent on the length of the transmission line [16]. The parameters L and C can be calculated using image method. For a single conductor they can be expressed as

$$\begin{aligned} L &= 0.20 \ln \frac{2h}{r} \quad [\mu\text{H/m}] \\ C &= \frac{10^{-3}}{18 \ln \frac{2h}{r}} \quad [\mu\text{F/m}] \end{aligned} \tag{2.6}$$

where h is the average height of the conductor above the ground plane and r is the radius of the conductor [1]. It is important to notice that the values of L and C from (2.6) is with respect to ground and not the same as the line inductance and capacitance parameters used in power system calculations. Furthermore, the velocity of a wave propagating on a transmission line can be calculated as [1]

$$v = \frac{1}{\sqrt{LC}} \quad [\text{m/s}]. \tag{2.7}$$

By substituting L and C in (2.7) with (2.6) the resulting wave velocity is close to the the speed of light, independent of height and radius of the conductor [1].

2.2.1 Unshielded transmission lines

Figure 2.2 shows an example of a 132 kV wood portal tower with some of its important parts. The wood portal tower has a horizontal phase configuration. The cross arm is the horizontal bar to which the insulator strings are connected, the cross arm is typically made of steel [8]. The purpose of the arcing horns is that the flashover should take place in the air instead of on the insulator string, which could damage or destroy the insulators [4]. If shield wires are used they are connected to the cross arm which is connected to the earth electrodes via conductors called downleads [1].

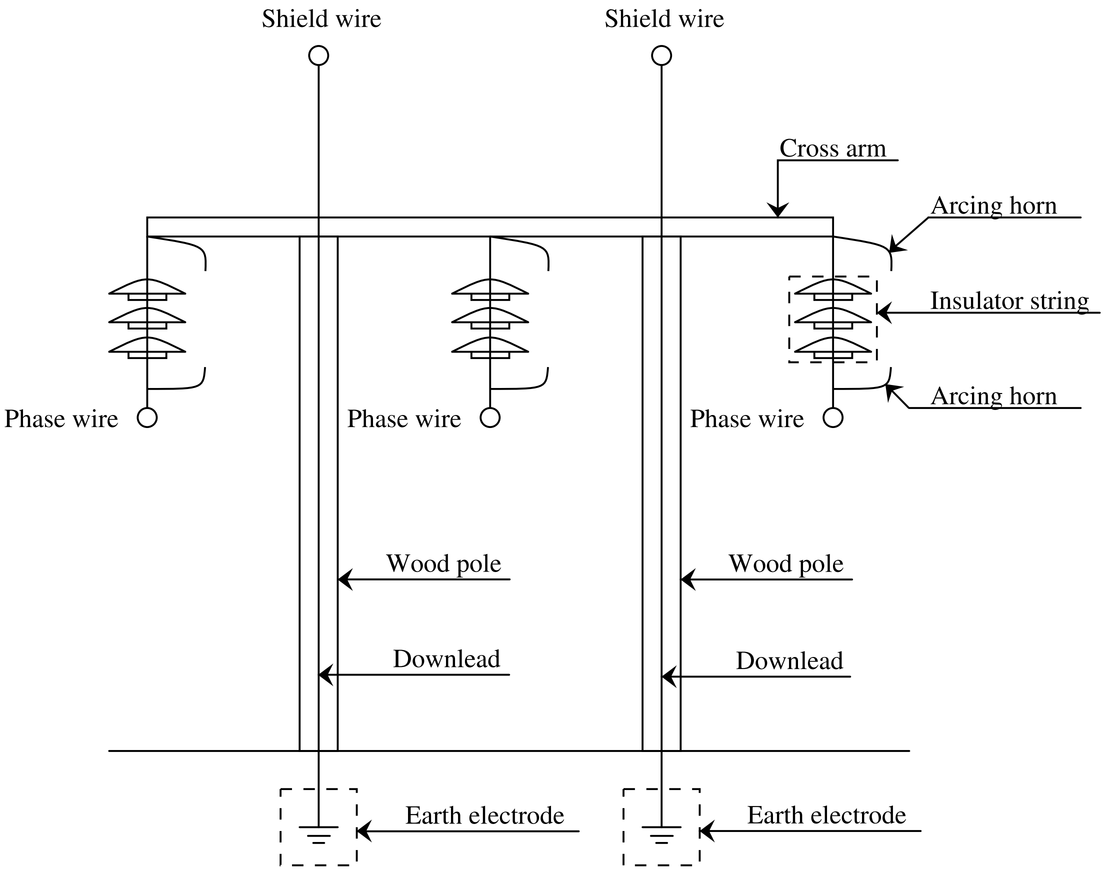


Figure 2.2: An example of a wood portal tower 132 kV and some of its most important parts.

The lightning stroke will face different wave impedances depending on if it hits a phase conductor or a shield wire [4]. If there are no shield wires the lightning stroke will terminate on one of the phase conductors. If the stroke terminates on a phase conductor the traveling wave is splitted up in two equal parts, propagating out in opposite direction from the stroke point, which can be seen in Figure 2.3 [4].

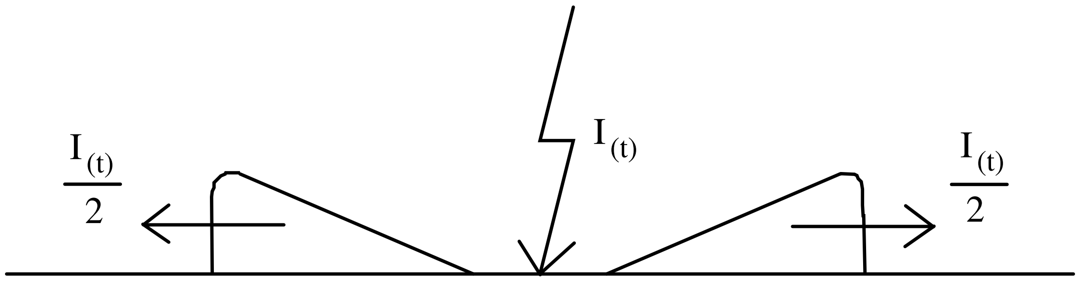


Figure 2.3: When the lightning stroke hits a conductor the wave is splitted up into two equal parts propagating out in each direction.

Thus, the voltage at any point on the conductor can then be expressed as

$$V(t) = Z\frac{I(t)}{2} \tag{2.8}$$

where Z is the wave impedance from (2.5) [4]. Typically the wave impedance of a conductor is in the range of 400-500 Ω [1]. The traveling wave will induce voltages resulting in traveling waves on the other conductors. The magnitude of the induced waves depends on the coupling factor between the conductors, which is a geometric property [4]. Furthermore, the stroke causes an overvoltage across the insulator string and across the air gap between the struck conductor and the other conductors in the span. The insulation strength of the air gap in the span always exceeds the insulation strength of the air gap between the arcing horns of the insulator string and thereby most of the flashovers will take place at the towers. Thus the amount of flashovers within the span is negligible [1].

For wood portal tower, which is the old Vattenfall standard, the combination of wood poles and lack of shield wires results in ungrounded cross arms [4, 9]. This was a standard that Vattenfall proposed for 132 kV and 220 kV where the wood poles were a part of the insulation in order to be cost efficient [9]. Lack of shield wires does not generally mean that the cross arm has to be ungrounded [4].

As a consequence of the isolated cross arm, the flashover voltage over the pole from the cross arm to ground is about 2-3 MV, which is far above the BIL. In practise the high flashover voltage of the pole causes almost all of the lightning strokes to lead to either two or three phase short circuits. If it is a two or three phase fault depends on the magnitude of the stroke current and which phase that it terminates on, since that will effect the amplitude of the induced waves on the other conductors [4]. Figure 2.4 shows the case when the lightning stroke terminates on one of the outer conductors. The middle conductor is located closer to the struck conductor, therefore a wave with higher amplitude is induced compared to the other outer conductor. This means that the largest potential difference occurs between the two outer conductors and if a two phase flashover takes place it is between the outer conductors via the cross arm [4].

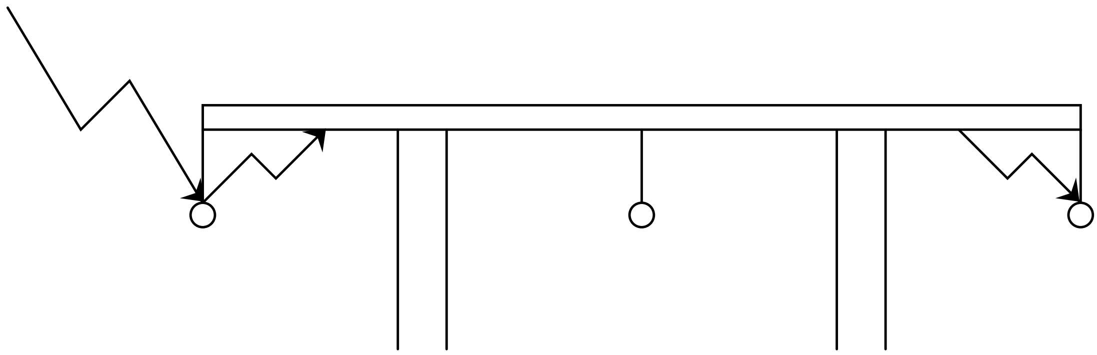


Figure 2.4: Two-phase short circuit due to a stroke to the outer conductor on a wood portal tower with ungrounded cross arm.

The flashover voltage required to cause a two phase short circuit is less than twice the BIL [4]. This can be explained by that before the breakdown occurs the overvoltage appears across two series connected insulator strings with the cross arm in the middle. Each insulator string is then exposed to a part of the total overvoltage. When flashover occurs over the first insulator string to the cross arm it causes the first insulator string to become short circuited and thereby the second insulator string is suddenly exposed to the whole overvoltage instead of a part of it, this causes a fast breakdown over the second insulator string and thereby the flashover voltage is not twice the BIL [4]. Furthermore, larger strokes may not only lead to three phase short circuits, it can also cause a flashover over the pole to ground, which could damage or destroy the pole. [4, 8].

2.2.2 Shielded transmission lines

A transmission line where the towers have grounded cross arms will have a different fault distribution compared to a line with ungrounded cross arms. In section 2.2.1 it was mentioned that almost all lightning strokes to a phase conductor of a line with ungrounded cross arms causes short circuits between two or three phases. There will still be a flashover from the struck phase conductor to the cross arm in almost all cases but when the cross arm is grounded there is a path to ground for the lightning current. If the tower foot resistance or the lightning current is high, the cross arm will be on a high potential and there might be a flashover to either one or both of the other phase conductors [4].

If shield wires are used many of the lightning strokes will terminate on the shield wires instead of the phase conductors [1, 4]. One important parameter that has been used in shielding design for many years is the shielding angle or protective angle, which is the angle between the shield wire and a phase conductor at the tower. In general terms, a small angle means less strokes to the phase conductors [1]. One interesting example of where both small and large shielding angles appears in reality is from the Swedish grid, which can be seen in Figure 2.5. The tower was originally intended to be used in a quadruple 800 kV line but it is used for two duplex 400 kV lines instead [9]. The shielding angle to the outer two phases is too large and therefore the insulation level had to be increased for those two phases, which can be seen by the increased length of the insulator strings [9].

Figure 2.5: Increased insulation level on the outer phases due to large shielding angles at a tower used in the Swedish grid which was originally intended to be used for a 800 kV line but is instead used for two 400 kV lines. Photo taken by Puggen.

If proper shielding angles are used for all phase conductors, unlike the example in Figure 2.5, many of the strokes will terminate on the shield wires but this does not mean that there will not be any faults. A stroke to the shield wire might cause a flashover from the cross arm to any of the phase conductors if the potential on the cross arm is high. This type of flashover from the cross arm to one or several of the phase conductors is known as a back flashover [1, 4]. For the case with one shield wire a lightning stroke to a tower will produce one wave propagating down on the tower and two waves propagating out in each direction on the shield wire [1]. The maximum voltage on the tower without considering any reflections can then be expressed as

$$e = \frac{Z_T Z_g/2}{Z_T + Z_g/2} I \tag{2.9}$$

where Z_T is the tower surge impedance and Z_g is the wave impedance of the shield wire [1]. If two shield wires would be used instead it would provide two additional paths for the waves [4]. Furthermore, (2.9) is valid for strokes to a tower. A stroke in the span results in the same voltage as a stroke to the tower if the front time is shorter than the travel time for the reflected wave from the other adjacent tower. Otherwise a stroke to the span results in a lower voltage at the tower compared to a stroke to the tower [1]. In [1] it was concluded that back flash rate, BFR, while also considering strokes in the span can be approximated good by calculating the BFR for strokes to the tower multiplied by 0.6 [1].

The wave that propagates down on the tower will be reflected against ground and reduce the voltage at the tower top. The resulting voltage on the tower top after the reflection from ground depends on front time, tower travel time and reflection coefficient. Tower travel time is the quotient between tower height and the wave velocity [1]. The reflection coefficient can be calculated as

$$\Gamma_T = \frac{R_i - Z_T}{R_i + Z_T} \tag{2.10}$$

where R_i is the impulse resistance of the grounding rod from (2.22) and Z_T is the tower surge impedance [1, 2]. The impulse resistance R_i is the current dependent tower foot resistance, which is lower than the measured value of the tower foot resistance [1].

As mentioned earlier the tower foot resistance and lightning amplitude dictates if there is a back flashover [1]. With practical values the tower foot resistance accounts for about 80% of the potential on the tower due to a stroke to the tower [1]. One way to estimate the potential on a tower due to a lightning stroke to the tower is then (2.11)

$$U \approx R_0 I \tag{2.11}$$

where R_0 is the measured tower foot resistance and I is the lightning stroke amplitude [4]. This is however an approximation, as mentioned earlier the tower foot resistance is not a constant parameter, all of the current from the stroke will not flow through the struck tower and furthermore reflections from ground will reduce the potential at the tower [1, 4].

As mentioned earlier waves also propagate out on the shield wires. As soon as these waves reach a discontinuity a portion of the wave is reflected. For a transmission line this means that there will be reflections from every tower the wave reaches back towards the point where the lightning stroke took place [1]. There are also reflections from ground at these towers. Reflections that reach the lightning stroke point will further reduce the voltage at this point. Towers located far from the stroke point will not have a large effect on the voltage at the stroke point since not so much is reflected back [1]. Furthermore, if the distance is long the reflected waves might not reach the stroke point before the crest value is reached and thereby only reduce the tail voltage. In practise towers beyond the adjacent towers has a negligible effect on the voltage [1].

The tower surge impedance Z_T is a time varying parameter which reaches its maximum value after two times the tower travel time. However, the tower surge impedance is not a sensitive parameter and thereby the average value is used in calculations [1]. The average tower surge impedance can be calculated as

$$Z_T = 60(\ln(\sqrt{2}\frac{2h}{r} - 1)) \tag{2.12}$$

where h is the tower height and r is the radius [1]. The equation is actually for a cylinder shape but since the tower surge impedance is not a sensitive parameter it is also used for portal towers [1]. If two downleads are used on portal tower the mutual surge impedance needs to be considered. The mutual surge impedance can be expressed as

$$Z_m = 60(\ln(\sqrt{2}\frac{2h}{D} - 1)) \tag{2.13}$$

where D is the distance between the poles [1]. The total surge impedance for two downleads on a portal tower can then be calculated from

$$Z_{Total} = \frac{Z_T + Z_m}{2} \tag{2.14}$$

where Z_T is the tower surge impedance according to (2.12) and Z_m is the mutual impedance from (2.13) [1].

If shield wires are used it is important to determine if the lightning stroke terminates on a shield wire, phase conductor or on ground. The electrogeometric model, which can be seen in Figure 2.6, is used to determine this [2]. The model is limited to vertical negative downward strokes. The phase conductors are the lower three circles located at height y from the ground. The upper two circles at height h, separated by the distance S_g are the shield wires [1, 2].

With the phase conductors and shield wires drawn a horizontal line at the stroke to ground height, r_g, is drawn. The next step is to draw four circle arcs, each with radius r_s, the striking distance to phase conductor respectively shield wires, from the shield wires and phase conductors. If two shield wires are used then the middle phase is protected from direct strokes, thereby it is not necessary to draw a circle arc from it [1, 2].

Lightning strokes that terminate within the bands D_g and S_g will hit the shield wires. Phase conductors are exposed to lightning strokes within D_c while strokes outside D_c will hit the ground or any other object located in the vicinity [1]. The angle α between the shield wire and the conductor is known as the protective angle or shielding angle [1, 2]. It is used to specify the location of the shield wires in transmission line designs [2].

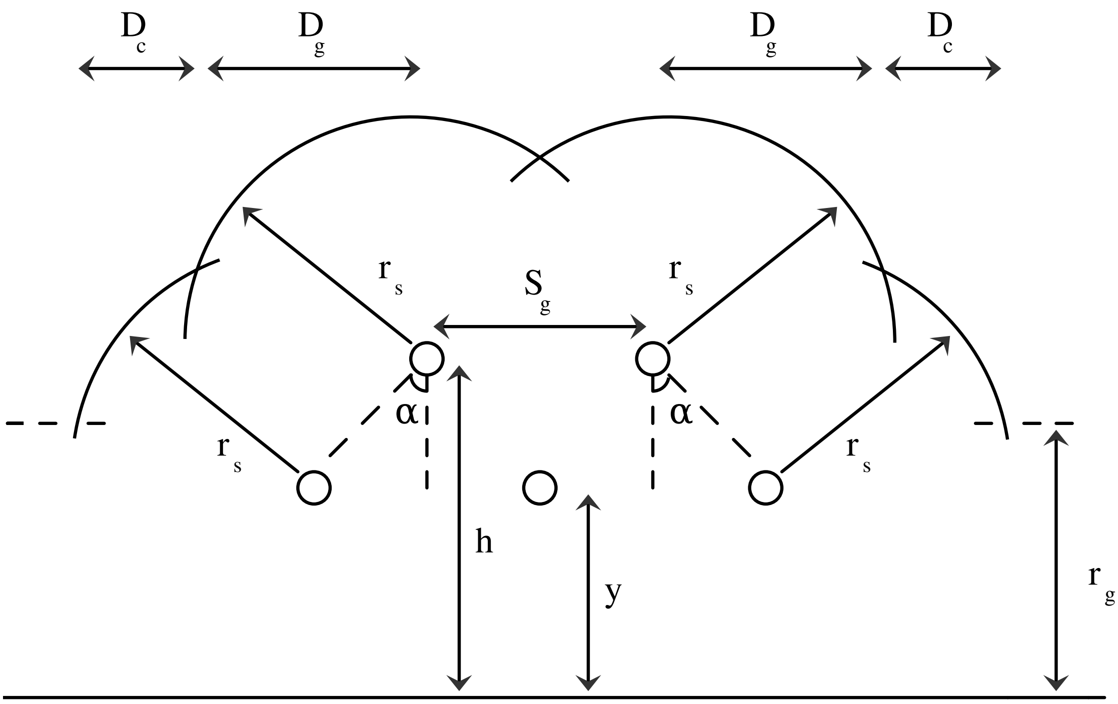


Figure 2.6: Electrogeometric model for a portal tower with horizontal phase configuration and two shield wires.

Two important quantities in Figure 2.6 are the striking distances r_g respectively r_s. In [2], five different authors tried to determine the striking distances. This resulted in five different characterizations. All of them may however be written on the form of an exponential function

$$r = AI^b \tag{2.15}$$

where I is the stroke current in kA and A respectively b are constants. The constants have different values for different characterizations. Once the striking distances r_s and r_g are known it is possible to calculate the bands D_g respectively D_s [2]. The number of strokes that terminate on the phase conductors, which is usually denoted as the shielding failure rate, SFR, can then be calculated as

$$SFR = 2N_gL\int_{I_{min}}^{I_{max}} D_c f(I)dI \tag{2.16}$$

where N_g is the ground flash density, L is the length of the line and f(I) is the probability density of the current. The expression is multiplied by 2 since it only covers one side. The upper integration limit I_{max} corresponds to the maximum current that can hit the conductor while I_{min} is the minimum current required for a lightning stroke [2]. In [2] the lower limit is set to 3 kA. When the stroke current increases both r_s and r_g increases according to (2.15), and the maximum current I_{max} is found when the two circles from the shield wire respectively phase conductor intersects at a certain height r_g, which is then denoted r_{gm} [1]. At this distance the stroke distance to the phase respectively shield wire is r_{sm} [1]. This can be seen in Figure 2.7.

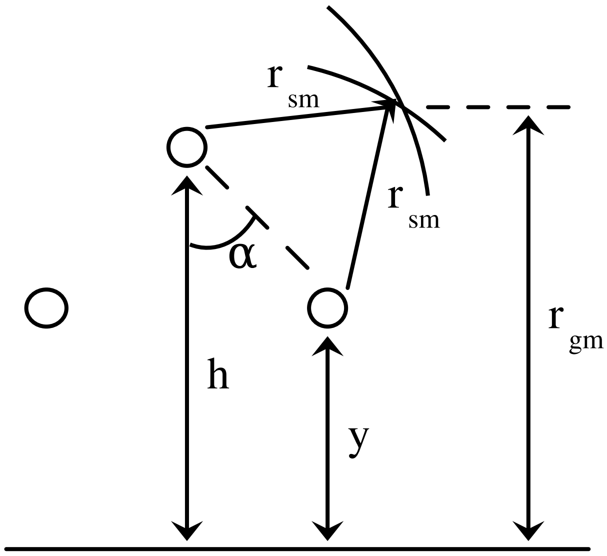


Figure 2.7: Electrogeometric model at maximum stroke current to phase conductor.

From Figure 2.7 it can be seen that if the stroke current increases further r_g will intersect the circle from the shield wire above the circle from the phase conductor and thereby theoretically all lightning strokes with higher amplitude than I_{max} will terminate on either the shield wire or the ground [1]. The distance r_{gm} is calculated with the following equation

$$r_{gm} = \frac{h+y}{2(1 - \frac{r_{sm}}{r_{gm}} sin(\alpha))}. \tag{2.17}$$

Once the distance r_{gm} is known the maximum current I_{max} can be calculated by rearranging (2.15) to (2.18) [1]

$$I_{max} = (\frac{r_{gm}}{A})^{\frac{1}{b}}. \tag{2.18}$$

Furthermore, (2.16) can be modified in order to calculate the amount of shielding failure that causes a flashover from the phase conductor to the cross arm, which is known as the shielding failure flashover rate or SFFOR. This can be done by replacing the lower limit in the integration with I_{crit}

$$SFFOR = 2N_g L \int_{I_{crit}}^{I_{max}} D_c f(I) dI. \tag{2.19}$$

In (2.19) I_{crit} is the critical current required to cause a flashover. It can be calculated by rearranging (2.8) into

$$I_{crit} = \frac{2U_{CFO}}{Z} \tag{2.20}$$

where U_{CFO} is the critical flashover voltage and Z is the wave impedance of the phase conductor, which is calculated using (2.5) [1].

2.3 Tower groundings

A decrease of the tower foot resistance can be achieved by grounding the pole in different ways. For the wood portal tower these different ways could be deep earth electrode, shallow earth electrode or an underground earth electrode. Shallow earth electrode is ground rods placed radially at a depth of 1 m while deep earth electrode is placed vertically deeper than 1 m. An underground earth electrode is a conductor which is buried in the ground along the transmission line. The most used one however is deep earth electrode, but this is depending the earth geology and how high the soil resistivity is. Even if deep earth electrode is used it might not be enough in order to decrease the tower foot resistance. Therefore an underground earth electrode can be added to further decrease the tower foot resistance or even more deep earth electrodes has to be added. The material used for these methods is often iron and copper [17, 18].

High currents causes the tower foot resistance to decrease below the measured values due to soil breakdown around the electrode [1, 2]. Figure 2.8 shows a ground rod which is exposed to a high current due to a lightning stroke. The high current causes a potential build up on the ground rod. Soil has a certain breakdown strength and when the critical gradient E_o, which is typically 400 kV/m, is exceeded breakdown of soil around the ground rod occurs [1, 2]. Streamers are produced evaporating moisture followed by arcs in the soil. The resistivity within the affected area is decreased drastically and it behaves as a conductor. The ground rod will increase in size to the limit that is denoted as "first" in Figure 2.8. As the breakdown process continues, the equivalent ground rod will take on a hemispherical shape, which is denoted as "last" in Figure 2.8 [1].

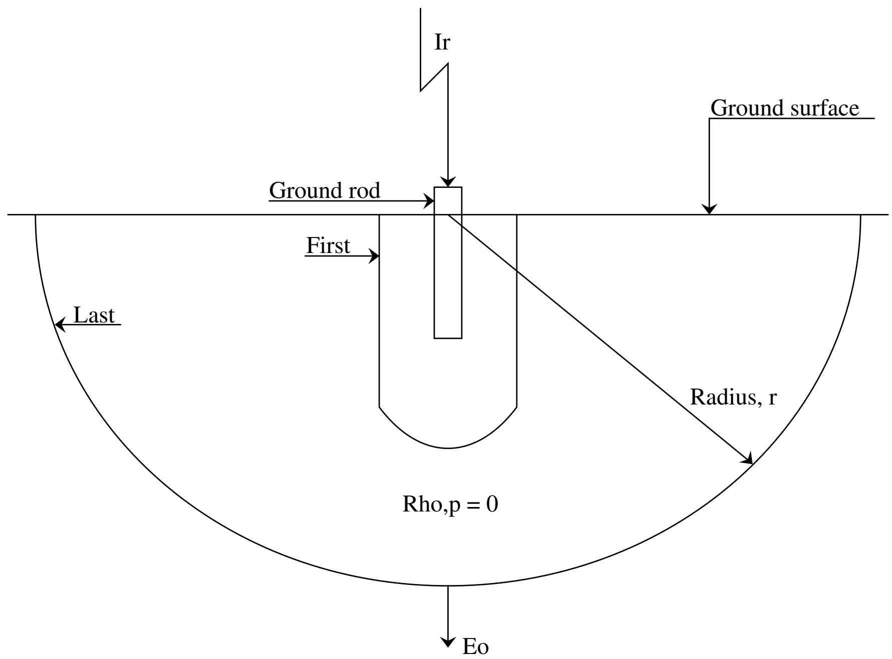


Figure 2.8: Ground rod acts like a hemisphere when exposed to a high current.

It is possible to describe this mathematically by assuming that the ground rod has the shape of a hemisphere before the lightning stroke, which is seen in Figure 2.9.

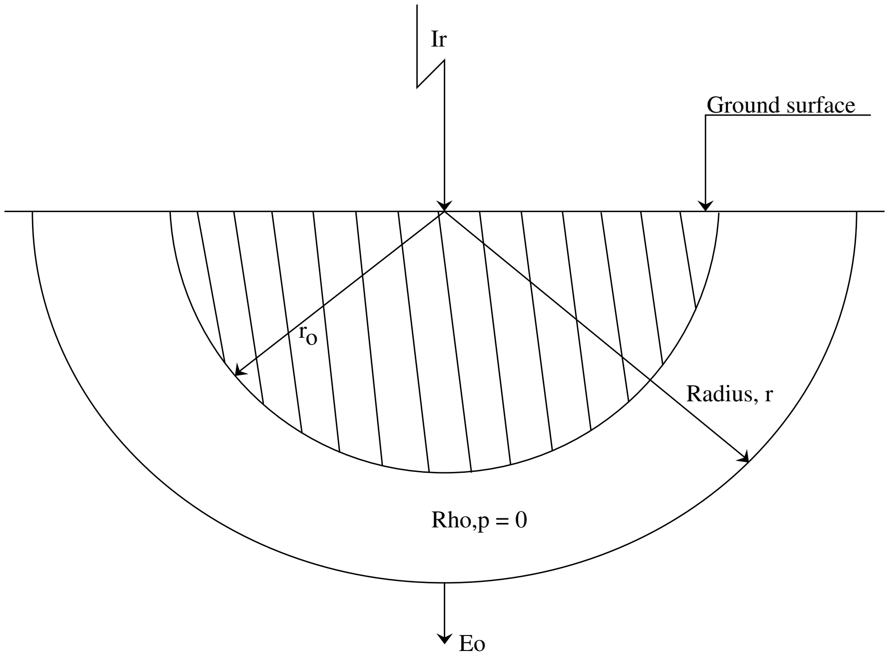


Figure 2.9: By assuming that the ground rod has a hemispherical shape before breakdown it is possible to describe the breakdown process mathematically.

The amount of current that is required to the break the boundary labeled r_0 can be referred to as I_g and it can be represented by the following equation

$$I_g = \frac{E_o \rho}{2\pi R_o^2} \tag{2.21}$$

where R_o is the measured value for the tower foot resistance for low currents, E_o is the critical gradient as explained earlier and ρ is the soil resistivity [1, 2]. The breakdown process will continue as long as the current is larger than I_g. In Figure 2.9 this is the case until the radius r is reached. The soil resistivity inside this radius r, is about zero and therefore the soil can be seen as a conductor. The resulting resistance is known as the impulse resistance R_i and it is calculated with the following equation [1]

$$R_i = \frac{R_o}{\sqrt{1 + \frac{I_R}{I_g}}} \tag{2.22}$$

where I_R is the current through the tower foot and I_g is the current required for soil breakdown according to (2.21). The number one in the denominator makes the equation valid for both low and high currents [1].

3

Transmission line models

This chapter presents the different transmission line models that are used in the project and describes how they are implemented in LPE and PSCAD.

3.1 Line performance estimator

LPE, line performance estimator, is a software which is used to estimate the performance of different transmission line structures. It can be used for lightning performance, switching studies, icing tests and pollution of insulators [13]. The output of LPE is the number of faults due to these events, which is given in faults per 100 km and year or for each section of the line. As mentioned in section 1.4 only lightning is considered in this study. For lightning studies LPE outputs the number of shielding failure flashovers and back flashover events. LPE utilizes the electrogeometric model described in section 2.2.2 for lightning studies. The striking distances are calculated using (2.15) with the constants determined by Brown and Whitehead [12]. According to Brown and Whitehead the constant b equals 0.75 for both striking distances while A differs. For striking distance to ground A equals 6.4 and for striking distance to conductor respectively shield wire A equals 7.1 [2].

The SFR, shielding failure rate, is calculated with (2.16), where the minimum current is set to 3 kA. The upper limit is calculated from (2.17) and (2.18). LPE is then calculating the SFFOR, shielding failure flashover rate, by implementing (2.19). Back flashovers are considered in LPE but there is no distinction between different types of short circuits. Furthermore, some assumptions are used in the software. The corona effect on shield wires is neglected. All flashovers are assumed to occur at the tower, no flashovers can occur in the span [12]. In section 2.2.2 it was mentioned that strokes within the span results in equal or less voltage at the tower compared to a stroke at the tower. In the backflash calculation this is considered by calculating the backflash rate, BFR, based on strokes to the tower and then multiplying it with 0.6. BFR is calculated with the following equation

$$BFR = 0.6 N_L P(I > I_c) \tag{3.1}$$

where N_L is the amount of of strokes per year for a 100 km line and $P(I>I_c)$ is the probability of a current larger than the critical current I_c which is required to cause a backflashover. The critical current is calculated with (3.2)

$$I_c = \frac{CFO_{NS} - V_{PF}}{K_{SP}(K_{TA} - C_A K_{TT})}. \tag{3.2}$$

In (3.2) V_{PF} corresponds to the effect of the system voltage. For a vertical phase configuration V_{PF} is 0.4 times the peak phase voltage and for a horizontal configuration it is 0.7 times the peak phase voltage [12]. In general the waveshapes of the voltages across the insulator strings deviates from the CFO, critical flashover voltage, for standard lightning impulse [1]. In LPE this is considered by by using CFO_{NS}, the non-standard CFO, which is calculated from a regression analysis of the leader progression model LPM. C_A is the coupling factor between either a single or two shield wires and the phase conductor. K_{SP} is the reduction of tower voltage caused by reflection from all adjacent towers and K_{TT} is the combined impedance of the shield wires and the tower foot impulse resistance with reflection from the tower foot seen from the top of the tower. K_{TA} is defined in the same way as K_{TT} but it is seen from the same height as the phase conductor. Furthermore, tower surge impedance is modeled using (2.12) respectively (2.14) and tower foot impulse resistance with (2.22) [12]. One limitation for the tower foot resistance is that it is possible to use different values for different towers but LPE will only use the largest value in the calculations. Furthermore, there needs to be a tower foot resistance for every tower which means that it is not possible to leave some towers ungrounded [13].

3.1.1 Environmental parameters

Only negative downward strokes and first stroke is considered in LPE. Furthermore, LPE assumes a flat terrain around the transmission line and thereby any effects caused by vegetation is neglected. For lightning studies the distribution characterized by CIGRE in section 2.1.1 is used. The only lightning related parameter which may be changed by the user is the ground flash density, GFD, which is the number of strokes that terminate on 1 km^2 per year [12]. SMHI has collected data over the lightning activity in Sweden during several decades. GFD in most parts of Sweden is 0.2-0.25 per km^2 and year. The exception is the northern parts, where the ground flash density is close to zero in some areas [11]. In LPE the GFD was selected to 0.25 per km^2 and year.

Another environmental parameter which is used in lightning studies is soil resistivity. The soil resistivity in different parts of Sweden has been measured by a committee from The Royal Swedish Academy of Engineering Sciences [7]. Based on this the soil resistivity in all simulations was selected to $3000\,\Omega\,\mathrm{m}$. The soil reisistivity in Sweden varies a lot from the southern part to the northern part of Sweden, which can be seen in 3.1. It can be seen that southern part has a very low soil resistiviy compared to the northern part were it is very high, but overall it varies between 2500 Ω m to 10 000 Ω m in Sweden [7].

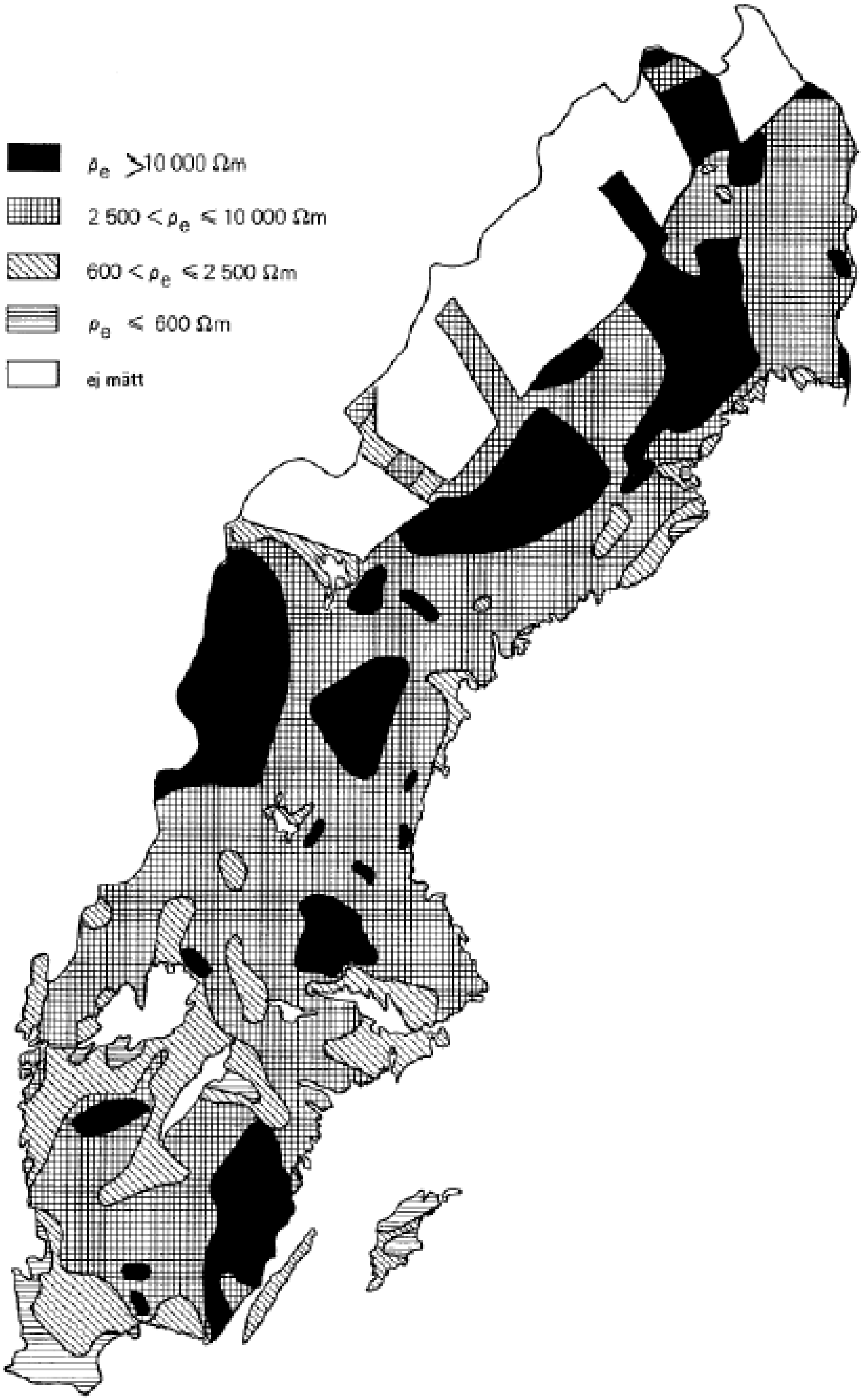


Figure 3.1: A map over Sweden that shows the different soil resistivities in different areas. With permission from The Royal Swedish Academy of Engineering Sciences [7].

3.2 Tower configurations

The different tower configurations that are considered are the wood portal tower without shield wire and with one respectively two shield wires. These towers are constructed in LPE based on pole design data acquired from Vattenfall. There are two types of wires: AlMgSi phase conductors with a diameter of 31.7 mm and ACSR shield wire with a diameter of 15.4 mm. The insulator strings used in all studies are cap and pin type with a total length of 2 m, considering mechanical couplings the nominal length is 1.95 m and the distance between the arcing horns is 1.02 m.

3.2.1 Wood portal tower

An example of a wood portal tower without shield wire can be seen in Figure 3.2. The poles are located in the middle between the phase conductors. The height of a 132 kV portal tower on plain ground is 14 m. The phase conductors are located 2 m below the cross arm, they have a sag of 5.5 m in the middle of the span.

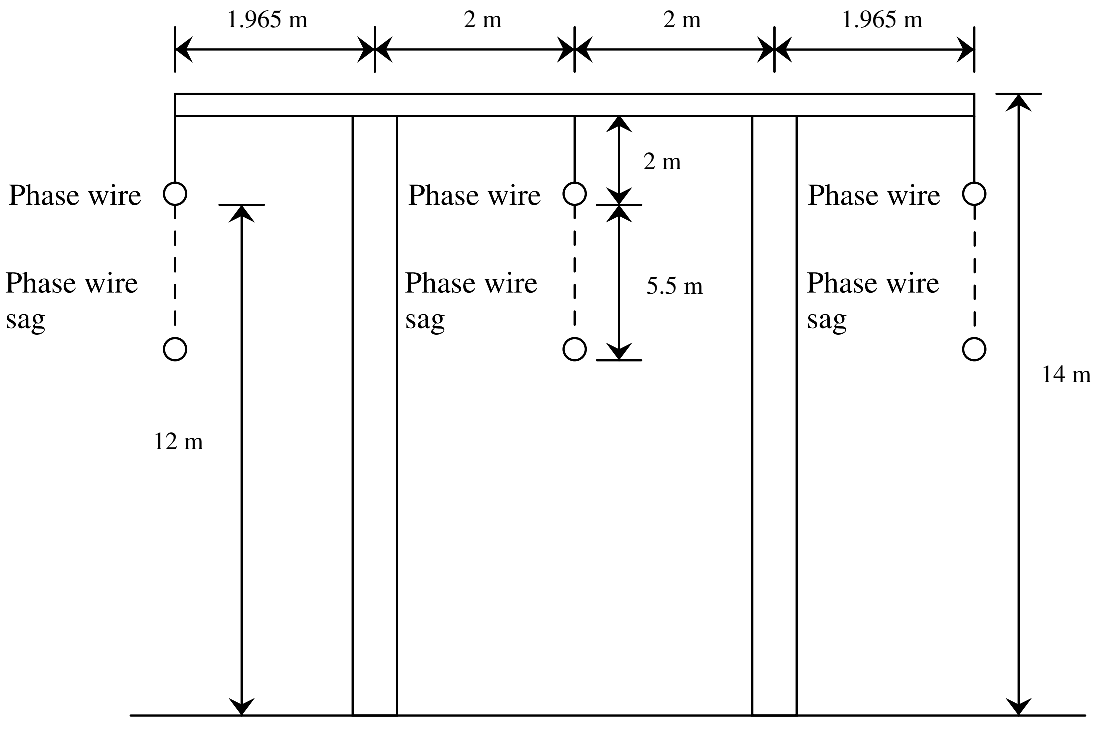


Figure 3.2: Wood portal tower without shield wire.

In Figure 3.2 it can be noticed that the distance between the phase conductors is roughly 4 m, compared to the same tower type with shield wires where the distance between the phase conductors is 4.5 m instead. Figure 3.3 shows an example of a portal tower with one shield wire. The sag of the phase wires is 5.5 m as previously while the sag of the shield wire is 3.8 m. The sag is effected by line temperature, span length, line area and spanned. The values of the sags that are used in the simulations is for a phase conductor temperature of 50 °C and a shield wire temperature of 15 °C.

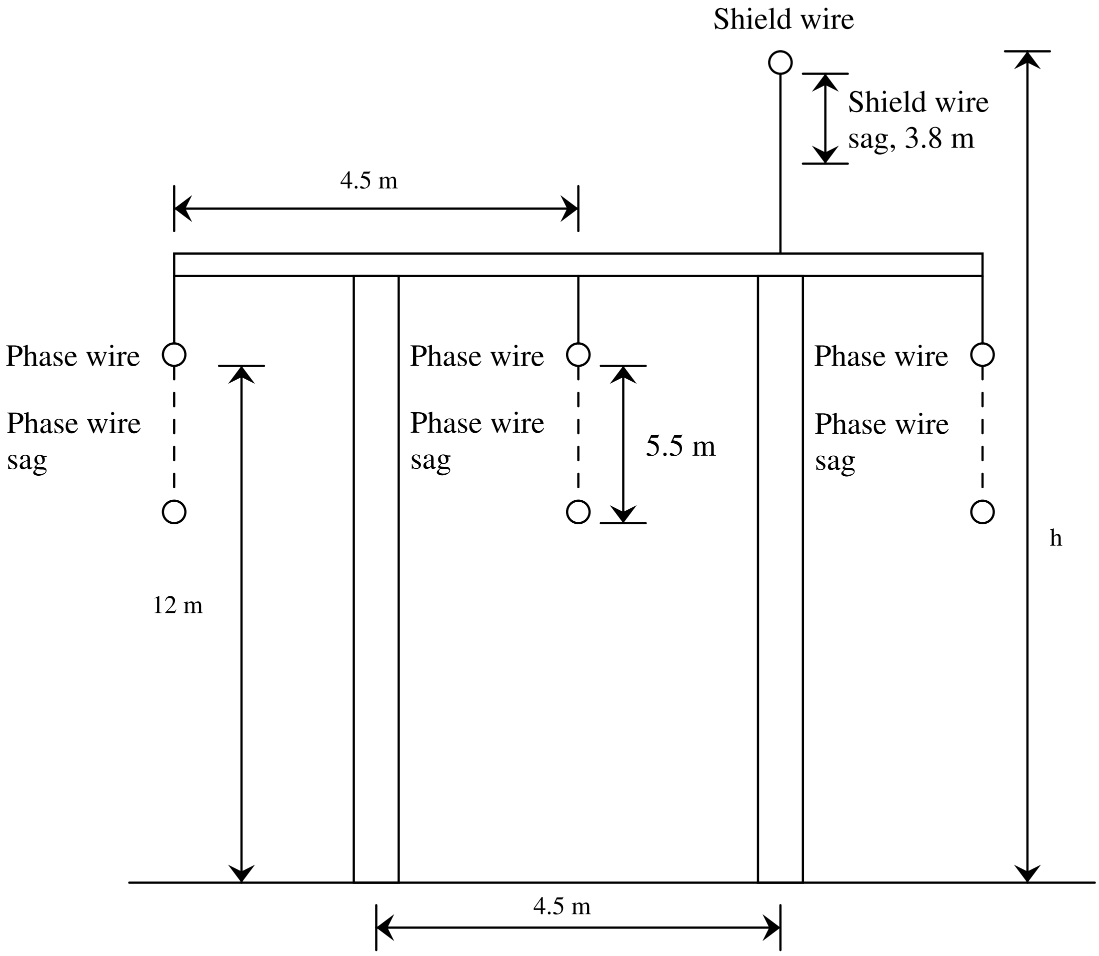


Figure 3.3: Wood portal tower with one shield wire.

The height of the shield wire at the tower, labeled as h in Figure 3.3, is one of the parameters of interest. The current Vattenfall standard is 16 m. In the simulations the height of the shield wire at the tower is swept from 16 m to 23 m in steps of 0.5 m.

Figure 3.4 depicts a wood portal tower in real life with one shield wire. Compared to the schematic in Figure 3.3 it can be noticed that the shield wire is placed on the cross arm and a little bit under instead of having it placed on the pole. Furthermore, the insulator strings are equipped with arcing horns, which can be seen at both ends of the insulator string, compared to the front cover.

Figure 3.4: Wood portal tower with one shield wire and insulator strings with arcing horns.

Figure 3.5 shows an example of the portal tower with two shield wires. The sag of phase wires respectively shield wires are the same as previously. Same shield wire height sweeping is performed for this configuration.

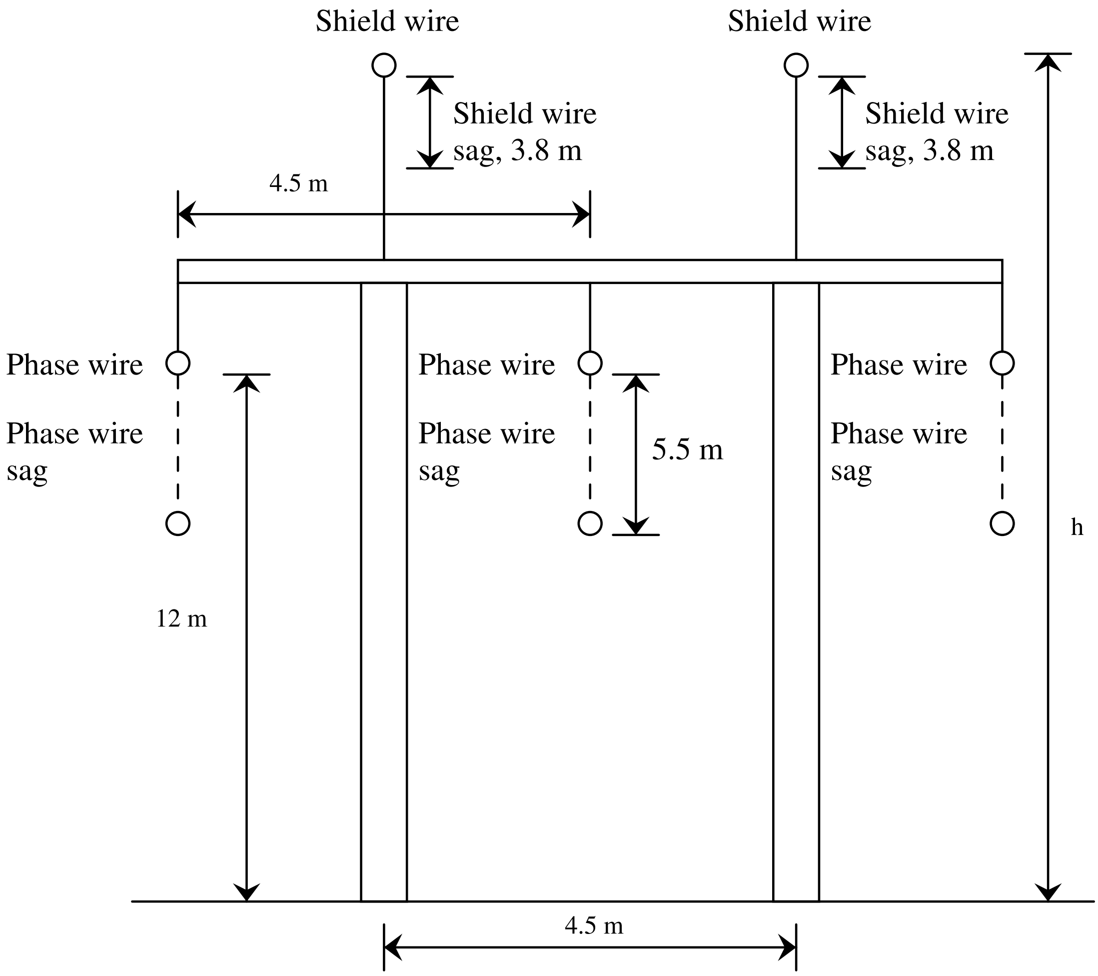


Figure 3.5: Wood portal tower with two shield wires.

These are the three different configuration used for the wood portal tower in this study. Once the tower is designed the next step is to build line sections in LPE. A line section includes section length, span length, number of towers, tower foot resistances and highest allowed phase to phase voltage. The highest allowed voltage for the 132 kV grid is 145 kV. The length of the transmission line used for all three configurations is set to 30 km, which is divided into six equaly longs section with a length of 5 km. The span length for portal tower is 200 m, which means that each section contains 25 towers and the whole line contains 150 towers in total.

3.2.2 Steel tower

An example of a steel tower configuration can be seen in Figure 3.6. The simulations are performed with the same transmission line length and section length as before.

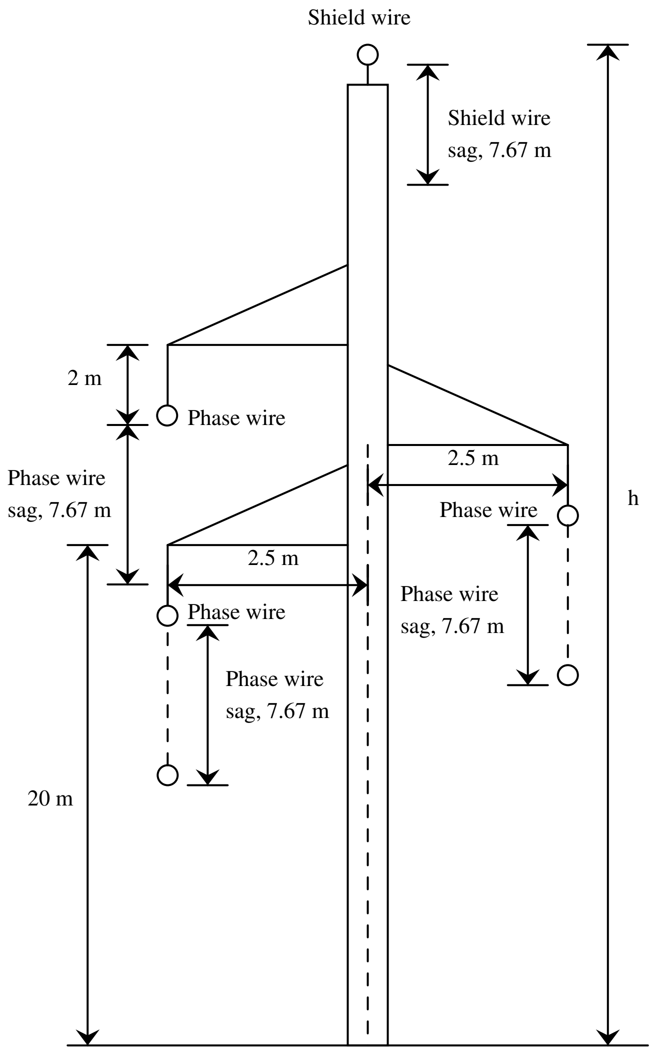


Figure 3.6: Steel tower with vertical phase configuration and one shield wire.

In Figure 3.6 it can be observed that the phase configuration has changed compared to the portal tower. For steel and concrete tower the phase configuration is vertical in a triangular shape. The height of the shield wire is initially 28.5 m and it is swept in steps of 0.5 m up to 33 m. Furthermore, the phase wires are located at a higher height compared to the portal tower. As a consequence the average span length is 250 m. When the span length is increased the sag is also increasing. With a span length of 250 m the sag for the phase wires is about 7.67 m for a temperature of 50 °C and the shield wire sag is about 5.14 m for a temperature of 15 °C.

3.2.3 Concrete tower

The concrete tower is the last tower structure that is simulated in LPE, an example of its configuration can be seen in Figure 3.7. It has the same phase configuration at the steel tower, the only difference is that the phase wires are slightly closer to ground. Initially the height of the shieldwire is 26 m and it is swept in the same way as for the steel tower. Furthermore, sag and span distances are the same as for steel tower. It can be seen in Figure 3.8 how the concrete tower looks like in real life.

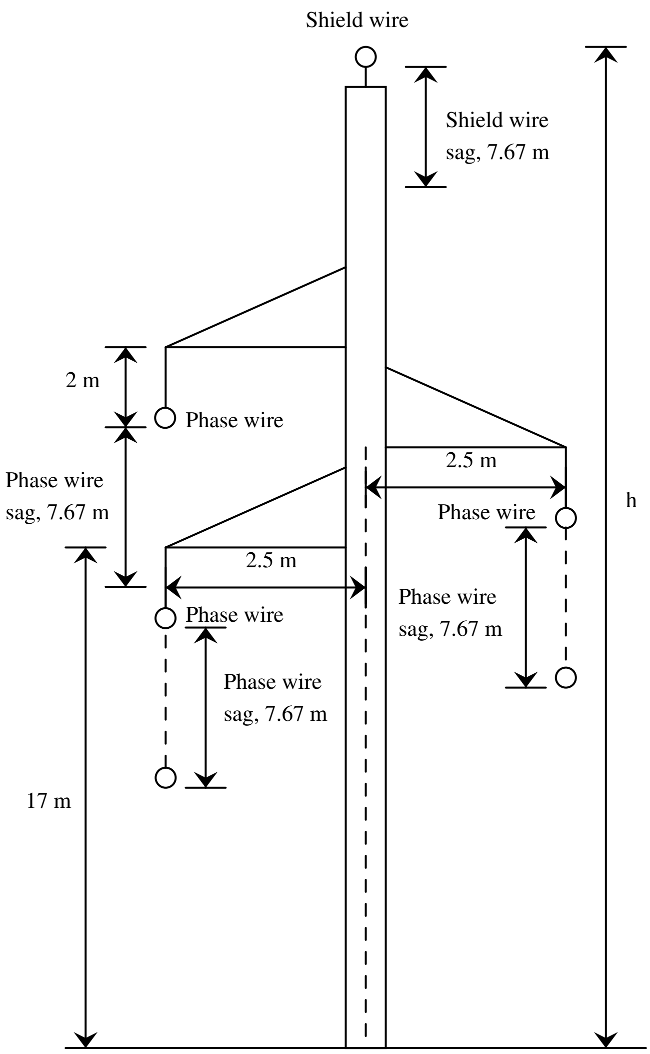


Figure 3.7: Concrete tower with a vertical phase displacement and one shield wire.

Figure 3.8: Concrete tower with a vertical phase displacement and one shield wire.

3.3 PSCAD model

A model was developed in PSCAD since LPE cannot distinguish between different short circuits caused by the lightning and the limitations in the software with different tower foot resistances and ungrounded poles. The aim with the PSCAD model is to estimate the fault distribution for portal tower and to determine if every pole needs to be grounded. Furthermore, it is also used to determine the performance of a transmission line with mixed tower foot resistances. There are two separate models, one with portal towers with one shield wire and one model with portal towers with two shield wires. Each model consists of 9 towers. The system voltage is set to 145 kV. The towers, phase conductors and shield wires are modeled with parameters from section 3.2.1.

A small section of the model with one shield wire can be seen in Figure 3.9. The Figure shows one of the towers with adjacent span on each side. Towers are built as modules. In [19] it is recommended to use the Frequency Dependent (Phase) model for the lines in the span. It is a distributed model and it has a high accuracy for calculations with wave propagation [19]. Therefore the phase conductors and shield wires are modelled using Frequency Dependent (Phase) model. Furthermore, as suggested in [14], phase conductors and shield wires are terminated at the ends by their respective wave impedance according to (2.5) in order to avoid reflections.

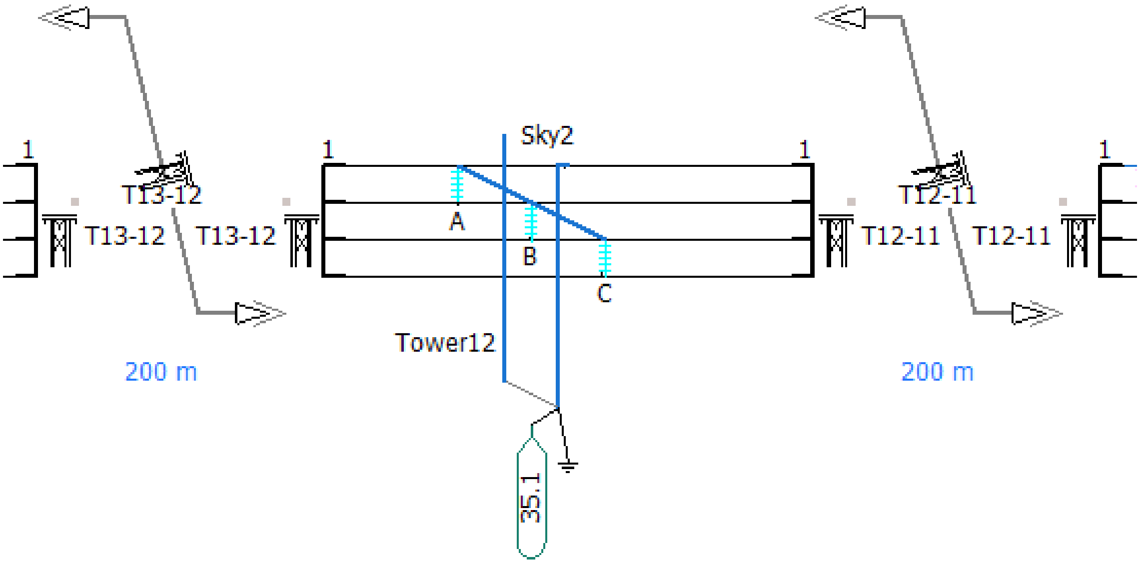


Figure 3.9: Portal tower with one shield wire and adjacent spans in the PSCAD model.

Tower foot impulse resistance is modeled using (2.22), the constant I_g is calculated according to (2.21) with a soil resistivity of 3000 Ω m. For the model with one shield wire the towers are modeled with one downlead and a wave impedance of 247.3 Ω according to (2.12) while the model with two shield wires is using two downleads with a resulting wave impedance of 162.9 Ω according to (2.14). In PSCAD the wave impedance of the towers is modeled using a Bergeron model as wave impedance. The Bergeron model is a PSCAD model of a wave impedance which can be used to model transmission towers, apart from the value of the wave impedance it also considers height and travel time [19]. Ungrounded towers are modeled without any downlead.

The flashover characteristic for the insulator strings are modeled with a nonstandard flashover voltage using the leader progression model, LPM, which is valid for a large range of impulse shapes. LPM describes the leader propagation in a gap after the gap was bridged by streamers [1, 2]. It is based on experimental results presented in [20], where the performance of air gaps exposed to lightning impulses were investigated [20]. The leader propagation is described by the following equation

$$\frac{dL}{dt} = ku(t)(\frac{u(t)}{d_g - l_1} - E_0) \tag{3.3}$$

where u(t) is the voltage across the gap, d_g is the gap length, l_1 is the current length of the leader, k is a constant and E_0 is the breakdown gradient constant which determines when the breakdown process may start. The values of k and E_0 are geometry and polarity dependent. For cap and pin insulators with a positive polarity CIGRE recommends E_0 equal to 520 kV and k equal to 1.2 µm^{2}v^{-2}s^{-1} [2].

Based on the work in [21], the insulator string are modeled as modules containing a stray capacitance in parallel with a switch. The length of the leader at every time step is calculated with (3.3) and once the gap is bridged and breakdown occurs the switch is closed.

The lightning in PSCAD is modeled using a double exponential function

$$i(t) = \frac{I}{\eta}(e^{-t/\tau_1} - e^{-t/\tau_2}) \tag{3.4}$$

where I is the current amplitude, η is a correction factor used to achieve the correct amplitude, τ_1 and τ_2 are constants determining front and tail time [22]. They are selected in order to achieve a front and tail time of 2.2 µs respectively 77.5 µs.

In [14] it is mentioned that flashover from cross arm to ground can be modeled using (3.3) by adjusting the gap distance. Furthermore, in [23] it is mentioned that the flashover voltage of a dry wood pole can be assumed to be 3000 kV. Therefore (3.3) is used to model flashover over the pole with d_g adjusted to achieve a flashover voltage of 3000 kV.

3.3.1 Distributed tower foot resistance

Two different models are used to calculate the lightning performance with mixed tower foot resistance. These models are exactly the same as described in section 3.3, with one respectively two shield wires, but with different tower foot resistances. Every pole is grounded, but some of the poles are poorly grounded with a high tower foot resistance. This is done in order to compare the case with every second pole grounded as mentioned in section 3.3 to a case where every pole is grounded but some of the poles are left with a high tower foot resistance. Figure 3.10 shows the first model. The numbers in the Figure corresponds to the low current value of the tower foot resistance.

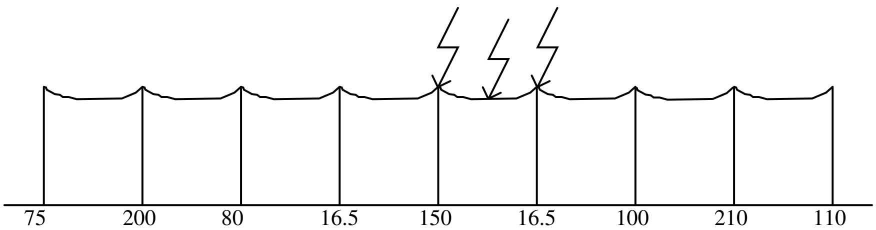


Figure 3.10: First distributed tower foot resistance model with lightning stroke points and tower foot resistances of poles marked.

Lightning strokes takes place at at the 16.5 Ω tower, 150 Ω tower and at the shield wire in the span between the two towers. The second distributed tower foot resistance model can be seen in Figure 3.11. The lightning strokes takes place at the 35.1 Ω respectively 150 Ω towers and at the shield wire in the span between them.

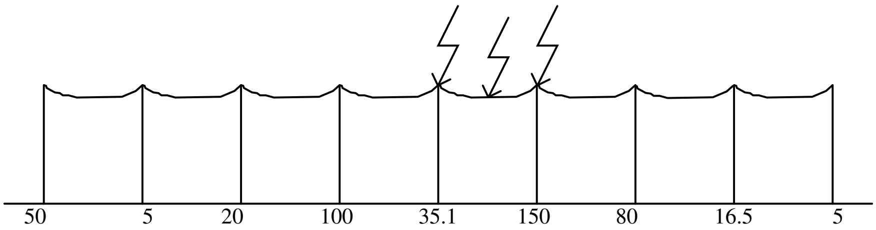


Figure 3.11: Second distributed tower foot resistance model with lightning stroke points and tower foot resistances of poles marked.

4

Lightning performance

This chapter presents the lightning performance for three tower configurations with different shield wire positions and tower foot resistances. According to Vattenfall's fault statistics a portal tower without shield wires has about 2.5 faults per 100 km and year [9]. Initially it was believed that the average lightning stroke was about 20 kA and that a foot resistance of 27.5 Ω is something to strive for. However, in section 2.1.1 it is shown that the average lightning stroke has an amplitude of 33.3 kA or less, therefore a new resistance value was calculated from BIL to 16.5 Ω. Furthermore, some real tower foot resistance values are also used in the simulations. These are based on field measurements of tower foot resistances and they are: 5 Ω from an area with clay in the soil, the average value of the poles on a line in the Swedish inland 35.1 Ω and 150 Ω, which corresponds to poles located on mountainous soil.

4.1 Steel tower

As mentioned in section 1.3 the position of the shield wire for concrete and steel tower is evaluated. Figure 4.1 shows the total line performance for steel tower with a tower foot resistances of 16.5 Ω, 35.1 Ω and 150 Ω. It can be seen that number of faults per 100 km and year increases almost linearly with increased shield wire height. An increased height does not improve the lightning performance. Independently of the tower foot resistance the lightning performance would improve if the height of the shield wire is decreased slightly. For example, if the shield wire is placed at 28.5 m it gives 1.25 faults per 100 km and year for a tower foot resistance of 16.5 Ω. If it is possible to move the shield wire down to 26 m the number of faults would decrease by 0.13 faults per 100 km and year to 1.12 faults per 100 km and year.

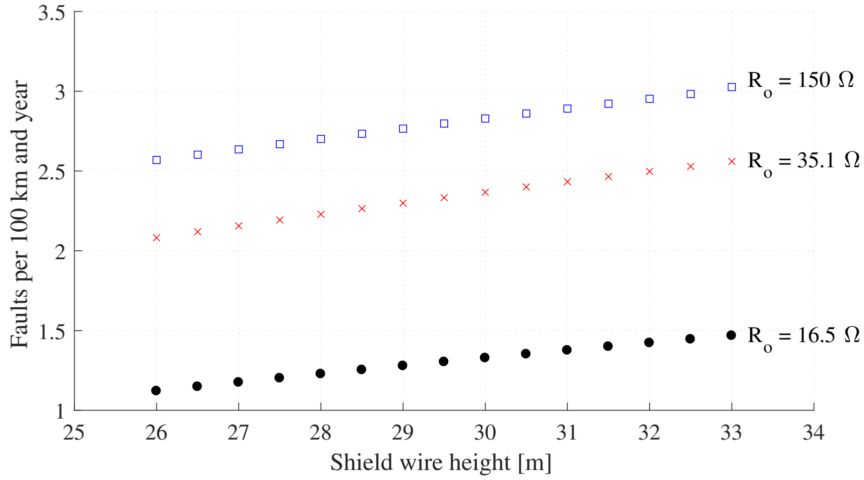


Figure 4.1: Total line performance of a steel tower for different shield wire heights and with different tower foot resistances.

The total amount of faults in Figure 4.1 consists of shielding failure flashovers and back flashovers. Figure 4.2 shows the shielding failure flashover rate per 100 km and year. It is important to notice that the y-axis is with ten to the power of minus three. If the shield wire height is increased the shielding failure rate is slightly reduced until a height of about 30 m is reached where the amount of shielding failure flashovers starts to increase again.

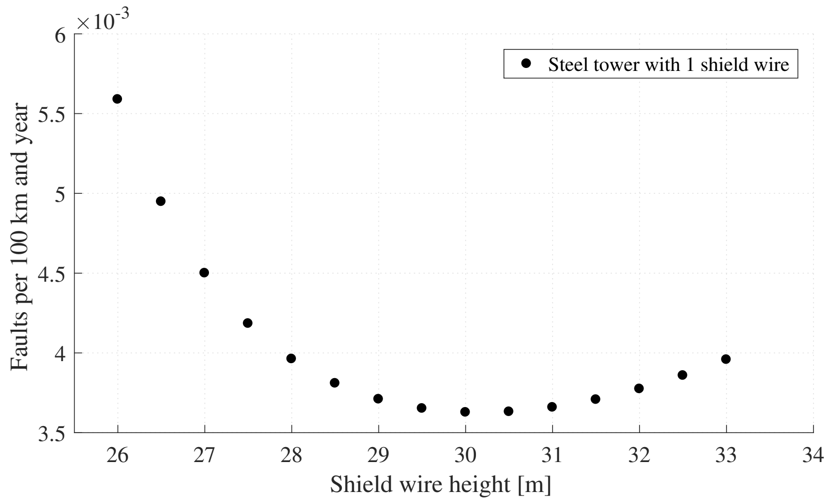


Figure 4.2: Amount of shielding failure flashovers as a function of the shield wire height for steel tower.

If one would only look at shielding failure flashover rate a higher position of the shield wire would be better. However, Figure 4.1 showed that the total amount of faults increased anyway. This can be explained by looking at Figure 4.3, which shows the amount of back flashovers at different tower foot resistances.

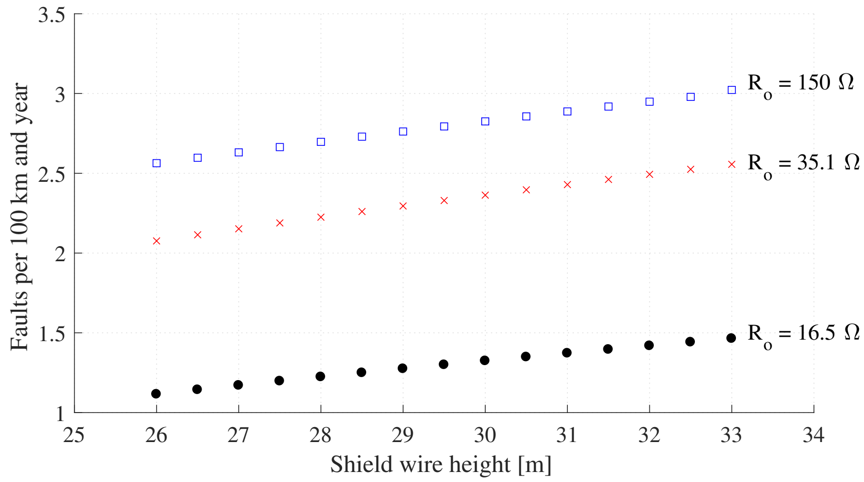


Figure 4.3: Back flashovers for steel tower with different tower foot resistances and different shield wire heights.

Figure 4.3 shows that the amount of back flashovers increases with an increased height. When the shield wire height is increased the amount of back flashovers increases faster than the amount of shielding failures decreases, which causes the total amount of faults to increase. This is also valid in the other direction when the shield wire height is decreased which causes the amount of backflashovers to decrease faster than the shielding failures increase. This is why a shield wire located at 26 m has a better lightning performance than the current shield wire location at 28.5 m even though the amount of shielding failures would increase if the height is reduced.

4.2 Concrete tower

The shield wire height of the concrete tower was swept in a similar way, from the current height of 26 m up to 33 m in steps of 0.5 m. The total amount of faults can be seen in Figure 4.4.

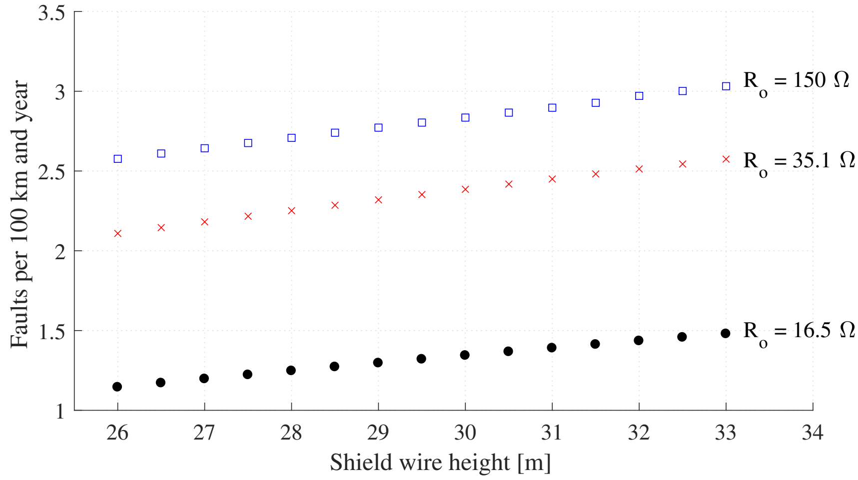


Figure 4.4: Total line performance for concrete tower with different tower foot resistance and different shield wire heights.

Figure 4.4 shows that the total amount of faults would increase if the height of the shield wire is increased. The shielding failure flashover rate can be seen in Figure 4.5. Similar to the case with steel tower the amount of shielding failures decreases with an increased height to a minimum at 29 m. If the shield wire height is increased further the amount of shielding failure flashovers increases.

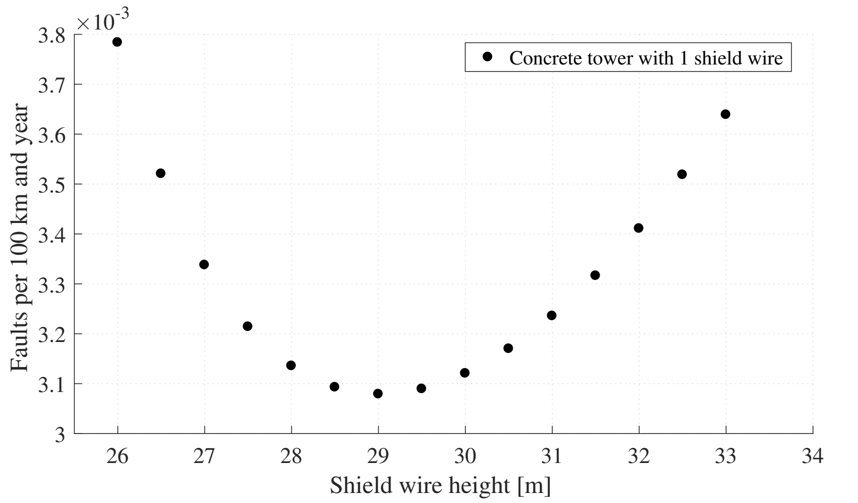


Figure 4.5: Amount of shielding failure flashovers as a function of shield wire height for concrete tower.

As for the steel tower the amount of back flashovers increases faster than the decrease in shielding failure flashovers for concrete tower, which can be seen in Figure 4.6. It can be concluded that the height of the shield wire should remain at 26 m for the concrete tower. Furthermore, the concrete tower has a similar lightning performance as the steel tower. The main difference is that the steel tower has a higher amount of shielding failure flashovers.

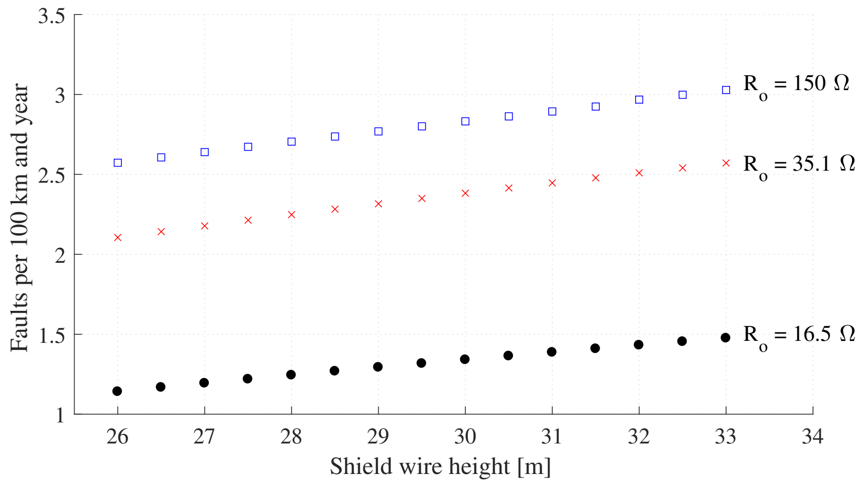


Figure 4.6: Back flashovers for concrete tower with different tower foot resistances and shield wire heights.

4.3 Portal towers

The portal tower is evaluated with one respectively two shield wires. The simulations are performed by gradually pushing the shield wire upwards in steps of 0.5 m. Figure 4.7 shows the total amount of faults per 100 km and year for portal tower with one shield wire in red respectively with two shield wires in black as a function of shield wire height. In this case the tower foot resistance is 16.5 Ω.

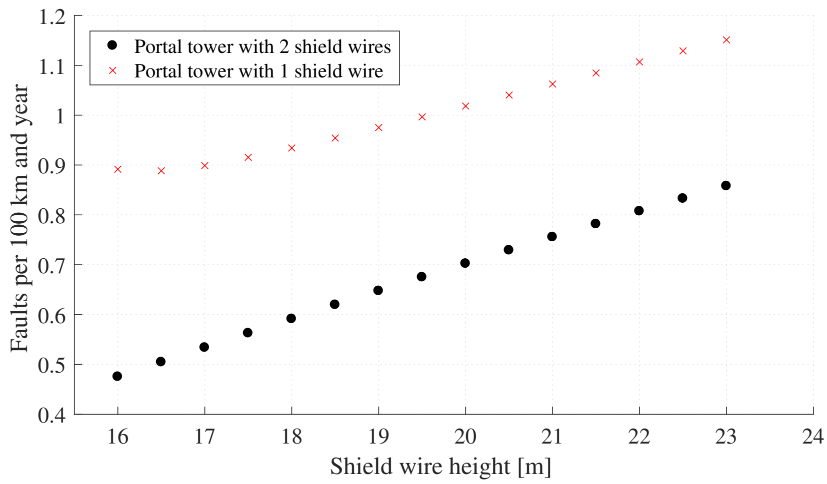


Figure 4.7: Total line performance for wood portal towers for different shield wire heights with one respectively two shield wires and a tower foot resistance of 16.5 Ω.

The current shield wire height for portal tower with one shield wire is 16 m and it is clearly seen that the number of faults would increase if the shield wire height is increased. Another important observation is that the number of faults decreased by applying a second shield wire. For a shield wire height of 16 m the amount of faults with one shield wire is 0.89 per 100 km and year and for two shield wires it is 0.48 per 100 km and year. In order to see how shielding failure and back flashover contributed to the total amount of faults they were calculated.

The amount of shielding failure flashovers per 100 km and year with one respectively two shield wires can be seen in Figure 4.8. As the shield wire height increases the amount of shielding failures decreases for the tower with one shield wire. The difference between the towers is biggest at 16 m.

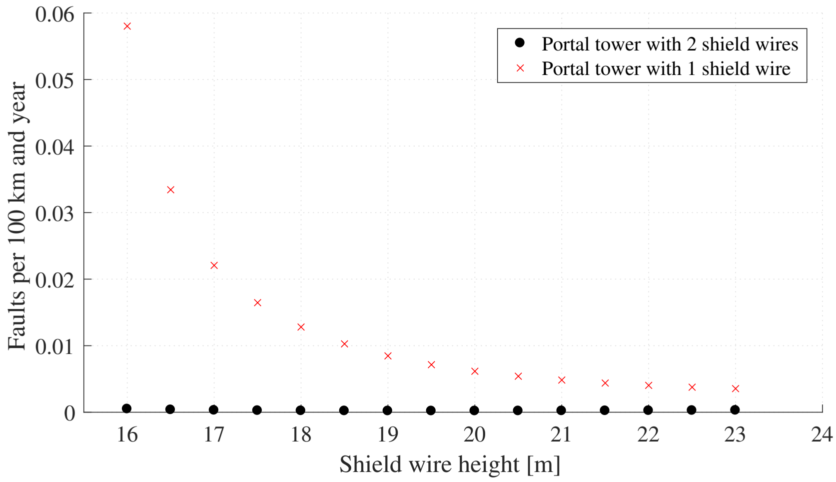


Figure 4.8: Amount of shielding failure flashovers as a function of shield wire height with one respectively two shield wires for wood portal tower.

Furthermore, the amount of shielding failure flashovers with two shield wires is almost zero regardless of the shield wire height. This does not mean that the total amount of faults with two shield wires is zero since the back flashovers needs to be considered. Figure 4.9 shows the back flashover contribution to the total line performance for one respectively two shield wires. There is a large difference in the amount of back flashovers for the two configurations. Back flashovers are increasing with shield wire height and they account for the majority of the faults for both configurations.

So far the simulations showed that two shield wires are superior to one shield wire for a tower foot resistance of 16.5 Ω. In order to verify that this holds even if the tower foot resistance is changed simulations were performed for a range of different tower foot resistances.

Figure 4.10 shows the total amount of faults per 100 km and year with these tower foot resistances for a portal tower with one shield wire. The tower foot resistance has a large influence on the amount of faults due to lightning strokes. The dashed line shows the amount of faults for a portal tower without shield wires. As mentioned earlier a portal tower without any shield wires has about 2.5 faults per 100 km and year according to Vattenfall's fault statistics [9]. This is quite close to the dashed line in Figure 4.10, where the total amount of faults without any shield wire is slightly below 2.5 faults per 100 km and year.

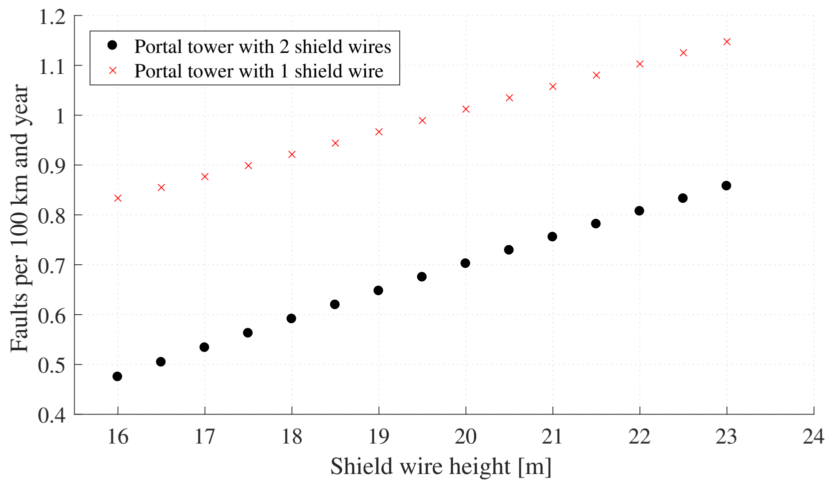


Figure 4.9: Back flashovers for wood portal towers with one respectively two shield wires as a function of different shield wire heights and with a tower foot resistance 16.5 Ω.

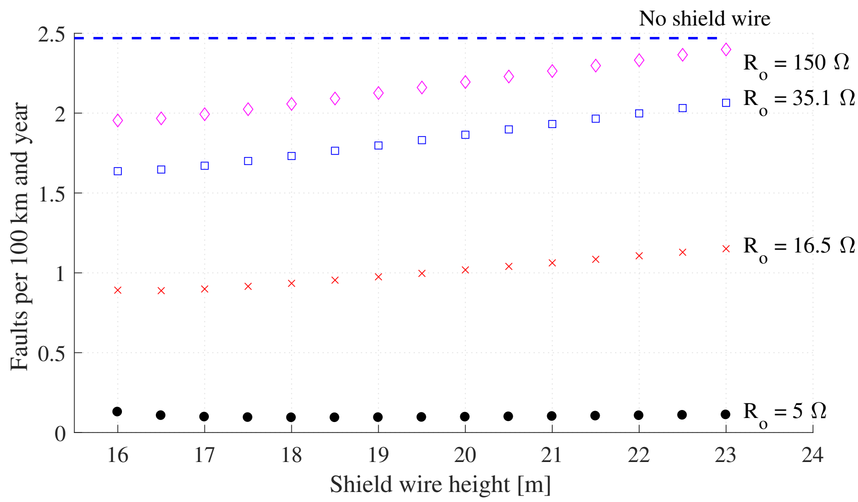


Figure 4.10: Total line performance for a wood portal tower without shield wire and a wood portal tower with one shield wire placed at different heights and different tower foot resistances.

From Figure 4.10 it can be seen that the tower foot resistance has a large impact on the amount of faults. By adding one shield wire the amount of faults are decreased much even for a high tower foot resistance. For a tower foot resistance of 16.5 Ω the amount of faults are decreased by about 1.5 faults per 100 km and year by placing a shield wire at 16 m. The performance is best for a shield wire height of 16 m independently of the tower foot resistance. Furthermore, 16 m is the current location of the shield wire which means that the shield wire should be kept at its current placement. The reduction in faults with a low tower foot resistance and a slightly increased shield wire height to 16.5 m is negligible.

The same simulation was also performed for portal tower with two shield wires. The total amount of faults per 100 km and year can be viewed in Figure 4.11. As previously, the dashed line marks the amount of faults for portal tower without shield wire, while the dotted lines are portal tower with two shield wires with different tower foot resistances. Once again it can be seen that the tower foot resistance has a big influence on the amount of faults.

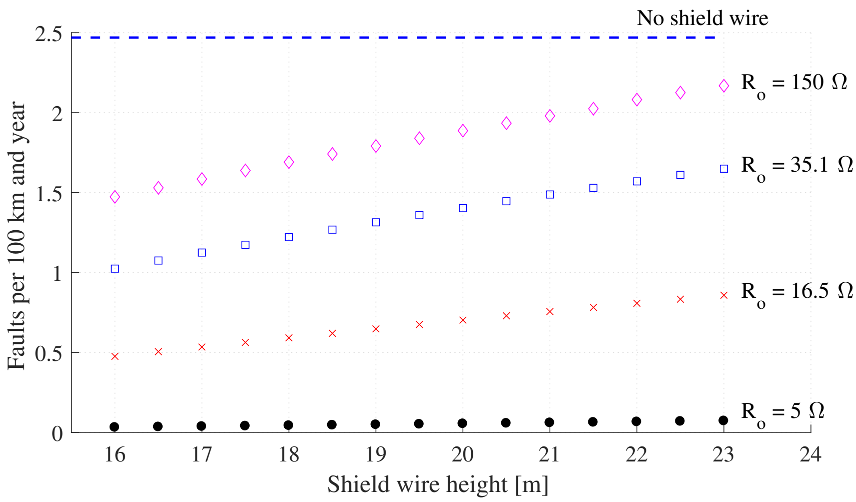


Figure 4.11: Total line performance for a wood portal tower without shield wire and a wood portal tower with two shield wires placed at different heights and different tower foot resistances.

By applying two shield wires at a height of 16 m and a tower foot resistance of 16.5 Ω the amount of faults is reduced by about 2 faults per 100 km and year compared to a portal tower without shield wires. It is however sufficient with a tower foot resistance of 35.1 Ω in order to decrease the amount of faults by half. Furthermore, if a portal tower is equipped with two shield wires they should be placed at 16 m independently of the tower foot resistance. The amount of faults for portal tower with one respectively two shield wires with the different tower foot resistances can be seen in Table 4.1.

Table 4.1: Number of faults per 100 km and year.

Tower foot resistance	5 Ω	16.5 Ω	35.1 Ω	150 Ω
One shield wire	0.1277	0.8916	1.6365	1.9542
Two shield wires	0.0304	0.4753	1.0240	1.4733
Difference	0.0973	0.4163	0.6125	0.4809

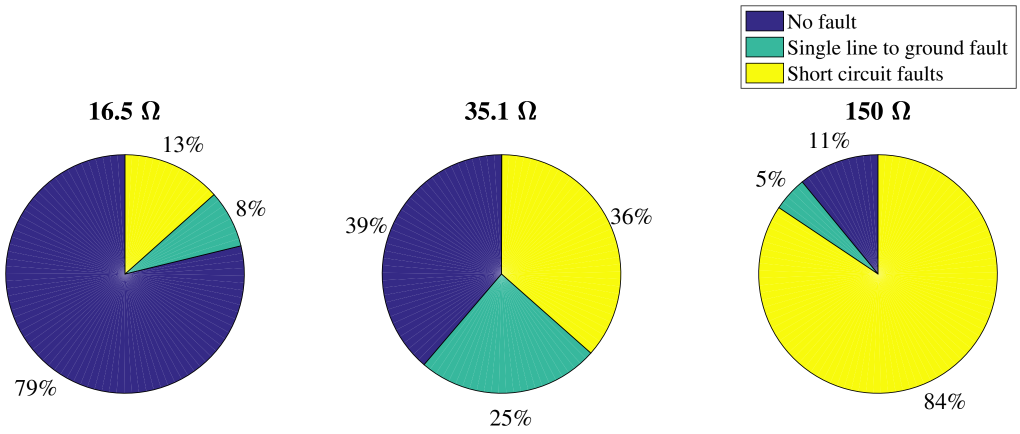
4.3.1 Fault distribution

Earlier it is only mentioned how the amount of faults changed with different tower foot resistances, an additional shield wire and the location of the shield wires. This chapter presents the fault distribution for strokes to towers and shield wires in the span. Furthermore, in the previous section it was seen that the number of faults due to strokes to the phase conductors was small and therefore the distribution of those faults are not calculated. Lightning amplitude required to cause a certain fault is calculated in PSCAD with the models described in section 3.3 and the result is presented in Appendix A.1 and A.2. The results in this chapter are however presented as the percentage of the strokes that are expected to cause a certain fault. This is calculated by translating a current amplitude to how often it occurs by using the CIGRE distribution from section 2.1.1. First it is done for the tower setup with one shield wire with the same tower foot resistance for every pole and later with every second pole grounded. Furthermore, it is also done with the distributed tower foot resistance models from section 3.3.1. The same procedure is also carried out for the portal tower with two shield wires. In section 4.3 it was concluded that the shield wires should be placed at a height of 16 m for an optimal lightning performance. Therefore the shield wires are placed on a height of 16 m in all of the PSCAD simulations.

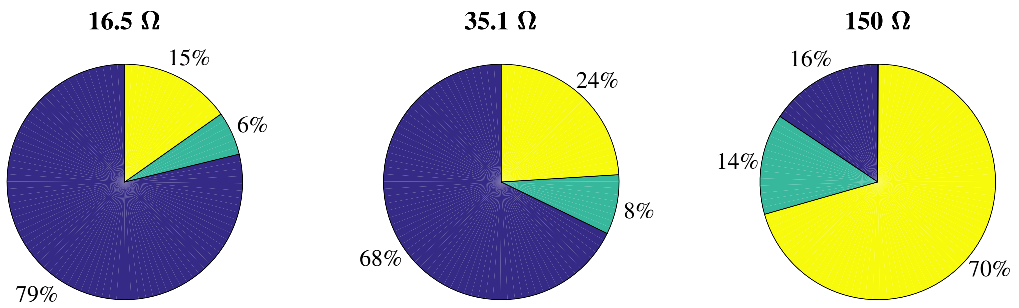
4.3.1.1 Portal tower with one shield wire

The first case is a portal tower with one shield wire and every pole grounded with the same tower foot resistance. The results for strokes to the tower is depicted in Figure 4.12a. It shows the expected fault distribution for a system with three different tower foot resistances. It should be noted that the yellow pie chart contains both the two-phase short circuits and three-phase short circuits. They are lumped together since they are both considered severe and it is not necessary to distinguish between them. The lightning performance is very good for the case when all the towers has a tower foot resistance of 16.5 Ω. Almost 80 % of the strokes will cause no faults. As the tower foot resistance is increased to 35.1 Ω respectively 150 Ω the amount of faults increases, especially the short circuits. With a tower foot resistance of 150 Ω a majority of the strokes will lead to a short circuit.

In Figure 4.12a it is seen what happens when the lightning stroke hits the tower. However, all strokes are not expected to hit towers and therefore it is interesting to calculate the lightning performance for strokes to the span. This can be seen in Figure 4.12b. For the system with a tower foot resistance of 16.5 Ω it has not changed much but the difference is large for the systems with high tower foot resistance, especially for 35.1 Ω. Almost 70 % of the strokes to the span causes no fault compared to 40 % from the previous case when the lightning stroke hit the tower. As explained in section 2.2.2 a stroke to the span is expected to produce either the same or less overvoltage at the tower compared to a stroke at the tower. However, since strokes also are expected to hit the towers a tower foot resistance of 35.1 Ω with one shield wire is not sufficient to manage half the lightning strokes without any faults.



(a) Lightning strokes to the tower.



(b) Lightning strokes to shield wire in the span between two towers.

Figure 4.12: Fault distribution for wood portal tower with one shield wire and three different tower foot resistances. Strokes to the tower (a) and strokes to the shield wire in the span between two towers (b).

Furthermore, the fault distribution with every second tower grounded is calculated. Figure 4.13a shows the expected fault distribution for strokes to a grounded tower. It has slightly worse performance compared to the system with every tower grounded and strokes to the tower. The back flashovers occurs first at the grounded tower which was struck by the lightning.

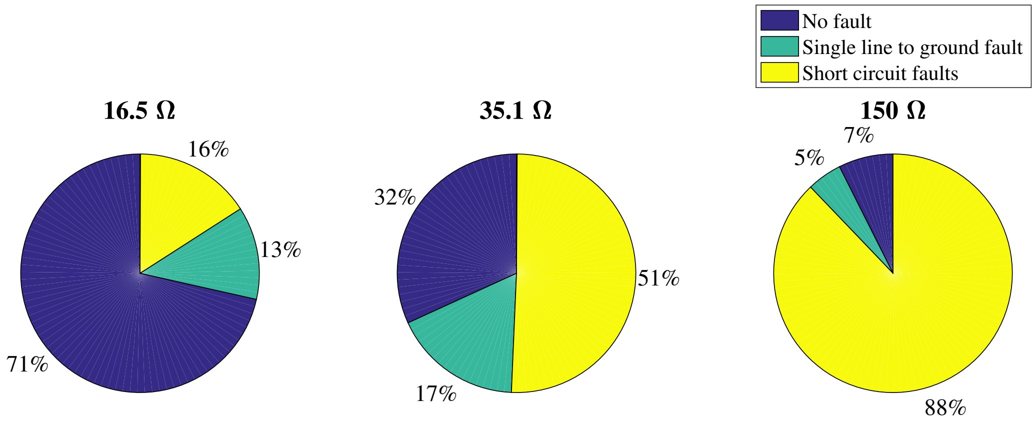
A lightning stroke in the span between a grounded and ungrounded tower decreased the lightning performance a lot, which is seen in Figure 4.13b. Almost all of the strokes results in short circuit independently of the tower foot resistance. It should also be noted that the back flashovers occurs first at the closest ungrounded tower.

Figure 4.13c shows the lightning performance for strokes to an ungrounded tower. As with strokes to the span the back flashovers occurs at the ungrounded tower, but now its even worse than a stroke to the span. For a tower foot resistance of 16.5 Ω respectively 35.1 Ω 96% of the strokes to an ungrounded tower causes short circuits.

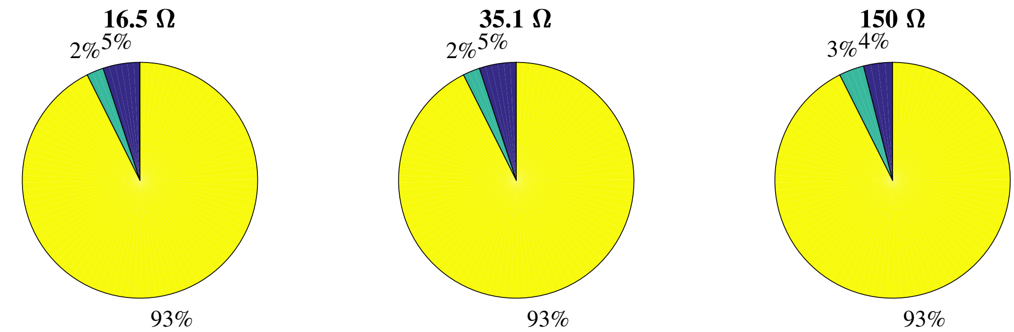
The lightning performance for a system with every third pole grounded or even less frequent is not calculated since the lightning performance is so poor for a system with every second tower grounded. Another interesting question is then how the lightning performance is if every tower is grounded but if some of the groundings has a high tower foot resistance. The two different models with mixed tower foot resistance that are used are the ones which can be seen in Figure 3.10 and 3.11. The lightning performance with one shield wire for the first model is depicted in 4.14a. It shows when the lightning stroke hits the tower with a tower foot resistance of 16.5 Ω, a tower with 150 Ω tower foot resistance and the span between the towers. When the lightning hits the tower with a tower foot resistance of 16.5 Ω the lightning performance is almost the same as for the case with every pole grounded. However, if the lightning stroke hits the shield wire in the span or the tower with 150 Ω tower foot resistance the lightning performance is severely reduced and the amount of short circuits is increased.

The fault distribution for the second case of mixed tower foot resistances from Figure 3.11 can be seen in Figure 4.14b. As with the previous case, the lightning performance is more or less the same for strokes to the 35.1 Ω tower as for the case with every pole grounded. Furthermore, the amount of short circuits increases rapidly when the lightning stroke takes place in the span or at the 150 Ω tower.

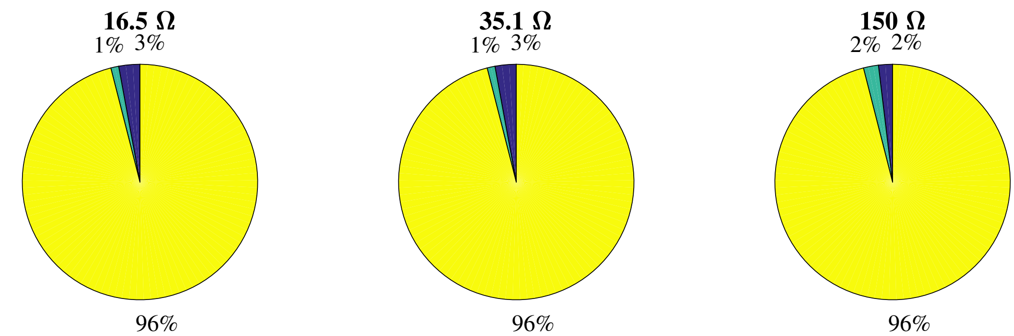
So far it can be concluded that for a portal tower with one shield wire every pole needs to be grounded with a low tower foot resistance. It is not sufficient to ground every second tower or to leave every second tower with a tower foot resistance of 35.1 Ω.



(a) Lightning strokes to a grounded tower.

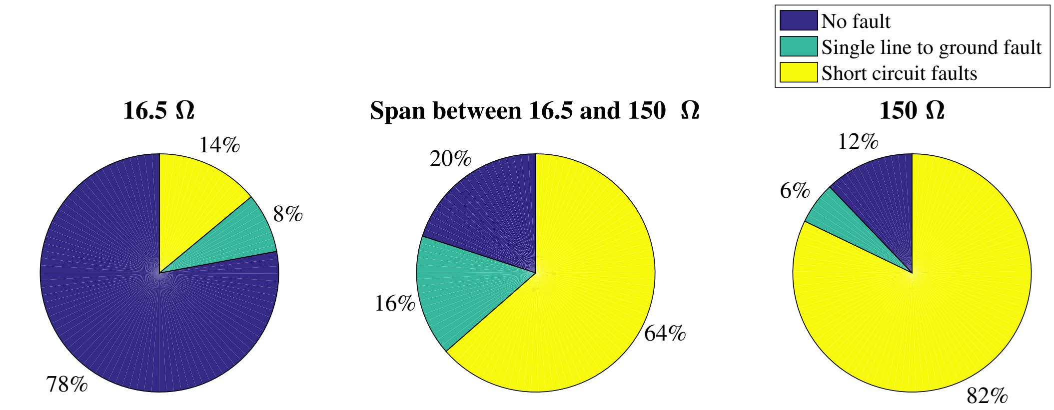


(b) Lightning strokes to the shield wire in the span between a grounded and an ungrounded tower.

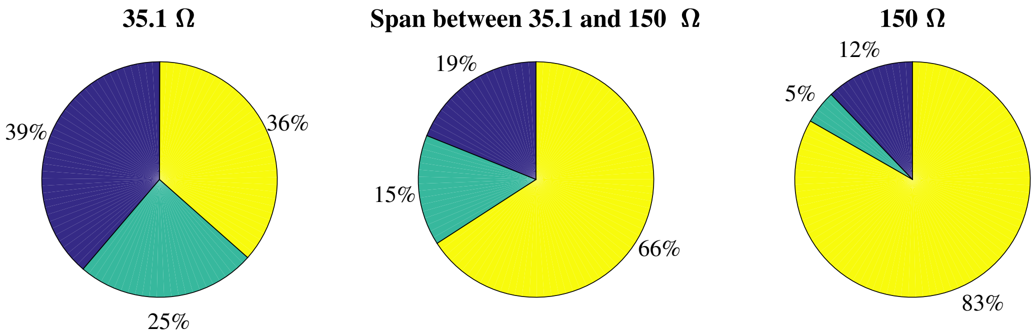


(c) Lightning strokes to an ungrounded tower.

Figure 4.13: Fault distribution for wood portal tower with one shield wire and every second tower grounded with three different tower foot resistances. Strokes to the grounded tower (a), strokes to the span between a grounded and an ungrounded tower (b) and strokes to an ungrounded tower (c).



(a) Strokes to two different towers and the span between them using the first distributed model.



(b) Strokes to two different towers and the span between them using the second distributed model.

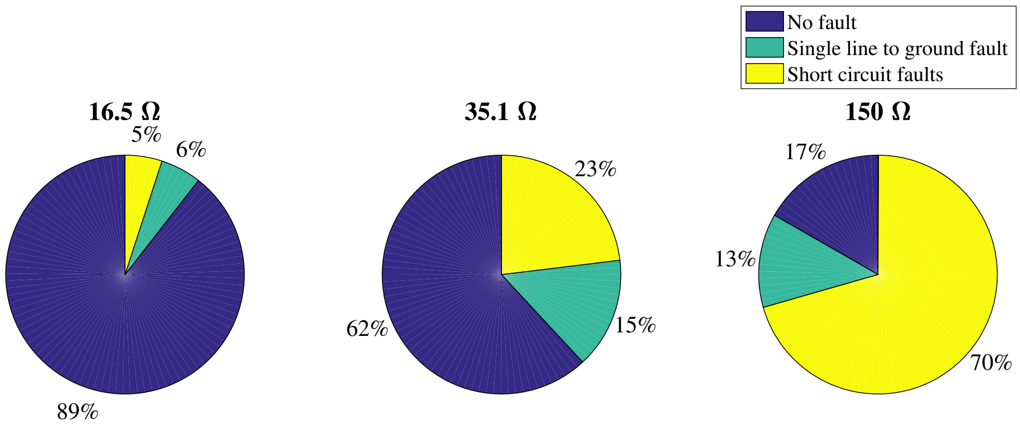
Figure 4.14: Fault distribution for a wood portal tower with one shield wire using the first distributed tower foot resistance model (a) and the second distributed tower foot resistance model (b). Lightning strokes hits two towers with different tower foot resistances and the span inbetween.

4.3.1.2 Portal tower with two shield wires

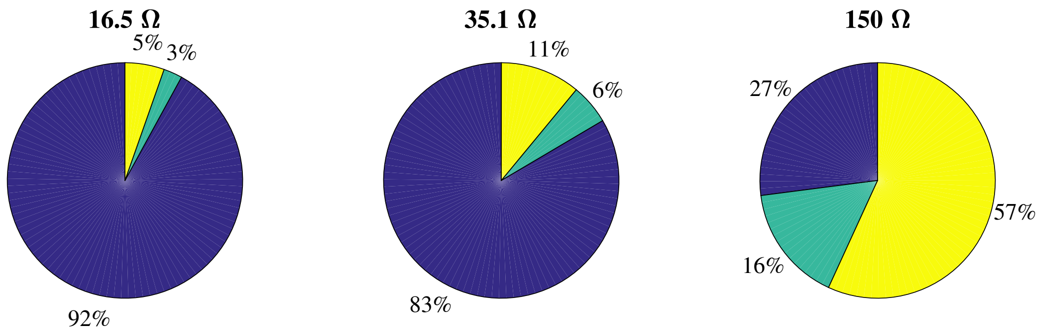
This chapter presents the fault distribution for a portal tower with two shield wires. Results are presented in the same way as in the previous chapter, in terms of how large amount of the lightning strokes that will cause a certain fault. Strokes takes place at towers or to the shield wires in the span. Figure 4.15a shows the lightning performance with every pole grounded with the same tower foot resistance. The amount of faults has decreased compared to the setup with one shield wire, though it is still not good enough when the tower foot resistance is as high as 150 Ω. The major difference between one and two shield wires occurs when the tower foot resistance is

35.1 Ω. For this case with two shield wires there are no faults for about 60% of the lightning strokes to the tower compared to about 40% of the strokes to the tower with one shield wire.

The fault distributions for strokes to the span is depicted in Figure 4.15b. For the low tower foot resistance it is slightly better compared to a stroke to the tower. Similar to the case with one shield wire the amount of short circuits decreases when the stroke hits the span. For the case when the system has a tower foot resistance of 35.1 Ω there are no faults for slightly more than 80% of the strokes to the shield wire in the span.



(a) Lightning strokes to the tower.



(b) Lightning strokes to one of the shield wires in the span between two towers.

Figure 4.15: Fault distribution for wood portal tower with two shield wires and three different tower foot resistances. Strokes to the tower (a) and strokes to the shield wire in the span between two towers (b).

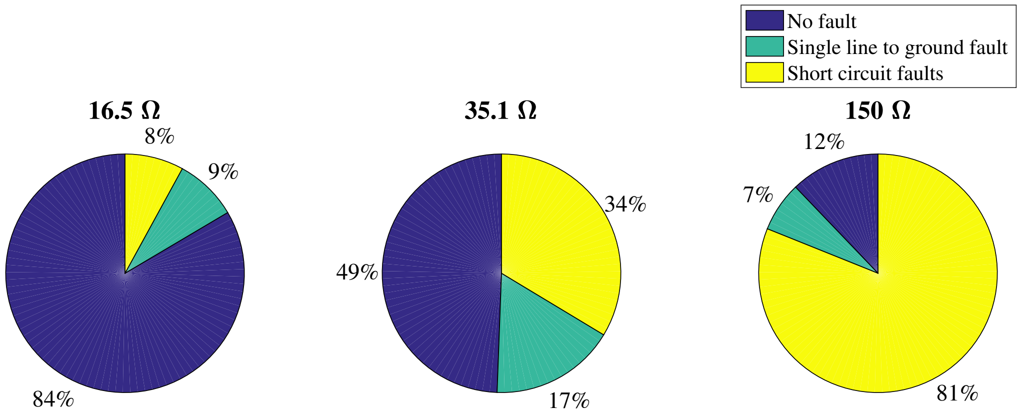
The performance with every second pole grounded is also calculated for the case with two shield wires. First when the lightning stroke hits a grounded tower, which is seen in Figure 4.16a. In this case the back flashovers occurs at the grounded tower first. The performance is still good for a tower foot resistance of 16.5 Ω. For the case with a tower foot resistance of 35.1 Ω the amount of strokes that does not cause a fault has decreased to about 50%. For the high tower foot resistance the short circuits are dominating.

Figure 4.16b shows the fault distribution when the lightning hits the span between an ungrounded and a grounded tower. Similar to the case with one shield wire the lightning performance is poor. More than 80% of the strokes causes a short circuit independently of the tower foot resistance value. It should also be noted that the first back flashovers takes place at the ungrounded tower.

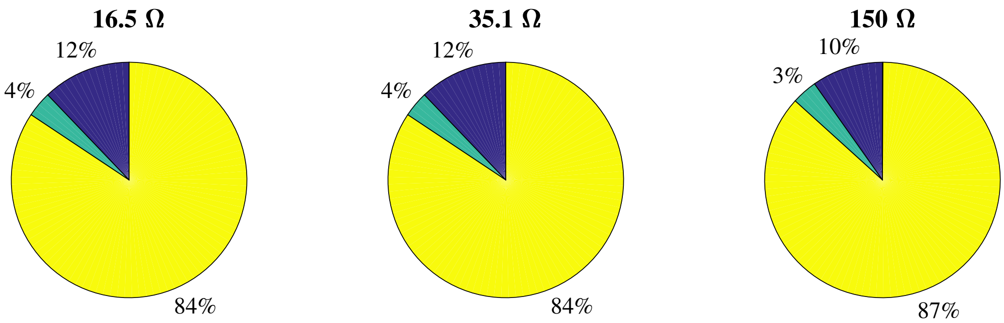
Furthermore, the expected fault distribution when the lightning stroke hits an ungrounded tower in the system can be seen in Figure 4.16c. It is slightly worse than a stroke to the span. The short circuits are dominating regardless of the tower foot resistance. The flashovers occurs at the ungrounded tower.

So far it has been observed that the fault distribution contains a large amount of short circuits if every second poled is grounded. It can be concluded that every pole needs to be grounded, regardless of if one or two shield wires are used. As with the previous case with one shield wire it is not necessary to calculate the fault distribution with every third pole grounded, instead it is calculated with every pole grounded and a mixed tower foot resistance. The same models with mixed resistances that was used for the case with one shield wire is used again. The fault distribution with the first model from Figure 3.10 and two shield wires can be seen in Figure 4.17a. The performance for strokes to the 16.5 Ω tower is slightly better than the case with one shield wire. The big difference occurs for strokes in the span, where the amount of strokes which causes no fault has doubled with two shield wires. Furthermore, for strokes to the 150 Ω tower the performance is slightly better than for the case with one shield wire.

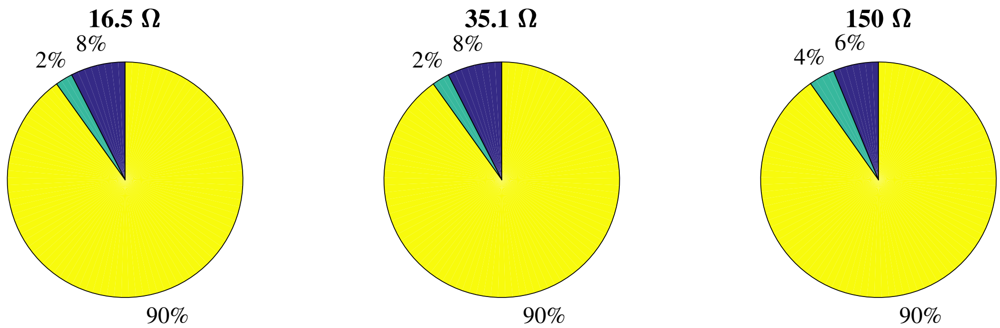
The final simulation is the second model with mixed tower foot resistances from Figure 3.11 with two shield wires. The resulting fault distribution can be seen in Figure 4.17b. The performance is quite poor for strokes in the span and for strokes to the 150 Ω tower.



(a) Lightning strokes to a grounded tower.

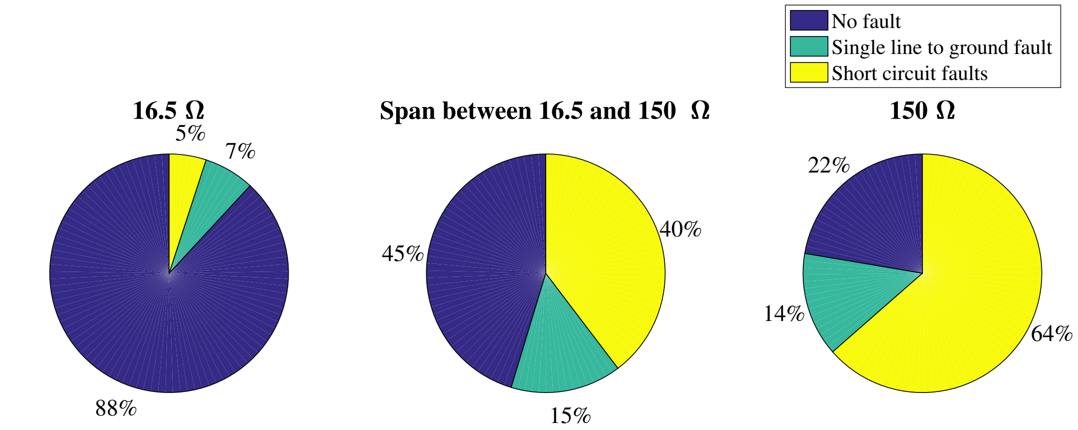


(b) Lightning strokes to one of the shield wires in the span between a grounded and an ungrounded tower.

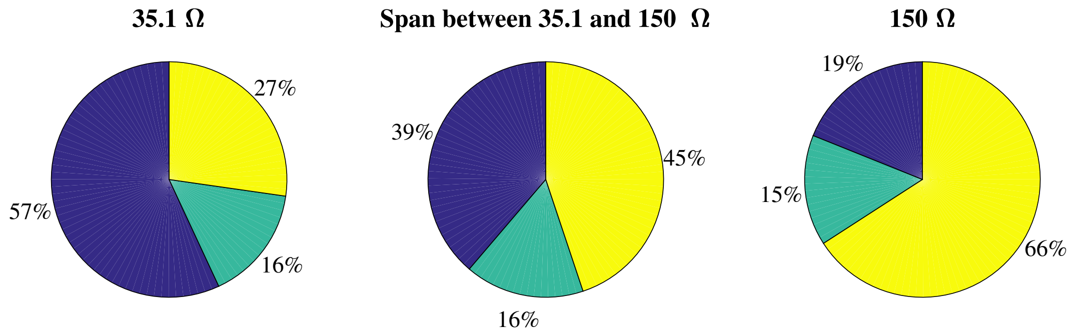


(c) Lightning strokes to an ungrounded tower.

Figure 4.16: Fault distribution for wood portal tower with two shield wires and every second tower grounded with three different tower foot resistances. Strokes to the grounded tower (a), strokes to the span between a grounded and an ungrounded tower (b) and strokes to an ungrounded tower (c).



(a) Strokes to two different towers and the span between them using the first distributed model.



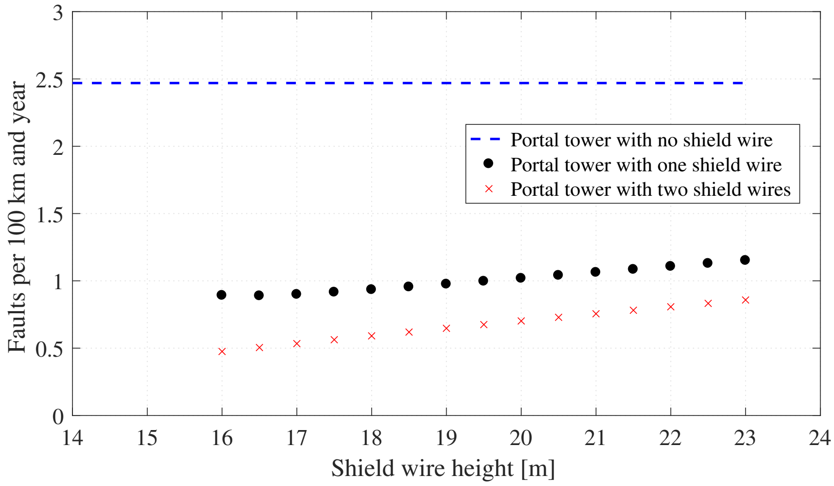
(b) Strokes to two different towers and the span between them using the second distributed model.

Figure 4.17: Fault distribution for a wood portal tower with two shield wires using the first distributed tower foot resistance model (a) and the second distributed tower foot resistance model (b). Lightning strokes hits two towers with different tower foot resistances and the span inbetween.

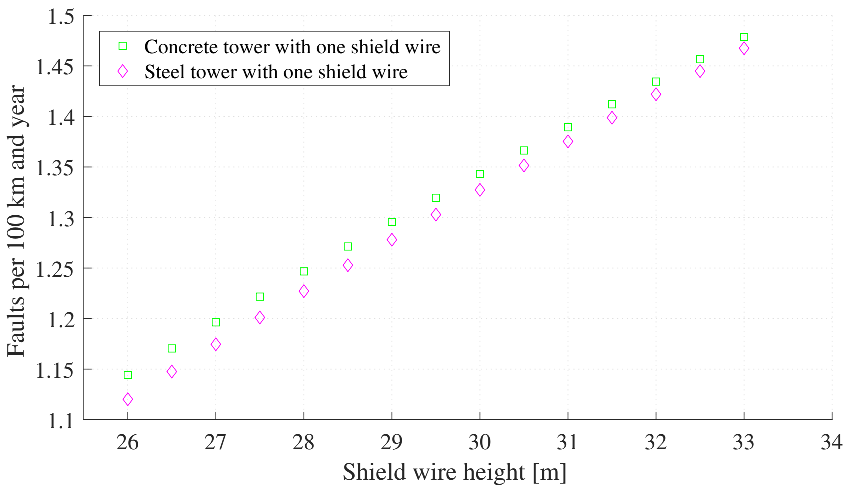
One important observation that was obtained during the fault distribution simulations is that every pole needs to be grounded with a low tower foot resistance. Furthermore, back flashovers takes place at the closest tower which is ungrounded or has a high tower foot resistance except for the case when the lightning stroke hits a grounded tower with low tower foot resistance. The difference is small in the fault distribution for a tower foot resistance of 16.5 Ω regardless if one or two shield wires are used. The main difference is when the tower foot resistance is 35.1 Ω, where the performance is a lot better with two shield wires. This means that a setup with two shield wires can tolerate a higher tower foot resistance than a setup with one shield wire with the same fault distribution.

4.4 Comparison between the three tower types

In this section a comparison of the total line performance for the three different tower types is done. These are concrete tower, steel tower and tree portal tower without shield wire or with one respectively two shield wires. Figure 4.18(a) shows the portal towers while 4.18(b) shows steel and concrete tower. All tower foot resistances are 16.5 Ω in this case. Firstly, the tower that has the most faults per 100 km and year is the portal tower without shield wire. It has almost 2.5 faults per 100 km and year. The tower configuration that has the lowest amount of faults is the portal tower with two shield wires. It never goes above 1 fault per 100 km and year even if the shield wires are placed high. The lowest amount of faults for two respectively one shield wire occurs when the shield wire is placed at 16 m. At 16 m the difference between one and two shield wires is almost 0.5 faults per 100 km and year. The concrete and steel tower has more faults per 100 km and year than any of the portal towers with shield wires even when they have the same tower foot resistance. Furthermore, in section 4.1 respectively 4.2 it was shown that the amount of shielding failures was low for both concrete and steel tower. The total amount of faults is higher since the back flashover rate is higher. Since their structures are higher they attract more lightning strokes. After all these simulations it can be concluded that the tower foot resistance has a large impact on the amount of faults for all tower configurations



(a)



(b)

Figure 4.18: Total line performance for all configurations for the wood portal towers (a) with a tower foot resistance 16.5 Ω and total line performance for steel and concrete tower in (b).

Furthermore, for the portal tower with one shield wire, the shielding failure is lower when the shield wire is placed higher on the tower. For shielding failure the steel tower has an optimal height of about 30 m and for concrete tower it was about 29 m. However, these heights does not improve the overall lightning performance since the amount of back flashovers increases faster than the decrease in shielding failure. The back flashover rate is the main contributor to lightning faults. Therefore the the shield wire position should be kept at its current location for concrete tower and portal tower with one shield wire. For the steel tower the shield wire height should be reduced from 28.5 m to 26 m if possible.

4.5 Cost estimation

The construction cost for a steel or concrete tower is about 2.9 million SEK/km , which includes the cost for one shield wire. The wood portal tower without any shield wire costs 1.8 million SEK/km [9]. The cost for the first shield wire on a portal tower for a new construction is estimated to 160000 SEK/km [9]. If the portal tower is built with a second shield wire the additional shield wire is slightly cheaper than the first one since the work is slightly reduced. Therefore the cost for an additional shield wire for a new construction can be estimated to 150000 SEK/km [9]. As mentioned in section 1.4 only new constructions are considered since it is expected to be to expensive to rebuilt an existing line with an additional shield wire. However, the cost for rebuilding an existing line with an additional shield wire is estimated to 260000 SEK/km [9]. It is very expensive since the height of the pole needs to be increased, either by replacing the pole with a longer one or building a steel frame on top of the existing poles.

An average Vattenfall 132 kV line is used as a reference case. The average length of a 132 kV line is 20 km and the average load is 75 MW. Since the 132 kV grid is meshed, customers are usually not experiencing an outage due to a lightning fault. However, industries may still experience severe disturbances and therefore half of the cost for a fault is used as a reference by Vattenfall [9]. The fault cost consists of a fixed part and a time dependent part. The lightning faults are however expected to be cleared fast and thereby only the fixed cost is used in the estimation, according to Vattenfall the cost is 24 SEK/kW [9]. The annual cost for faults per year for the reference line can then be estimated as

$$\text{annual cost per km} = \frac{\text{faults per 100 km and year} \cdot \frac{l}{100} \cdot P_{avg} \cdot \text{cost per kW}}{2 \cdot l} \tag{4.1}$$

where P_{avg} is the average load mentioned earlier, l is the line length and l/100 is used to recalculate it from faults per 100 km and year to the reference line of 20 km. The whole expression is divided by 2 in order to get half the cost according to what was described earlier and 20 in order to get the annual cost per km. If (4.1) should be comparable to an investment cost it needs to be capitalized, or in simple terms, the cost needs to be calculated in SEK/km instead of SEK per km and year. This is done by using an interest of 5% and a time frame of 30 years, which is approximated by multiplying (4.1) with 15.4 [9]. Table 4.2 shows the result of the economic calculations. The annual cost per km for the different configurations is calculated using (4.1) and it is displayed in the second column. The third column shows the annual cost difference per km between the portal tower without a shield wire and the actual configuration, or in other words how much that is saved per year and km due to the reduction in amount of faults. This is then capitalized as described earlier. The last column is the difference in SEK/km between the estimated cost for the construction and the capitalized value.

Table 4.2: Cost estimation for portal towers with different shield wire configurations and tower foot resistances.

Configuration	Annual cost per km	Savings [SEK/km and year]	Capitalized [SEK/km]	Difference [SEK/km]
Without shield wire wire	22 500	-	-	-
One shield wire 16.5 Ω	8024	14 476	222 930	62 930
One shield wire 35.1 Ω	14 729	7771	119 673	-40 327
Two shield wires 16.5 Ω	4278	18 222	280 619	-29 381
Two shield wires 35.1 Ω	9216	13 284	204 574	-105 426

Since lines with a 150 Ω tower foot resistance has a terrible lightning performance and the configurations with a tower foot resistance of 35.1 Ω is not profitable the cost for 150 Ω is not calculated. As shown in section 4.3 a portal tower with one shield wire and a tower foot resistance of 16.5 Ω has a similar lightning performance as a portal tower with two shield wires and a tower foot resistance of 35.1 Ω. However, the only one which is profitable according to (4.1) is the solution with one shield wire and a tower foot resistance of 16.5 Ω. It is very important to notice that the cost for an improved grounding is not included in the comparison. This means that the cost difference between two shield wires and a tower foot resistance of 35.1 Ω and one shield wire and 16.5 Ω would be less in reality. However, it is hard to estimate the cost for an improved grounding since it is very terrain and location dependent. Therefore it is necessary to consider the local conditions where the transmission line is supposed to be constructed. It can however be concluded from Table 4.2 that the reference case equipped with two shield wires and a fault reduction by half can not cover its own costs.

As mentioned earlier the cost for two shield wires for a new construction is 310000 SEK/km. By back calculating using (4.1) with an interest of 5% and a time frame of 30 years the break even cost with two shield wires occurs when the number of faults per 100 km and year equals 0.2073. According to LPE this corresponds to a tower foot resistance of 9.8 Ω. The difference can be changed by except from including the cost of the groundings as mentioned earlier either reducing the cost of the second shield wire, if a larger portion customers are affected by the faults or if the load is higher.

The load required to reach a break even state with the different tower foot resistances is calculated by setting the annual cost per km equal to the estimated cost of the shield wire topology and putting the power as unknown in (4.1). The break even load can be seen in Table 4.3. The costs of groundings is not included in this calculation either. If it is pure industrial loads the break even power can be reduced by a maximum of 50%.

Table 4.3: Power required to reach a break even cost for different portal tower configurations.

Configuration	16.5 Ω	35.1 Ω
Break even power, 1 shield wire	55.3 MW	102.9 MW
Break even power, 2 shield wires	85.1 MW	116.7 MW

5 Discussion

The CIGRE characterization of the negative downward stroke is used in all simulations. It is based on more observations and they are more recent in time than the IEEE characterization. Both characterizations are based on measurements and observations. In reality it can probably deviate a bit from the used amplitude distribution. In section 2.1 it was mentioned that the most common stroke type to transmissions lines is the negative downward stroke. This means that in reality there is a small chance that large positive strokes might hit the transmission lines. This has not been accounted for in the simulations. However, it is rare and at the same time statistical insulation coordination is used so some faults are tolerated. Furthermore, the terrain around the transmission lines are flat in the simulation, which means that effects of objects in the vicinity has not been considered. This could affect the results in both directions since tall objects can provide some shielding against lightning strokes while strokes to trees near the line may result in flashover from the tree to a phase conductor. In order to judge if the results from LPE are credible or not it was compared to Vattenfalls fault statistics for the portal tower without shield wires. According to the statistics it has about 2.5 lightning faults per 100 km and year, which is very close to the simulation results which were slightly below 2.5.

All heights mentioned in the report is for towers on flat terrain. When transmission lines are built the heights may have to be adjusted due to the topography so that the safety regulations regarding the distance to ground from the phase conductors and distance between shield wires and phase conductors are followed. Therefore the heights needs to be considered individually for each line project, maybe even individually for each tower depending on the topography. The heights in the previous section are however the recommended height for shield wires at flat terrain.

The PSCAD model is based on LPM which is used in many lightning studies. It is important to notice that it is a model of the breakdown between the arcing horns for non-standard lightning impulses. Therefore the fault distributions are estimated expectations. Neither LPE or PSCAD considers flashovers within the span. They are however rare in reality since the breakdown strength of the air between the conductors is higher than the breakdown strength between the arcing horns at the insulator strings. In order to verify that the reflections in the model worked as expected it was initially fed with a lightning stroke with linearly increasing amplitude. This made it possible to calculate potentials at towers before and after reflections by hand. Front time was changed with respect to the travel times in order to make sure that all reflections were considered. LPM was verified by calculating the fault distribution for a transmission line with different parameters. This was done since STRI had done a fault distribution for this line. The resulting fault distribution matched the one obtained by STRI.

In section 4.3.1 it is concluded that every pole needs to be grounded in order to achieve a good lightning performance. However, it is important to remember that this is a recommendation and that in practise there are regulations which must be followed in order to avoid dangerous step voltages due to the 50 Hz fault current. If it is not possible to achieve a safe grounding at a pole then the downlead could be removed. As shown earlier this will result in a poor lightning performance for strokes to the ungrounded tower or in the adjacent spans.

Steel and concrete tower has a good lightning performance if the tower foot resistance is as low as 16.5 Ω. They are however more expensive than portal towers and it is not possible to recommend a tower type only based on its lightning performance since there are many other parameters which needs to be considered when a new transmission line is built. The price difference might change in the future though. Today the wood poles of the portal tower is impregnated with creosote. The environmental impact of creosote is discussed and the future is uncertain, since it might be forbidden. This means that in the future the wood poles might need to be impregnated by something else or maybe made of composites or similar. This could change the cost difference between portal tower and steel respectively concrete tower.

The cost estimation showed that the reference case equipped with two shield wires could not cover its own costs. This does not consider the cost of the groundings, which means that it is not entirely true. Since a portal tower with two shield wires and a tower foot resistance of 35.1 Ω has almost the same performance as a portal tower with one shield wire and a tower foot resistance of 16.5 Ω it might be possible to save money by not improving the tower foot resistance and instead building with an additional shield wire instead. Cost of groundings are however hard to estimate since they are very terrain and location dependent. This is something that Vattenfall has to do from case to case. It was also shown that another shield wire reduced the amount of short circuits, which is desired by Vattenfall. This is not considered in the cost estimation either. Furthermore, two shield wires can be profitable if the load is higher or more valuable, like an important industry or similar. This is also something that needs to be considered from case to case.

Industries is probably also where the greatest sustainable gain could be with an improved lightning performance. As mentioned in section 1.1 an interruption due to lightning results in scrapping of the paper that is currently on the production line. A reduction of the amount of lightning related faults is therefore assumed to reduce the amount of paper that needs to be scrapped every year, which would be a gain from a sustainable perspective. Paper mills are just one example of sensitive industries.

In order to be more precise of how lightning disturbances affects industries it is necessary to know how long faults last and how the supply is designed at the actual industry, with several connections to the grid or UPS for example. So far it is easy to believe that an improved lightning performance would be sustainable. However, by using an additional shield wires for the portal tower the material consumption is increased. The shield wire currently used by Vattenfall, which is mentioned in section 3.2, is an ACSR wire. It is quite thin compared to the phase conductors and it does not contain any rare materials or similar. Therefore it is believed that an improved lightning performance is beneficial for the environment.

Another possible solution would have been to use line surge arresters. They are however considered to be too expensive at the moment. If the price of line surge arresters drops it could maybe be an alternative to shield wires in the future.

6

Conclusions and future work

The shield wires should be placed as a low a possible. When the height is increased the protective angle is improved and less strokes terminates on the phase conductors. However, the back flashovers increases faster and therefore the amount of faults is increasing at higher shield wire heights. The height of the shield wire at the steel tower should be decreased from 28.5 m to 26 m if possible. For the concrete tower the shield wire is already optimally placed at 26 m. The portal tower should be built with a shield wire height of 16 m independently of if one or two shield wires are used. All these heights corresponds to towers located on flat ground.

In order to reduce the amount of lightning faults by half a portal tower with one shield wire requires a tower foot resistance of 16.5 Ω while a portal tower with two shield wires requires 35.1 Ω. An additional shield wire boosts the fault distribution where it reduces the amount of short circuits. Furthermore, every tower needs to be grounded properly. If a tower is left ungrounded or with a high tower foot resistance the performance will be very poor for lightning strokes to the tower or the adjacent spans.

According to the cost estimation used in this project a portal tower with two shield wires could not cover its own costs. This did not include the costs for groundings. Since a portal tower with two shield wires may have roughly twice the tower foot resistance of a portal tower with one shield wire and still have the same performance it might be possible to save money in many areas in Sweden by not improving the grounding and instead building an additional shield wire. Costs of groundings are hard to estimate and this needs to be considered from case to case when new transmission lines are constructed.

One of the advantages of portal towers made of wood is that they are cheap compared to concrete and steel towers. If creosote is banned the cost difference might be changed or even decreased. If this happens it is necessary to make a new cost estimation.

If the price of line surge arresters drops significantly they should be evaluated and compared to the shield wire configurations of the different towers. Furthermore, it can also be investigated to add a lightning rod on every second tower to attract the lightning to them instead of the shield wire and have a separate grounding system for that. It can also be further investigated if a lightning rod on a grounded tower with every second wood portal tower grounded could increase the chance of having the lightning stroke hit the grounded tower instead of hitting the span or the ungrounded tower.

Another solution can be to change the location of the phase wires to a new topology for the wood portal tower. The lowest height cannot be changed but the the placement of the phases can be further investigated.

The grounding for the system can also be further evaluated with another solution with an underground earth electrode that is connected to every tower in order to reduce the tower foot resistance. Furthermore, it can also be investigated if it is possible to somehow decrease the high soil resistivity but pouring something in the ground or similar.

Bibliography

[1] A. R. Hileman, *Insulation Coordination for Power Systems.* New York: Marcel Dekker, Inc, 1999.

[2] A Eriksson et al, *Guide To Procedures For Estimating The Lightning Performance Of Transmission Lines.* Cigre Working Group 01 (Ligtning) of Study Committee 33 (Overvoltages and Insulation Coordination), 1991.

[3] Ashkish Bendre et al, "Are Voltage Sags Destroying Equipment?," *IEEE Industry Applications Magazine*, July/August 2006.

[4] R. Lundholm, *ÖVERSPÄNNINGAR OCH ÖVERSPÄNNINGSSKYDD I ELEKTRISKA STARKSTRÖMSANLÄGGNINGAR.* Stockholm, 1944.

[5] C.A. Warren et al, "Power Quality at Champion Paper - The Myth and the Reality," *IEEE Transactions on Power Delivery*, vol. 14, no. 2, 1999.

[6] E Kuffel et al, *High Voltage Engineering: Fundamentals.* Oxford: Elsevier Ltd., 2 ed., 2009.

[7] G. Pettersson, *Den svenska markens och berggrundens elektriska resistivitet - speciellt med hänsyn till kraftfrekvent inverkan och åska.* Stockholm, Sweden: Ingenjörsvetenskapsakademien, 1975.

[8] C. Johansson, "LCC-ANALYS PÅ TRE OLIKA 130 kV LEDNINGAR," 1992.

[9] P. Norberg, "private communication," January 2017.

[10] Diarmid Loudon et al, "A compact 420 kV line utilising line surge arresters for areas with low isokeraunic levels," *CIGRE Session 1998, Paris - France*, 1998.

[11] L. Isaksson and L. Wern, "Åska i Sverige 2002-2009," *METEOROLOGI*, no. 141, 2010.

[12] *STRI Line Performance Estimator LPE 4.1 Reference Manual.* STRI AB., Ludvika, Sweden, 2011.

[13] *STRI Line Performance Estimator LPE 4.0 User Manual.* STRI AB., Ludvika,

Sweden, 2016.

[14] J. Lundquist and I. Gutman, “Tillförlitlighet hos isolationen i trästolpledningar för 130-220 kV,” 2006.

[15] J.G. Anderson et al, “A Simplified Method for Estimating Lightning Performance of Transmission Lines,” *IEEE Transactions on Power Apparatus and Systems*, no. PAS-104, 1985.

[16] D. K. Cheng, *Field and Wave Electromagnetics.* Harlow, England: Pearson Education Limited, 2 ed., 2014.

[17] Vast-Vattenfall, “Överspänningsskydd i 0,4-132 kV anläggningar,” 1985.

[18] Vast-Vattenfall jordningskommitté, “Jordning av stationer och ställverk,” 1987.

[19] *PSCAD User Guide v4.3.1.* MANITOBA-HVDC Research Centre., Winnipeg, Manitoba, Canada, 2010.

[20] A. Pigini et al, “Performance of large air gaps under lightning overvoltages: Experimental study and analysis of accuracy of predetermination methods,” *IEEE Transactions on Power Delivery*, vol. 4, no. 2, 1989.

[21] W. Naon and S. Premrudeepreechacharn, “Flashover Occurence Factor of Insulator String with Arc Horn on High Voltage Transmission Line,” *North American Power Symposium, Starkville, MS, USA*, 2009.

[22] F Heidler et al, “Calculation of Lightning Current Parameters,” *IEEE Transactions on Power Delivery*, vol. 14, no. 2, 1999.

[23] D. Karlsson and P. Norberg, “Earthing of 130 kV Power Lines - Effects on Dependability and Line Cost,” *IEEE/PES Transmission and Distribution Conference and Exposition*, 2001.

A

Appendix 1

A.1 Portal tower with one shield wire

Table A.1: Lightning current required to cause a fault during a stroke to a pole, with every pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-54	55-65	66-100
35.1	0-28	29-41	42-100
150	0-12	13-16	17-100

Table A.2: Lightning current required to cause a fault during a stroke to the middle of the span, with every pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-54	55-62	63-100
35.1	0-44	45-51	42-100
150	0-16	17-24	25-100

Table A.3: Lightning current required to cause a fault during a stroke to a grounded pole, with every second pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-47	48-61	62-100
35.1	0-25	26-33	34-100
150	0-9	10-13	14-100

Table A.4: Lightning current required to cause a fault during a stroke to the span between a grounded and ungrounded pole, with every second pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-7	8-9	10-100
35.1	0-7	8-9	10-100
150	0-6	7-9	10-100

Table A.5: Lightning current required to cause a fault during a stroke to a ungrounded pole, with every second pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-5	6	7-100
35.1	0-5	6	7-100
150	0-4	5-6	7-100

Table A.6: Lightning current required to cause a fault during a stroke to a grounded pole, for the first distributed tower foot resistance model (Figure 3.10) and a front time of 2.2 µs.

Lightning stroke	No fault [kA]	SLG [kA]	Short circuit [kA]
Hits the 150 pole	0-13	14-18	19-100
Hits between 150 and 16.5	0-20	21-27	28-100
Hits the 16.5 pole	0-53	54-64	65-100

Table A.7: Lightning current required to cause a fault during a stroke to a grounded pole, with the second distributed tower foot resistance model (Figure 3.11) and a front time of 2.2 µs.

Lightning stroke	No fault [kA]	SLG [kA]	Short circuit [kA]
Hits the 35.1 pole	0-28	29-41	42-100
Hits between 35.1 and 150	0-19	20-26	27-100
Hits the 150 pole	0-13	14-17	18-100

A.2 Portal tower with two shield wires

Table A.8: Lightning current required to cause a fault during a stroke to a pole, with every pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-71	72-90	91-100
35.1	0-40	41-52	53-100
150	0-17	18-24	25-100

Table A.9: Lightning current required to cause a fault during a stroke to the middle of the span, with every pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-78	79-88	89-100
35.1	0-60	61-70	71-100
150	0-23	24-30	31-100

Table A.10: Lightning current required to cause a fault during a stroke to a grounded pole, with every second pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-60	61-78	79-100
35.1	0-33	34-43	44-100
150	0-13	14-19	20-100

Table A.11: Lightning current required to cause a fault during a stroke to the span between a grounded and ungrounded pole, with every second pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-13	14-16	17-100
35.1	0-13	14-16	17-100
150	0-11	12-14	15-100

Table A.12: Lightning current required to cause a fault during a stroke to a ungrounded pole, with every second pole grounded and a front time of 2.2 µs.

Tower foot resistance [Ω]	No fault [kA]	SLG [kA]	Short circuit [kA]
16.5	0-9	10-11	12-100
35.1	0-9	10-11	12-100
150	0-8	9-11	12-100

Table A.13: Lightning current required to cause a fault during a stroke to a grounded pole, with the first different tower foot resistance model (Figure 3.10) and a front time of 2.2 µs.

Lightning stroke	No fault [kA]	SLG [kA]	Short circuit [kA]
Hits the 150 pole	0-21	22-27	28-100
Hits between 150 and 16.5	0-31	32-39	40-100
Hits the 16.5 pole	0-68	69-90	91-100

Table A.14: Lightning current required to cause a fault during a stroke to a grounded pole, with the second different tower foot resistance model (Figure 3.11) and a front time of 2.2 µs.

Lightning stroke	No fault [kA]	SLG [kA]	Short circuit [kA]
Hits the 35.1 pole	0-37	38-48	49-100
Hits between 150 and 16.5	0-28	29-36	37-100
Hits the 150 pole	0-19	20-26	27-100