

Underground cables in transmission networks



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Abstract

In our modern society it is almost impossible to get permits for new overhead lines. The power companies struggle against residents that do not want an overhead line in their neighborhood. This struggle takes years and costs a lot of money. A way of dealing with these problems could be to build an underground AC-cable. The buried cable would probably not cause such struggle to get permits.

When a cable is installed in an existing transmission grid it carries more load than an overhead line should have carried. The reason behind this is that the cable has lower impedance than overhead lines. This lower impedance has to be compensated in some way. The simplest way is to install a series reactor on the cable which increases the impedance.

The amount of reactive power produced by a cable is in the vicinity of 20 times larger than the reactive power produced by an overhead line. This reactive power needs to be taken care of by shunt reactors. The degree of compensation needs to be about 100 %, the degree of compensation is the ratio between created reactive power and shunt compensated reactive power. Most of the reactive power needs to be compensated in order to energize the cable; the voltage would otherwise become higher than the highest voltage for equipment.

The Sydälänken case is a 400 km long cable at 400 kV. The degree of compensation is 100 % and there are 14 shunt reactors with 200 Mvar each. In order to decrease the load flow through the cable a phase shifting transformer is installed. The phase shifting transformer can regulate the load flow and thereby increases the stability of the whole power system.

In a smaller city network, 130 kV, the cable can produce the amount of reactive power needed in the city. The reactive power feeds the city's transformers and loads. The city does not need to buy reactive power from the power grid, they can produce the amount needed them self.

Sammanfattning

I vårt moderna samhälle är det nästan omöjligt att få tillstånd för nya högspänningsluftledningar. Kraftbolagen har en hård kamp mot alla boende som inte vill ha en högspänningsledning i deras omgivning. Den här kampen tar år och kostar massor av pengar. En möjlig lösning på problemen kan vara att bygga en nedgrävd AC-kabel. En nedgrävd kabel skulle nog inte orsaka lika mycket problem med att få tillstånd.

När en kabel installeras i ett befintligt transmissionsnät tar den på sig för mycket last. Anledningen till detta är att kabeln har en mycket lägre impedans jämfört med en luftledning. Den lägre impedansen måste kompenseras på något sätt. Det enklaste sättet är att installera en seriereaktor på kabeln som ökar kabelns impedans.

Den mängden reaktiv effekt som produceras av en kabel är i närheten av 20 gånger mer än för en luftledning. Den reaktiva effekten behöver tas om hand av shuntreaktorer som förbrukar reaktiv effekt. Kompenseringsgraden behöver vara 100 %, kompenseringsgraden är förhållandet mellan shuntkompenserad reaktiv effekt och skapad reaktiv effekt. All reaktiv effekt behöver kompenseras när kabeln ska spänningssättas, spänningen skulle annars överstiga konstruktionsspänningen för utrustningen.

Sydälvenfallet har en nominell spänning om 400 kV och är 400 km långt. Kompenseringsgraden är 100 % och det är 14 stycken shuntreaktorer på 200 Mvar per styck. För att kunna minska effektlödet i kabeln installeras en fasvridande transformator. En fasvridande transformator kan reglera effektlödet och därmed hjälpa till att öka stabiliteten för hela kraftsystemet.

I ett mindre stadsnät, 130 kV, kan en kabel producera den mängd reaktiv effekt som staden behöver. Den reaktiva effekten matar transformatorer och laster. Staden behöver inte köpa reaktiv effekt från elnätet utan kan skapa den själva.

Preface

This master thesis concludes my studies at The Faculty of Engineering (LTH), Lund University, for a master degree in electrical engineering. This thesis work has been conducted in cooperation with ABB and the Department of Industrial Electrical Engineering and Automation (IEA) at Lund University.

I would like to thank my tutors Sture Lindahl at IEA and Stefan Thorburn at ABB for the indispensable guidance through this thesis.

Lund, 30 January 2007

Johan Engström

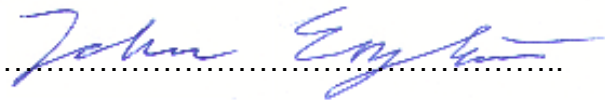


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1 Introduction

1.1 Background

In our modern society it is almost impossible to get permits for new overhead lines. No one wants an overhead line in their surroundings, it affects the landscape and people are afraid of the magnetic fields emitted from overhead lines. The power companies struggle against residents that do not want an overhead line in their neighborhood. This struggle takes years and costs a lot of money.

A way of dealing with these problems could be to build an underground AC-cable. The buried cable would probably not cause such struggle to get permits. The only thing noticeable with a cable is a 20 meter wide path of noting, compared to the overhead line that has a 40 meters wide path beneath the construction. The magnetic fields are also greatly reduced in a cable compared to an overhead line. These factors make a cable alternative more attractive. [4]

There are not many long 400 kV cables in power grids around the world. Cables are primarily used in densely populated urban areas; in cities, around airports, etc. The length of these cables reaches up to about 50 km.

An underlying reason behind why cables are not used is the old types of cables with oilpaper or oil insulation that are expensive. The new XLPE cables are better in both performance and price. A disadvantage with cables is that it is expensive to repair a fault; the good thing is that faults are much more uncommon in cables compared to overhead lines. The cost of underground cable circuits are 5-10 times higher than the cost for an overhead line, this price difference is steadily getting smaller. [12]. The reason is the increasingly amount of legal costs to get permits. Another reason behind the limited use of cables is probably that power companies are old fashion; they often use the old well-tried solutions, which in this case are overhead lines.

1.2 Objectives

The main objective for this master thesis is to investigate the possibility of implementing a longer cable section in an existing power grid. The difficulties with implementing a cable shall be described and presented with help of simulations and conclusions.

The second objective is to investigate a cable in a real case scenario, a long 400 kV circuit. The third objective is to implement a cable in a city network, 130 kV. Describing advantages and disadvantages with the cable and in some extent the other suggested options.

1.3 Scope of the thesis and delimitations

All calculations are made in steady state; therefore additional calculations have to be made in terms of short circuit calculations, dynamic stability, etc. in order to fully investigate the viability of the solution.

2 Theory

This chapter defines the theory used in this thesis.

2.1 Definitions

2.1.1 Nominal voltage (IEC 601-01-21)

A suitable approximate value of voltage used to designate or identify a system. i.e. 130, 220, and 400 kV. [6]

2.1.2 Operating voltage (IEC 601-01-22)

The value of the voltage under normal conditions, at a given instant at a given point of the system. [6]

2.1.3 Highest voltage for equipment (IEC 604-03-01)

The highest r.m.s. value of phase-to-phase voltage for which the equipment is designed in respect of its insulation as well as other characteristics which relate to this voltage in the relevant equipment standards. [7]

2.2 Complex power

The complex power consists of a real and a reactive part, $S = P + jQ$. [2] See figure 2.1-A.

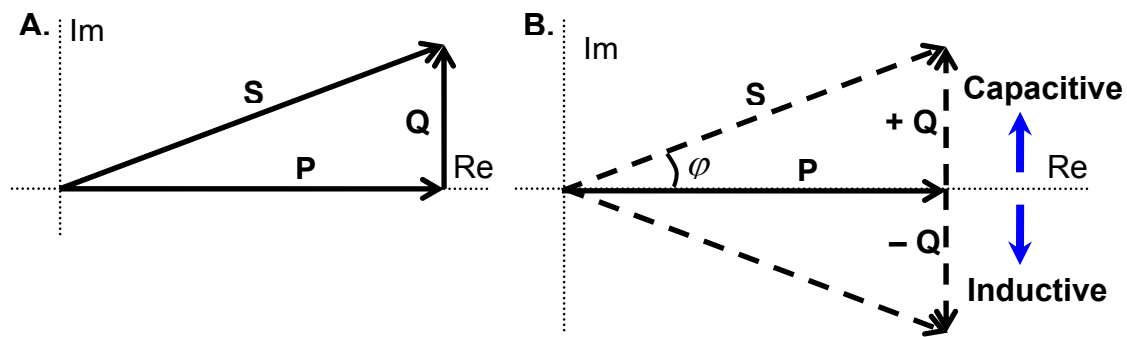


Figure 2.1: Representation of Complex power

A entirely real power, $S = P$, can only exist when voltage and current are in phase without any phase angle difference. Reactive power arises when voltage and current have a phase angle difference. The reactive power can either be capacitive or inductive, Figure 2.1-B. When the reactive power is capacitive it means that the current is leading the voltage and with inductive means that the current is lagging the voltage.

The power factor, PF is defined by using the relation $PF = \cos(\phi)$. The power factor is the ratio of active (real) power to apparent power. [13]

2.3 Transmission matrix, ABCD parameters

To calculate voltages and currents, long circuit theory with ABCD parameters is used in this thesis. The transmission matrix, ABCD parameters, makes it easy to connect different blocks of parameters together, either in series or in parallel. Equation 2.1 defines the parameterizations of a circuit. [13] (Derived from propagation constants in steady state).

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} = \begin{bmatrix} \cosh(\sqrt{yz} \cdot l) & Z_C \cdot \sinh(\sqrt{yz} \cdot l) \\ Y_C \cdot \sinh(\sqrt{yz} \cdot l) & \cosh(\sqrt{yz} \cdot l) \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \quad \text{Equation 2.1}$$

$$\text{where } Z_C = \frac{1}{Y_C} = \sqrt{\frac{z}{y}}$$

V_S, I_S The sending end voltage and current

V_R, I_R The receiving end voltage and current

z The series impedance / km, $r + jx$ resistance and reactance

y The shunt admittance / km, $g + jb$ conductance and susceptance

l The length in km

Figure 2.2 describes series and parallel connections of different networks.

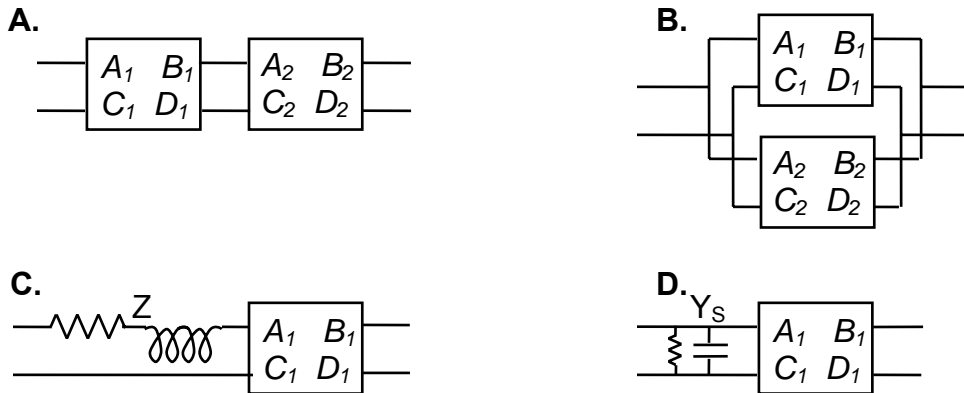


Figure 2.2: Series and parallel networks

Two networks in series (See Figure 2.2-A) results in a network with the calculations:

$$A = A_1 A_2 + B_1 C_2$$

$$B = A_1 B_2 + B_1 D_2$$

$$C = C_1 A_2 + D_1 C_2$$

$$D = C_1 B_2 + D_1 D_2$$

Two networks in parallel (See Figure 2.2-B) results in a network with the calculations:

$$A = \frac{A_1 B_2 + A_2 B_1}{B_1 + B_2}$$

$$B = \frac{B_1 B_2}{B_1 + B_2}$$

$$C = C_1 + C_2 + \frac{(A_1 - A_2)(D_2 - D_1)}{B_1 + B_2}$$

$$D = \frac{D_1 B_2 + D_2 B_1}{B_1 + B_2}$$

A series impedance, Z at the sending end with a circuit, $A_1 B_1 C_1 D_1$, (See Figure 2.2-C) results in a network with the calculations:

$$A = A_1 + C_1 Z$$

$$B = B_1 + D_1 Z$$

$$C = C_1$$

$$D = D_1$$

A shunt admittance, Y_s at the sending together with a circuit, $A_1 B_1 C_1 D_1$, (See Figure 2.2-D) results in a network with the calculations:

$$A = A_1$$

$$B = B_1$$

$$C = C_1 + A_1 Y_s$$

$$D = D_1 + B_1 Y_s$$

2.4 Cable design versus overhead line

The cable has an insulated conductor with a metallic screen around the insulation. Having the screen that close to the conductor increases the charging current in comparison with the charging current of an overhead line, this is the main reason why cables have higher charging currents than overhead lines. A representation of a cable is found in Figure 2.3.[9]

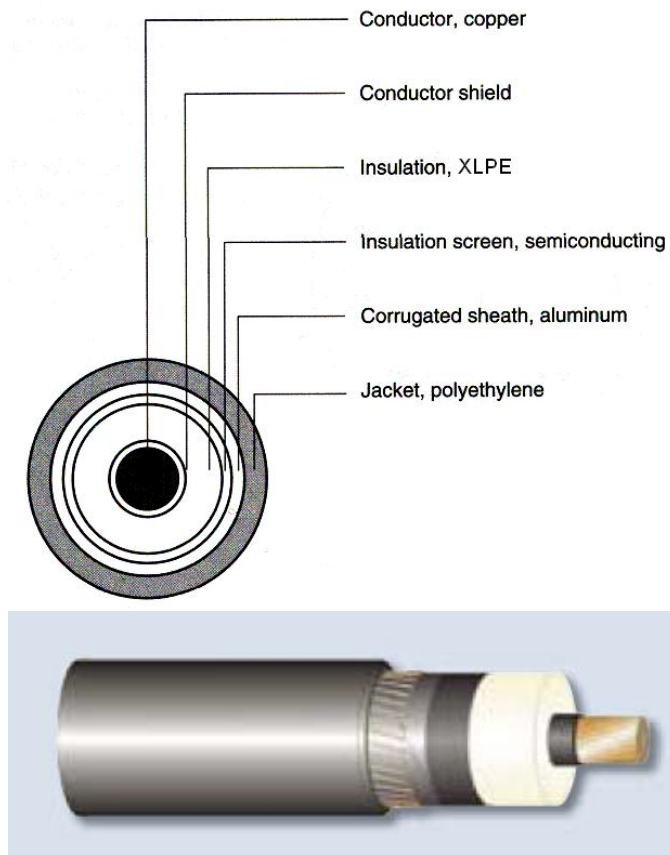


Figure 2.3: Description of a cable

An overhead may consist of one or several transmission circuits; single-circuit lines or multi-circuit lines. Each transmission circuit has three phase conductors. A phase conductor may have one or several subconductors; simplex, duplex, triplex or quadruple conductors. Ultra high voltage (>1000 kV line-to-line) overhead lines may have as many subconductors as eight. A typical subconductor consists of a stranded steel core with stranded aluminum around. The overhead line hangs in air and the air itself works as insulation. The Shunt capacitance is not as high because of the large distances. A representation of an overhead line is found in Figure 2.4.[14]

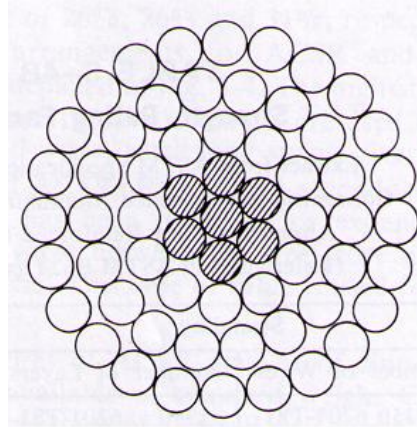


Figure 2.4: Typical overhead line conductor

2.5 Power transfer in a transmission circuit

The power transferred P_{12} between buses 1 to 2 is defined by equation 2.2.

$$P_{12} = \frac{|V_1||V_2|}{X} \sin(\gamma) \quad \text{Equation 2.2}$$

- V_x The voltage in bus x
- γ The phase angle between the two bus voltages
- X The reactance of the transmission circuit (the resistance is assumed to be much smaller than the reactance and is therefore neglected)

The reactance can be altered by implementing a series capacitor or a series reactor.

2.6 Resistive losses in cables

In order to calculate the resistive losses, a number of factors have to be calculated. The AC-resistance, R , of a cable is given by equation 2.3.

$$R = R'(1 + y_s + y_p) \quad \text{Equation 2.3}$$

- R' DC-resistance at a given temperature
 y_s The skin effect factor, explained in chapter 2.6.2
 y_p The proximity effect factor, explained in chapter 2.6.3

2.6.1 DC-resistance, R'

A conductor resistance is almost always given in the DC-resistance at 20 °C, R_0 . The resistance is temperature dependant and in order to resolve the DC-resistance at a given temperature, T , equation 2.4 is used. [8]

$$R' = R_0 [1 + \alpha_{20} (T - 20)] \quad \text{Equation 2.4}$$

2.6.2 Skin effect factor, y_s

The skin effect is the alternating electric current tendency to distribute a greater current density near the surface of the conductor, than at its core. The current flows at the “skin” of the conductor. The skin effect factor is given by equation 2.5. [8]

$$y_s = \frac{x_s^4}{192 + 0.8 \cdot x_s^4}, \text{ where } x_s^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_s \quad \text{Equation 2.5}$$

- k_s A coefficient depending on the conductor shape

2.6.3 Proximity effect factor, y_p

When an AC current flows through a conductor it creates an alternating magnetic field. If there are conductors nearby, their individual magnetic field will affect each other. The magnetic field will cause a change in the current density inside the conductor and shift or bias the current density in the wire. This will reduce the area of the current flow and increase the effective resistance of the conductor measured from outside. The proximity effect factor is given by equation 2.6. [8]

$$y_p = \frac{x_p^4}{192 + 0.8 \cdot x_p^4} \cdot \left(\frac{d_c}{s}\right)^2 \cdot \left[0.312 \cdot \left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\frac{x_p^4}{192 + 0.8 \cdot x_p^4} + 0.27} \right] \quad \text{Equation 2.6}$$

where $x_p^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_p$

- d_c The diameter of conductor (mm)
- s The distance between conductor axes (mm)
- k_p A coefficient depending on the conductor shape

2.7 Phase shifting transformer

A phase shifting transformer, PST, is used for regulating the power flow in a power system. The PST is often placed between two independent power systems

The transferred power between two points is defined by Equation 2.2,

$$P_{12} = \frac{|V_1||V_2|}{X} \sin(\gamma).$$

In an interconnected power system the bus voltage levels are kept fairly constant and the bus voltage is common for all circuits connected to the bus. The reactance, X , is a physical constant depending on the construction of the circuits.

One way to regulate power flowing through a circuit is to reduce/increase the phase angle in the circuit. The principal of a PST is that it inserts voltage into one phase by energizing voltage from the other two phases in order to alter the phase angle and alter the voltage. Figure 2.5 describes the connections of a single phase in a PST, there are similar connections for the other two phases. There are different types of PST:s, Figure 2.5 describes one simplified type. All PST:s have on-load tap changers which enables stepwise regulation. By having many steps the power flow can be regulated gradually. The regulation can be in a positive angle, θ which increases the power flow. The regulation can also be in a negative angle, $-\theta$ which decreases the power flow. The PST can increase or decrease the power by altering the phase angle ($\gamma + \Delta\theta$) in Equation 2.2. [2]

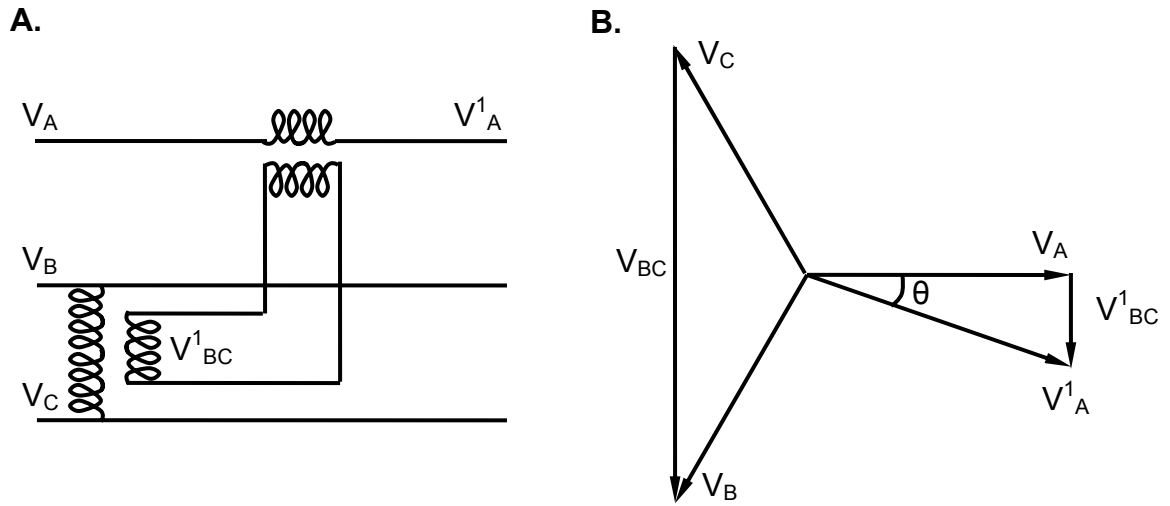


Figure 2.5: Simple description over one phase in a PST. (A) Connections between windings. (B) Corresponding phasor diagram

The transmission network matrix of an ideal phase shifting transformer can be expressed as: (Relates to chapter 2.3)

$$A = e^{-j\theta}$$

$$B = 0$$

$$C = 0$$

$$D = e^{-j\theta}$$

θ The angle that the phase shifting transformer will alter the voltage and current.

3 Simulation program

The simulation program is written in a Matlab M-file. This program builds on the transmission matrix theory (chapter 2.3). In order to determine the ABCD parameters for a circuit some basic data is needed: (see Equation 2.1)

- 1 The resistance of the circuit per phase and km. This is the “r” in the series impedance, z . The program takes the resistive losses into account, see Figure 2.3.
- 2 The inductance of the circuit per phase and km. This is the “x” in the series impedance, z .
- 3 The shunt capacitance of the circuit per phase and km. This is the “b” in the shunt admittance, y . The conductance “g” is assumed to be zero.

Normally the length of the transmission circuit has to be known before the calculation of the ABCD parameters, this program is built up of many small one km pieces. In other words the length, l is set to one km and the ABCD parameters can be calculated. Figure 3.1 describes how the networks are put together. All of the networks in the figure are one km of the actual circuit, by doing this other components like shunt reactors and series capacitors can be inserted along the circuit in one km steps. It is of course possible to use other step lengths in the analysis if needed.

One km steps were selected because this approximates the cable reach between two joints. The longest cable can only be about 1.5 km for a large single core 400 kV cable; a longer cable can only be transported on sea. 1 km steps are therefore more than enough for this program. [1]

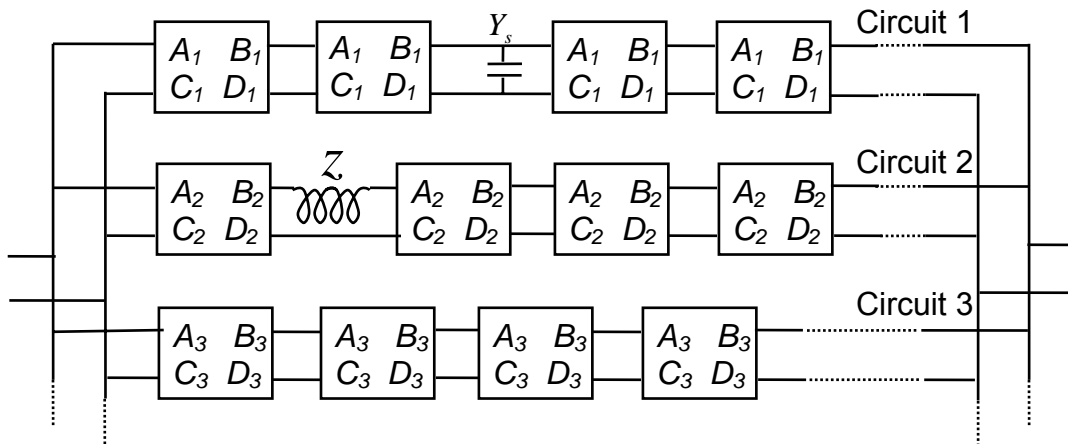


Figure 3.1: Connecting circuit blocks together

As an example; the first circuit in figure 3.1 has a shunt admittance, Y_s at two km, this shunt admittance can either be a shunt reactor or a shunt capacitor. Circuit 2

has series impedance, Z at one km, this series impedance can either be a series reactor or a series capacitor.

The program has a choice matrix which defines where all different series and shunt components are located, it also defines which circuit that is used i.e. A_1, B_1, C_1, D_1 or A_2, B_2, C_2, D_2 .

The program iterates along the circuit and saves the accumulated network every km. When all circuits are calculated respectively, the next thing is to make a parallel connection of all circuits. This parallel connection starts with connecting circuit 1 and 2 into one new network, after this the new network and circuit 3 is connected and so on. The result when all circuits are connected is a final network, $A_{tot}, B_{tot}, C_{tot}, D_{tot}$, which represent the whole system between two nodes in one set of parameters.

Now its time to calculate voltages and currents, the receiving end is normally used as a reference. The receiving end voltage, V_R is set to be phase reference, then the load at the receiving end defines how large and with what phase angle the current, I_R shall be. By using Equation 2.1 the sending end voltage, V_S and current, I_S can be calculated. The voltage and current at both the sending end and receiving end is now known. These currents are the total amount of currents through all circuits together. It is crucial to know the current going through every individual circuits; otherwise it would be impossible to calculate the voltages and currents at different points inside each circuit. By taking the network parameters for circuit 1 and solving the receiving end current when knowing the voltages and the sending end current, equation 2.1 is used. The current in each circuit is derived i.e. the sending end voltage and current for circuit 1 is known, it is now possible to go back to the saved accumulated network and derive the voltage and current at every km in the circuit.

The program only needs the voltages and currents to be able to calculate active power, reactive power, angle differences, power factors etc. The program displays the calculations in different diagrams; these diagrams are used in all cases later on.

4 Illustrative Cases

The purpose of this chapter is to analyze some cases that will result when underground cables are installed in transmission networks consisting mainly of overhead lines. The first case consists of two overhead lines in parallel, it describes a common situation in transmission grids used today, overhead lines. The later cases illustrate cables in parallel with overhead lines and the problems that occur.

4.1 Case 1, two overhead lines in parallel

To illustrate two overhead lines in parallel, theory of longer circuits is used. Circuit lengths are 200 km each and the nominal voltage is 400 kV. The reactance X_L is for both of the circuits 0.3 Ω /km. The resistance, R , for circuit 1 and circuit 2 is 0.015 Ω /km and 0.03 Ω /km each. The shunt capacitance is 12 nF per phase and km. At the receiving end the load is 1500 MVA with a variable power factor. Figure 4.1 represents the two circuits.

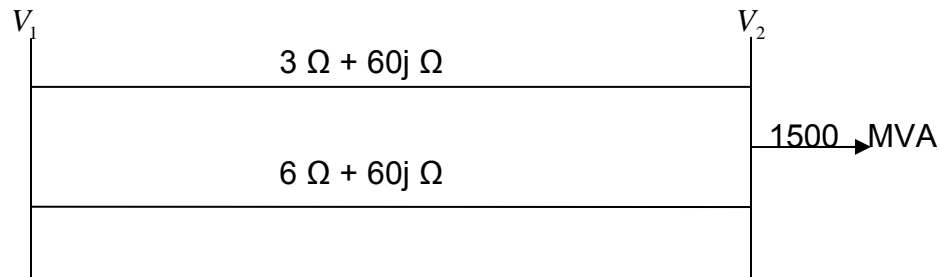


Figure 4.1: Representation of two overhead lines in parallel

The voltage, V_2 at receiving end is used for reference, $V_2 \angle 0^\circ$, and the line-to-line voltage is set to 400 kV. Circuit calculations made in Matlab are shown in figure 4.2. The voltage is shown in total magnitude of both real and complex voltage; line-to-line voltage is used.

Figure 4.2 also shows real power which is the resistive part of the complex power. The resistive power losses in the overhead line are shown by the reduction of transferred active power over the circuit. The losses are easily calculated by taking the injected real power minus ejected real power. The power factor is the proportion of real power transferred through the circuit, regarding to the total amount of complex power.

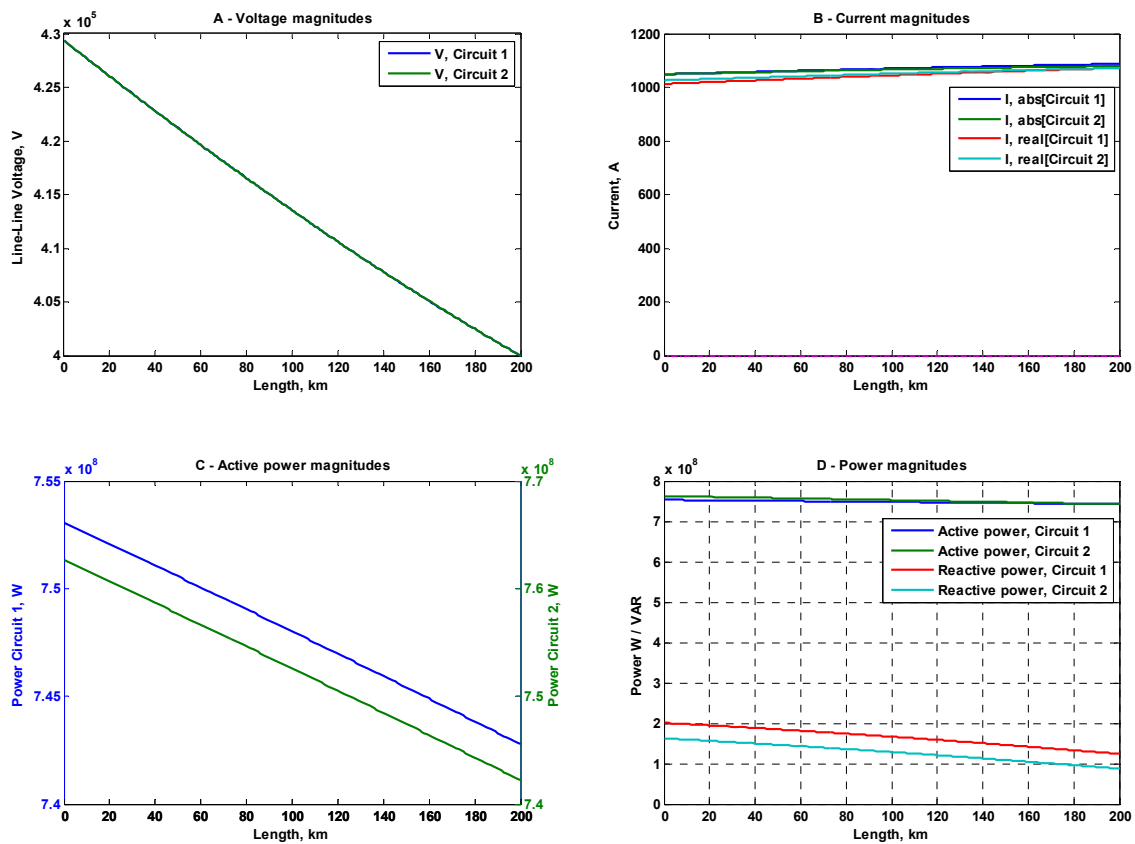


Figure 4.2: Data from Matlab calculations

Calculations made in this case have a load demand with a power factor of 0.99, i.e. almost a purely resistive load. The load is shared virtually equal over the circuits, even though circuit 1 has half the resistance as circuit 2. The circuit reactance has a great impact on the circuit impedance. A circuit has the reactance $0.3 \text{ } \Omega/\text{km}$ and the resistance $0.015 \text{ } \Omega/\text{km}$ or $0.03 \text{ } \Omega/\text{km}$. Circuit 1 has the impedance $60.1 \angle 87.1^\circ \text{ } \Omega$, circuit 2 has the impedance $60.3 \angle 84.3^\circ \text{ } \Omega$. Both impedances are virtually the same, which is a problem when circuit 1 should carry more of the load because of the lower resistance. Lower resistance means that the conductor is larger which indicates a larger cooling area; the result is lower losses and larger current rating. It is also an ampacity problem, a thin wire will have higher losses and become too hot. Sagging or mechanical brittleness may result. When overhead lines get hot they expand, if the conductor gets too close to the ground it could result in a short circuit.

Real power losses over the circuits are 10.3 MW for circuit 1 and 20.4 MW for circuit 2. Circuit 1 should carry a greater proportion of the load to reduce losses.

4.2 Case 2, two overhead lines and series compensation

This case has the same parameters as in case 1, the difference is that a series capacitor is introduced. Circuit lengths are 200 km each and the nominal voltage is 400 kV. The reactance, X_L , is for both of the circuits 0.3 Ω /km. The resistance, R , for circuit 1 and circuit 2 is 0.015 Ω /km and 0.03 Ω /km. The shunt capacitance is 12 nF per phase and km. At the receiving end the load is 1500 MVA with a variable power factor.

To reduce losses in this case a series capacitor is installed in circuit 1. The resistive losses depend on a 3 Ω and a 6 Ω resistance in parallel. A simple calculation by Kirchoff's Current Law, (KCL), gives a current share of 2/3 to circuit 1 and 1/3 to circuit 2. As shown in case 1, circuit 1 has the impedance $60.1 \angle 87.1^\circ \Omega$ and circuit 2 has the impedance $60.3 \angle 84.3^\circ \Omega$. In order to change the impedance of circuit 1, the reactance needs to be lowered. A series capacitor in the middle of the circuit reduces the reactance. If the reactance decreases to half its value, 60 Ω - 30 Ω , then circuit 1 lowered the impedance to $30.1 \angle 84.3^\circ \Omega$. The degree of compensation in this case is $30/60 = 50\%$, a rule of thumb is that the factor should be between 40-75%. Figure 4.3 represents the two circuits together with a series capacitor in circuit 1. The load sharing is now 2/3 to circuit 1 and 1/3 to circuit 2.

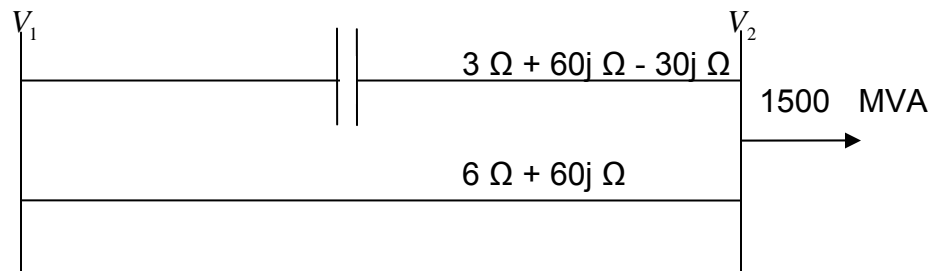


Figure 4.3: Representation of two overhead circuits in parallel with series compensation

V_2 at the load bus is used for reference, $V_2 \angle 0^\circ$, and the line-to-line voltage is set to 400 kV. Circuit calculations made in Matlab are shown in Figure 4.4. The voltage is shown in total magnitude of both real and complex voltage, Line-Line voltage is used. At the endpoint a purely real voltage is acquired, because of the reference voltage V_2 .

Figure 4.4 are quite different from the figure in case 1, the main difference is in the voltage diagram. The capacitor placed in the middle of the circuit alters the magnitude and angle of the voltage. The voltage level, at the middle of the circuit, is almost back to the origin magnitude, thanks to the capacitor. The voltage angle

returns to the origin value also. By introducing a capacitor to circuit 1 the electrical length of the circuit has been reduced.

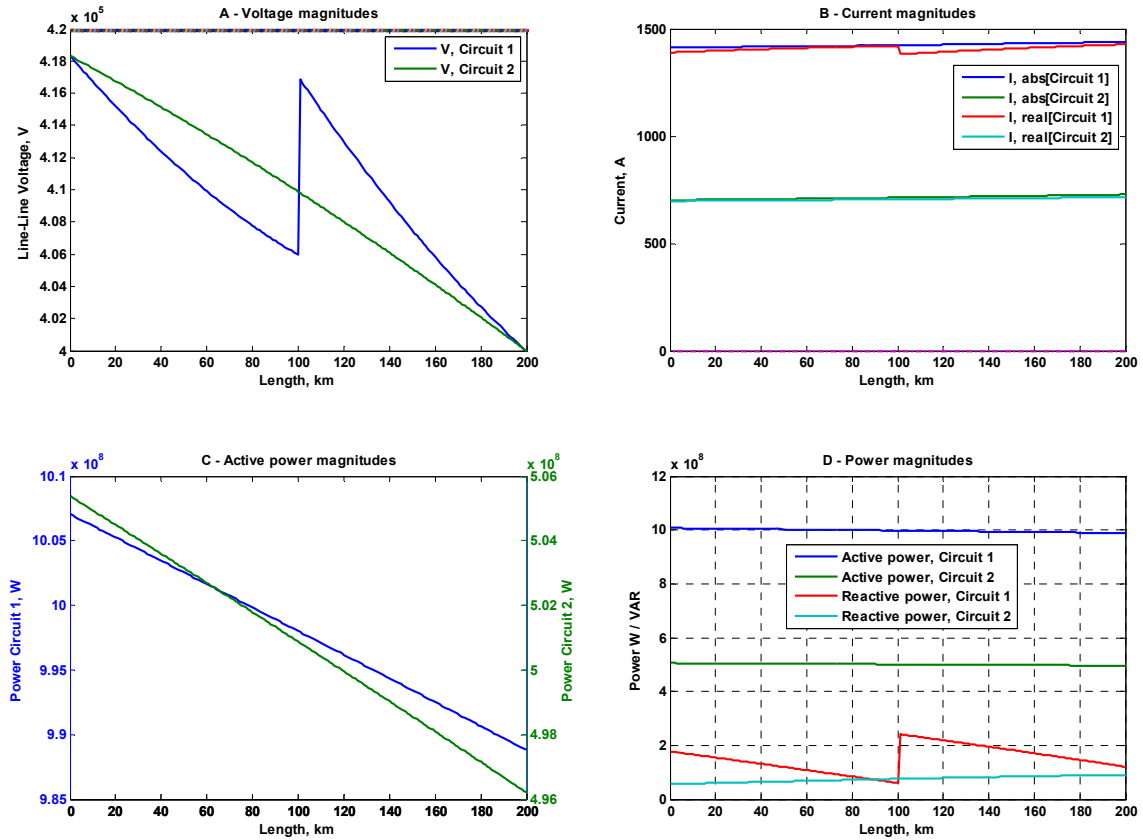


Figure 4.4: Data from Matlab calculations

Real power losses over the circuits are 18.3 MW for circuit 1 and 9.1 MW for circuit 2. By introducing a capacitor the resistive losses are reduced by 3.3 MW totally.

A series capacitor increases the system stability and increases the loadability of the two parallel circuits.

4.3 Case 3, overhead line + composite line

This case is made to illustrate an overhead line in parallel with a composite line, in other hand cable and overhead line in different parts of the circuit. The cable length is set to 80 % of the whole length of the circuit, 20 % of the length is then an overhead line. Circuit lengths are 200 km each and the nominal voltage is 400 kV. The overhead line parameters is $X_L = 0.3 \Omega/\text{km}$, $R = 0.03 \Omega/\text{km}$ and the shunt capacitance is 12 nF per phase and km. These parameters are used for the composite line's overhead lines to. The cable has $X_L = 0.16 \Omega/\text{km}$, $R = 0.013 \Omega/\text{km}$, the shunt capacitance is 220 nF per phase and km. The cable parameters are from a 2000 mm² single core cable with the current rating of 1610 A at 90°C. The conductors are laid in flat formation, 0.7 m apart, 1 m deep and cross-bonded screens. Figure 4.5 represents the two circuits. [1]

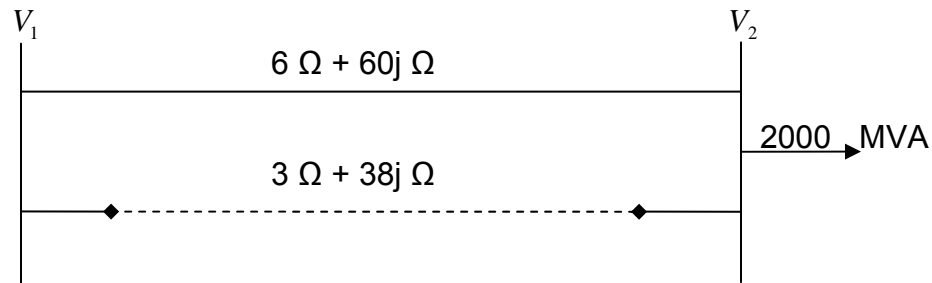


Figure 4.5: Representation of an overhead line in parallel with a composite line

Voltage, V_2 at the receiving end is used for reference, $V_2 \angle 0^\circ$, and the line-to-line voltage is set to 400 kV. The obvious thing to see is that the impedance for the second circuit is a great deal lower than for circuit 1. Circuit 1 has the impedance $60.3 \angle 84.3^\circ \Omega$ and circuit 2 has the impedance $37.7 \angle 85.1^\circ \Omega$. Because of the impedance it is also obvious that the composite line takes a larger part of the load. The Matlab calculations are shown in figure 4.6, and they confirm that the composite line has a higher load; circuit 1 takes 738 MW and circuit 2 takes 1242 MW. Almost twice the amount of power goes through the composite line compared to the overhead line. This is a common problem with cables in a meshed grid where the overhead line and underground cables are connected in parallel.

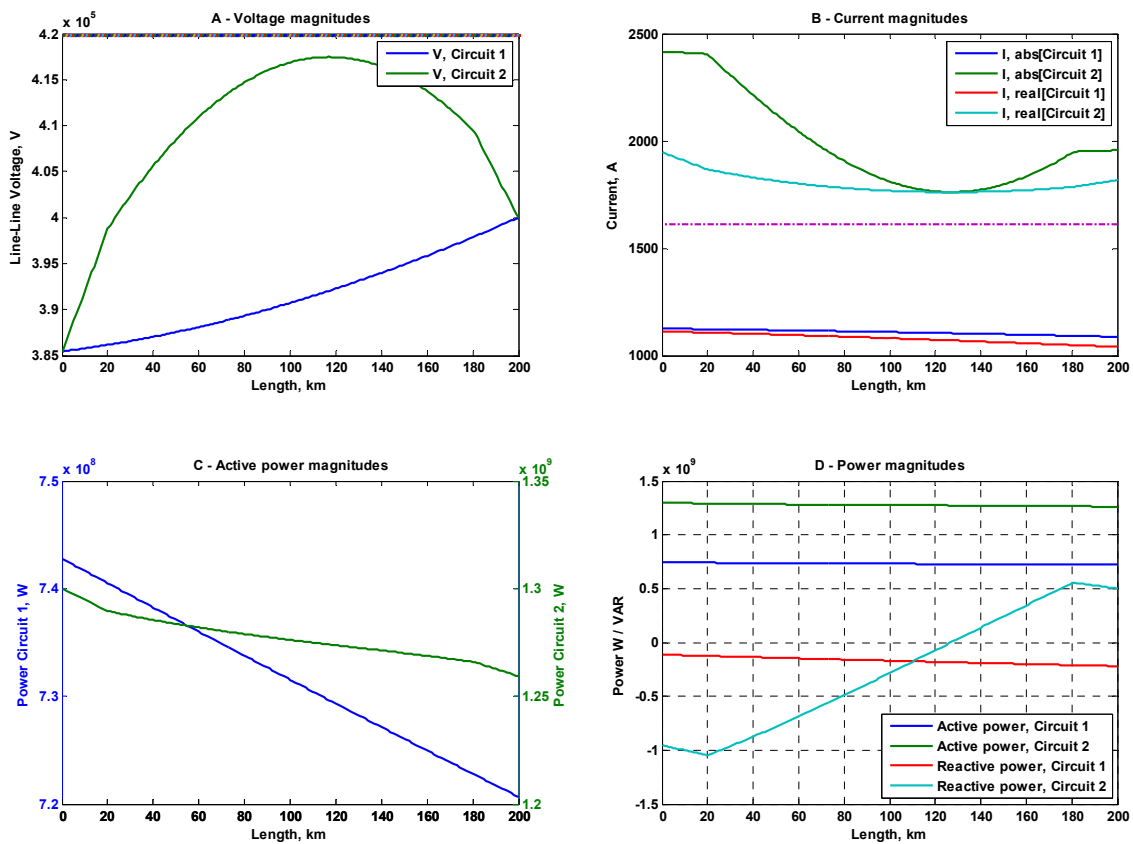


Figure 4.6: Data from Matlab calculations

Current magnitudes for circuit 2, the composite line, peaks at the sending end with almost 2400 Ampere whereas the maximum allowed current through the cable is 1610 Ampere. The cable can be operated at a higher load point for a limited time. The calculations are made in steady state, which means that the calculations are independent of time and therefore the maximum rating has to be followed. The shunt capacitance is almost 20 times larger in the cable compared to the overhead line and this capacitance generates a lot of excessive charging current. This current is generated all along the cable and is then transported through either the sending or the receiving end of the cable. In this way the cable ends carries the highest current loads.

Voltage magnitudes for circuit 2, the composite line, differs a lot from the previous cases, the voltage magnitude has a hill-like appearance. The voltage magnitude peaks at about 120 km; (figure 4.6-A) this is due to the reactive current in the cable. Reactive current flows from a higher voltage to a lower. The reactive current is near zero at 130 km and at this point the voltage is at its peak (figure 4.6-B). The resistive voltage magnitude is highest at the sending end and decreases down to the receiving end. Reactive currents is zero at 130 km, this means that the peak of the reactive voltage is at this point. The combined voltage

of the resistive and reactive is called complex voltage, this is the voltage shown in figure 4.6.

This case illustrates the difficulties when combining overhead lines and cables. The next cases introduce series compensation in the circuits in order to handle some of the obstacles.

4.4 Case 4, overhead line with compensation + composite line

This case is made to illustrate an overhead line in parallel with a composite line and series compensation is introduced. This case has the same parameter as in case 3. The difference is the series capacitance in circuit 1 with the value of -25Ω . Figure 4.7 represents the two circuits.

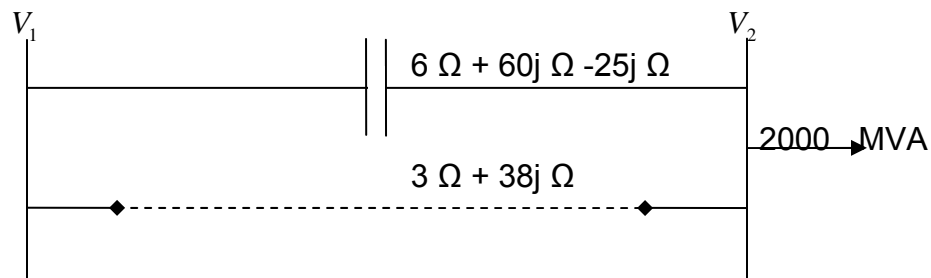


Figure 4.7: Representation of a composite line in parallel with a compensated overhead line

The voltage, V_2 at the load bus is used for reference, $V_2 \angle 0^\circ$, and the line-to-line voltage is set to 400 kV. Circuit 1 has the impedance $35.5 \angle 80.3^\circ \Omega$ and circuit 2 has the impedance $37.7 \angle 85.1^\circ \Omega$. The impedance are almost the same in both circuits, this shares the load almost equally. The degree of compensation in this case is $25 / 60 = 42 \%$.

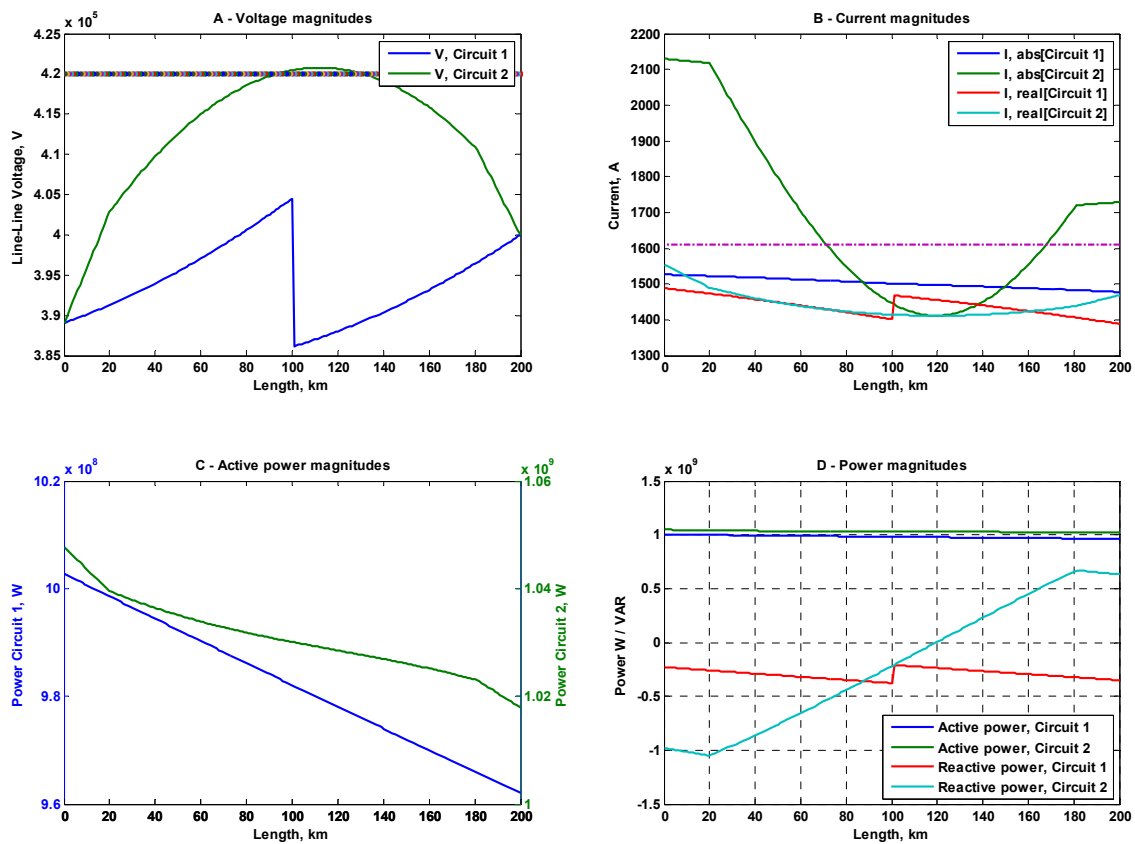


Figure 4.8: Data from Matlab calculations

Calculations made in Matlab are shown in figure 4.8-C; the calculations confirm that the load is shared equally. The voltage magnitude of circuit 2 touches the limit of 420 kV, which is the highest voltage for equipment.

Instead of lowering the impedance in circuit 1 to accommodate the impedance in circuit 2, it is possible to add a series reactor in circuit 2. This series reactor increases the impedance and accommodates circuit 1. The better way of the two options is the first method of lowering the impedance. The impedance in a transmission network should be as low as possible to be able to transfer as much power as possible, it also increases stability. Depending on different circumstances it may not be possible to reduce the reactance in an existing overhead line. One reason could be that the overhead line has a different owner.

The current through circuit 2 goes as high as 2150 A at the sending end (figure 4.8-B), the limit is 1600 A. The parameter changed from case 3 is only the series compensation of circuit 1. Nothing has been done to reduce the reactive current generated in circuit 2. The reactive power generation due to the capacitance in the cable is almost 1800 Mvar, this power needs to be taken care of. Next case introduces shunt reactors in the cable in order to handle the reactive power.

4.5 Case 5, overhead line + shunt compensated composite line

This case is made to illustrate a series compensated overhead line in parallel with a shunt compensated composite line to handle the reactive power. This case has the same parameter as in case 3 and 4, but instead of a series capacitor there will be a series reactor on the cable. The main difference in this case is that shunt reactors are placed along the cable, with a spacing of 20 km. Surge impedance loading (SIL) or natural the load defines the load point where a circuit consumes as much reactive power as it produces. An overhead line generally produces excess reactive power under low load and consumes reactive power under high loads. The SIL point for cables is not reachable, because of the high shunt capacitance. Cables are always below the SIL point and produces excess reactive power. This is a high load situation; the overhead line consumes reactive power. To take benefit of the reactive power there will not be any shunt reactors at the cable ends. This reactive power feeds the overhead lines, in this way the parallel lines do not load the power grid with that much reactive power.

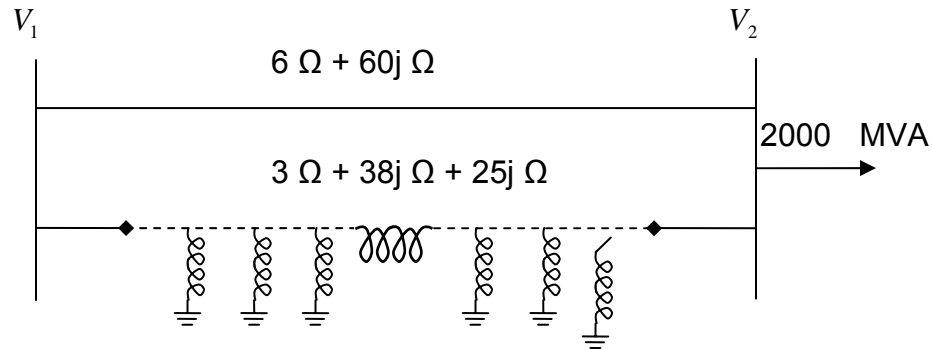


Figure 4.9: Representation of a composite line with shunt reactors and a series reactor in parallel with overhead line

The choice of shunt reactor is based on which standard sizes exists, the values in question for this case is 100, 150 and 200 Mvar. This rated reactive power output is from a three-phase reactor. This case consists out of six 200 Mvar reactors. The last reactor is not connected in this simulation, due to the flow of reactive power that creates a voltage drop over the series reactor. By having the last shunt reactor disconnected, the reactive power through the series reactor is reduced. The voltage drop is only 20 kV, see figure 4.10-A, another simulation made with all six reactors connected gave a drop of almost 100 kV. The reactive power coming from the sending end in this case is 100 Mvar and the receiving end is also delivering 50 Mvar to the reactor, See Figure 4.10-D. In the case with all six reactors connected it was 210 Mvar coming from the sending end and 80 Mvar was delivered to the receiving end. Because of reactive power passing through the reactor there was a large voltage drop, this case on the other hand delivers reactive power from both sides to the reactor. The series reactor thereby consumes reactive power, which is a good thing in a cable with a surplus of reactive power.

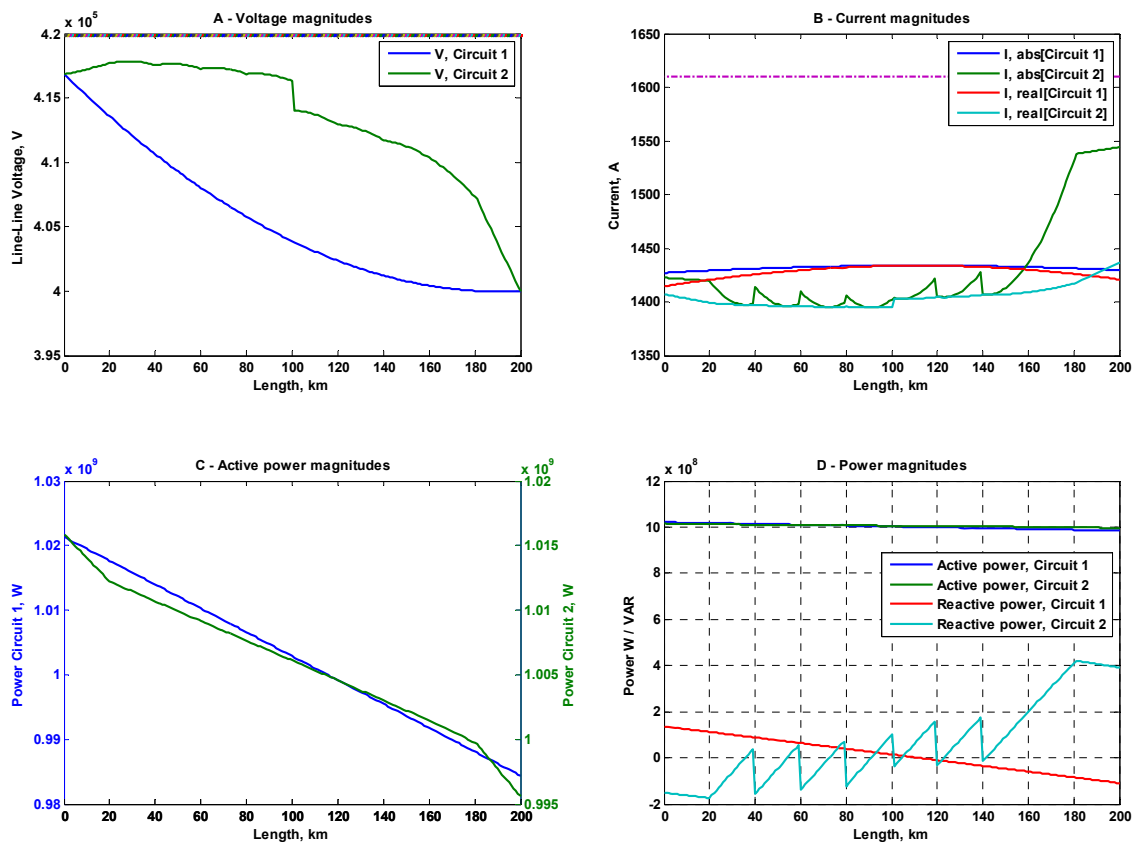


Figure 4.10: Data from Matlab calculations

The current plot, figure 4.10-B, is now below its maximum limit of 1610 A, the dashed line. There is a margin of about 100 A at circuit 2. All the five reactors consumes 1000 Mvar of reactive power and reduces the current in the cable. Reactive power is feed out from the cable in purpose of feeding the overhead lines and the load point.

The voltage magnitudes over the circuits are well below the upper limit of 420 kV, which is the highest voltage for equipment. In the case of all six reactors connected, the voltage at the sending end would be almost 430 kV, consequently above the limit of 420 kV. The degree of compensation, k , in regards of shunt reactor consumption, Q_f , relatively the reactive generation, Q_g , equals $1000/1793$ Mvar = 56 %. The rest of the power is consumed by the series reactor or feed out through the cable ends.

This case describes a possible way of implementing a cable of 160 km in a transmission system. A series reactor was chosen in this case because there might not be possible to compensate the other circuit, as told before in case 4. There can also be more than just one circuit in parallel in a power system, all

parallel circuits would have to be compensated. Later on in the Sydlänken case, there are four circuits in parallel. Compensation on the cable is bound to happen.

4.6 Case 6, overhead line + composite line with phase shifter

This case is made to demonstrate the difference between having a phase shifter or a series component in order to control the power flow. The parameters is the same as in case 5, the only difference is that the series reactor is replaced by a phase shifting transformer. Figure 4.11 describes the two circuits with a phase shifter installed in the middle of the cable. The PST has the phase angle $\theta = -3^\circ$ in this example but is stepwise adjustable in a real case.

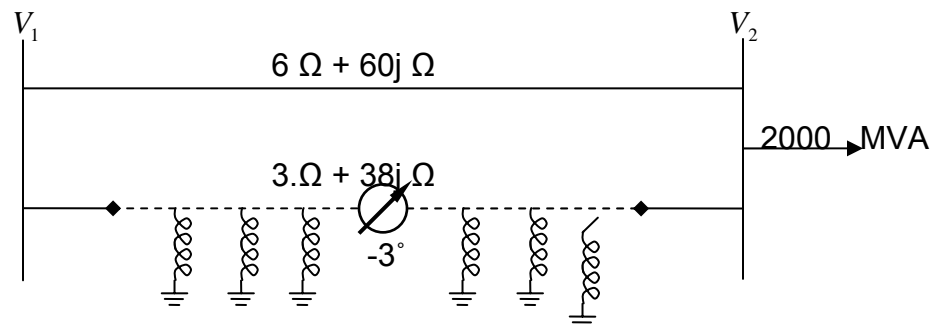


Figure 4.11: Representation of a composite line with shunt reactors and a PST in parallel with a overhead line

The last shunt reactor is also in this case disconnected. The reason is that reactive power is needed at the receiving end. With all six shunt reactors connected the voltage would reach up to 420.3 kV at the cable. The voltage goes beyond the highest voltage for equipment limit at 420 kV. The meaning of the sixth shunt reactor is to have symmetry in the circuit. The possibility of transferring power in the opposite direction is obvious if the circuit is symmetrical. The sixth shunt reactor is used when the load is lower, then the need for reactive power is lower.

The PST is built up of many windings, reactors, which affect the circuit. The equivalent series reactor of a PST is designed during construction and is in the order of 10% of the so called base impedance of the transformer which can be expressed by using the PST's power rating and line voltage. Taking 10% of the

transformer reactance, $X = \frac{(V_{Line-Line})^2}{MVA_{RATING}} \cdot 10\%$. For a 1000 MVA PST at 400 kV it

adds up to 16 Ω.

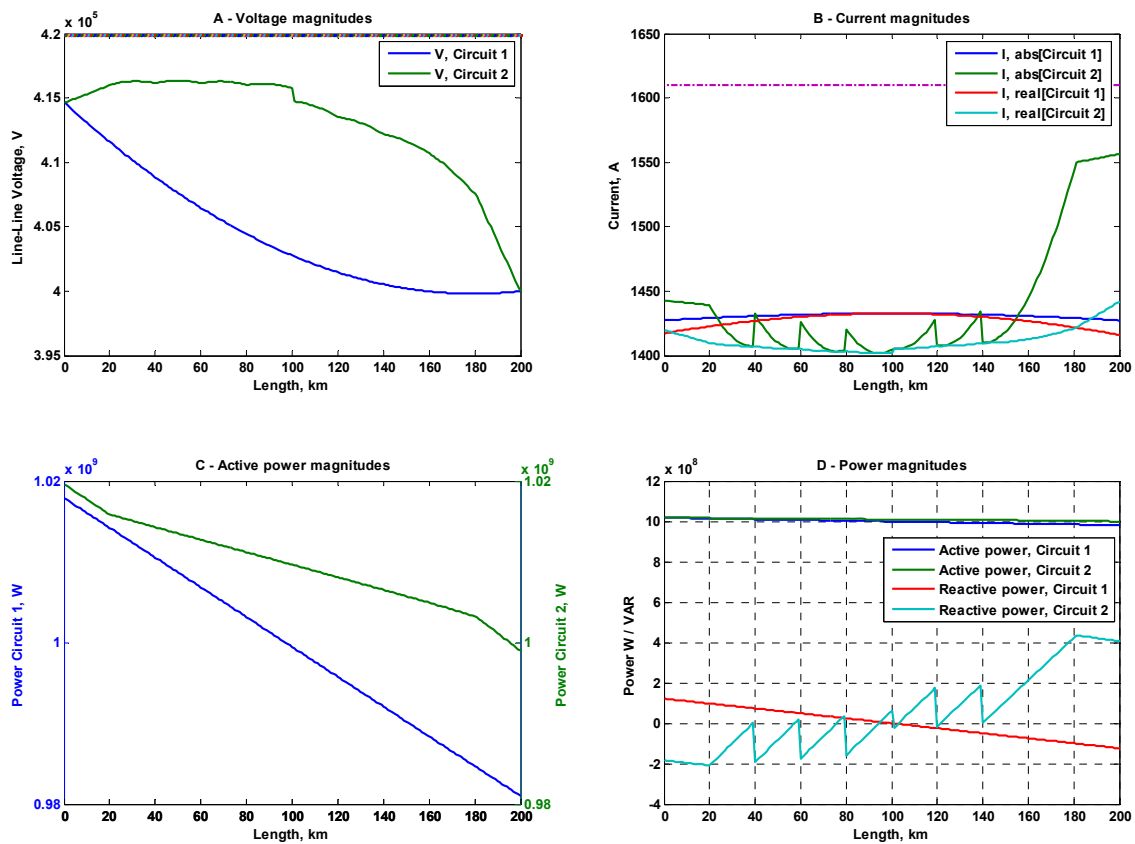


Figure 4.12: Data from Matlab calculations

The first obvious difference between the last case is that the voltage drop in the middle of circuit 2 is much smaller, see figure 4.12-A. The PST does not cause a large voltage drop, the equivalent series reactor is small. The PST simply alters the phase angle in order to reduce the power. The interesting part of this example is that a PST does not increase the impedance of the circuit that much, which keeps the stability of the system. The PST can also regulate the power being transferred through the cable, thus increasing the controllability of the load flow in the system. All good things come with a price, somewhere around 200 MSEK for a 1000 MVA PST.[10]

5 Transmission grid, Sydlänken, single core cable, 400kV

5.1 Background

Sydlänken is a project that shall reinforce the power grid in the southern parts of Sweden, in the province Skåne. This project connects the Hallsberg substation to a new substation at Hörby, see Figure 5.1. One of the underlying reasons behind building this circuit is the blackout that occurred 23 September in 2003. The blackout affected the southern parts of Sweden and east Denmark. The entire grid below Hallsberg and Kinna was affected. A reinforcement circuit from Hallsberg down to Hörby was then suggested. Another reason for the Sydlänken project is to increase the import/export capability of power to Denmark, Poland and Germany. [11]

5.2 Sydlänken parameters

The project has two main alternatives, an overhead line or an underground HVDC Light (High voltage direct current) cable. A HVDC Light alternative would also be a way of increasing and controlling the voltage in Skåne. Increasing the voltage in Skåne will ultimately result in a capacity increase of all the other circuits carrying power down to Skåne.

The Swedish power grid is split up into different sections; the blue dashed line in Figure 5.1 is called section 4. This section can under normal conditions transfer as much as 4500 MW. Worth mentioning is that this section lies precisely south of the two nuclear power plants, Oskarshamn (east coast) and Ringhals (west coast). The plants can regulate voltage and reactive power which increases the power capabilities in section 4. There are not many large power plants south of this section in Sweden; therefore most of the power flowing down is consumed by various load points along the way. In other terms, the transfer capability down to Hörby is much less than 4500 MW, a high estimate is 3500 MW. Together with the new Sydlänken circuit, which shall carry 500 MW, it sums up to 4000 MW.

The overhead line alternative must be able to carry 500 MW of power down to Hörby, this alternative does not increase the voltage. The HVDC Light alternative



Figure 5.1: Sydlänken, reinforces the southern parts of Sweden.

shall be able to carry 450 MW, because of its voltage increment factor. The case alternative shall be able to transmit 500 MW of power in an underground AC cable through 400 km. A comparison of the three alternatives is shown in Table 5.1. The resistance in the cable includes the calculations made in chapter 2.6. The thermal resistance is assumed to be calculated at 90°C. The cable will probably not be at that temperature, but the approximation assumes the worst case. The skin and proximity effect is also calculated. The total increase in resistance is 40% above DC-resistance, this is the value shown in Table 5.1. The resistance used for the overhead lines is taken from the DC-resistances, without adding any more losses. Therefore the losses for the overhead lines are set to the best case scenario. These approximations favor the overhead line.

Table 5.1 Comparison of the three alternatives

Circuit type	AC cable (underground)	Overhead line	HVDC Light (underground)
R	0.0396 / 0.0211 Ω/km	0.014 Ω/km	~0.03 Ω/km
X_L	0.185 / 0.166 Ω/km	0.307 Ω/km	Not important
C	130 / 180 nF/phase&km	12 nF/phase&km	Not important

The HVDC Light alternative will have two single core cables with ±300 kV. Because of the direct current, there will not be any reactance or crucial shunt capacitance. A direct current circuit is not that affected by a length of 400 km, as an AC-circuit. The only losses to talk about in a HVDC cable are the resistive ones.

The overhead line alternative will be a Swedish standard line, aluminum stranded with a stranded steel core, 3x774 mm² per phase (equivalent copper area 3x431 mm²). This line will be directly from Hallsberg to Hörby without being interconnected with any other 400 kV lines. The only compensation suggested is reactive compensation at the two connection points, most likely two shunt capacitors. This lines total amount of transferred power depends on the entire grid, therefore the output power is only expected to be 500 MW. [4]

5.3 Simulation

To make a simplified example of the power grid down to Skåne, a set of four overhead lines in parallel are assumed. The lines are of two different kinds; 2x593 mm² per phase and 3x774 mm² per phase. Both lines consist of a steel core with aluminum around. In reality the lines are interconnected in several points and there are two large nuclear power plants at Oskarshamn (east coast) and at Ringhals (west coast). The nuclear plants affect the voltage and load flow between Hallsberg and Skåne, the load flow is neglected. A number of the connection points in the grid have equipment for voltage regulation, shunt capacitors. Larger power plants and shunt capacitors and filters at the two HVDC converters at Karlshamn and Arrie can also be used to control the voltage. This case has two shunt capacitors placed on each line to simulate the voltage

regulation. The simulation case assumes all of the four overhead lines to be 400 km long and the receiving end voltage is set to 400 kV at Hörby.

The cable consists of a 630 mm² copper conductor per phase. The cable has a larger cross section area near the cable ends, 1200 mm², because the cable shall carry reactive power near the ends. This reactive power will be needed in order to feed transformers and overhead lines. Today shunt capacitors is used to produce the reactive power, the cable will fill this need of reactive power around the connection ends. Figure 5.2 shows a simplified representation of the five circuits in this case.

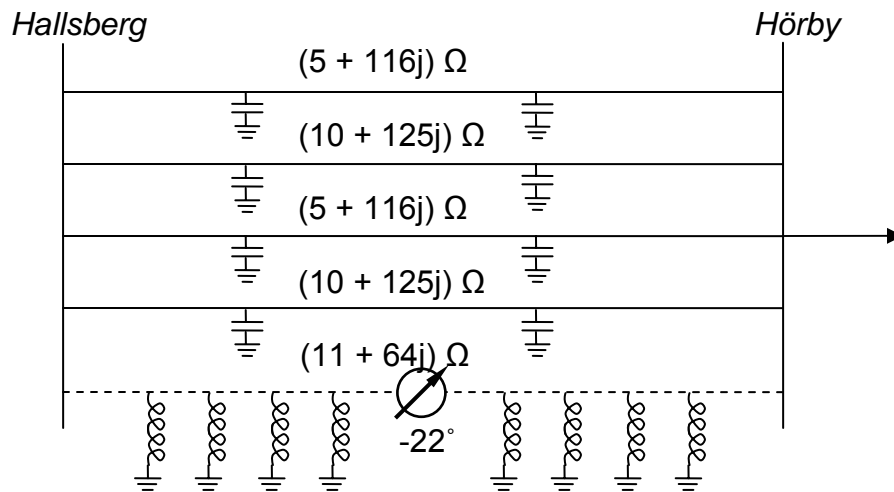


Figure 5.2: Representation of four parallel overhead lines and a cable with a phase shifting transformer

The cable in Figure 5.2 has a phase shifting transformer installed at 200 km, in the middle of the circuit. The PST decreases the phase angle between the connection points and thereby reducing the power flowing through the cable. Without the PST the cable would have taken about twice the amount of power as one overhead line, this would overload the cable. As described in previous cases, a PST regulates the power flow. The PST was chosen instead of a series reactor with the reactance 150 Ω . There is always best to keep the reactance as low as possible, in terms of stability and power throughput. With a series reactor the system would become very voltage sensitive and close to instable. The

equivalent series reactor of a PST is, $X = \frac{(V_{Line-Line})^2}{MVA_{RATING}} \cdot 10\%$ (defined in chapter

4.6). For a 550 MVA PST at 400 kV it adds up to 30 Ω . This is far less than the 150 Ω for a series reactor.

The cable creates about 2800 Mvar of reactive power, this power needs to be taken care of in shunt reactors. All shunt reactors has the size 200 Mvar and there are 14 shunt reactors installed along the cable with the distance of 30 km. The price tag of a 200 Mvar reactor is about 20 MSEK. The degree of

compensation, k , in regards of shunt reactor consumption, Q_f , relatively the reactive generation, Q_g , equals $2800/2800 \text{ Mvar} = 100\%$. This seems like a lot, but this is needed in order to manage the energization of the cable. Energizing a circuit means that the receiving end is open, the receiving end current, I_R , is then equal to zero. The receiving end is not connected and the cable must maintain a voltage below the highest voltage for equipment, which is 420 kV. Further harmonic studies are needed in order to establish that 100% compensation is a viable case. There could be resonance at this high compensation grade.

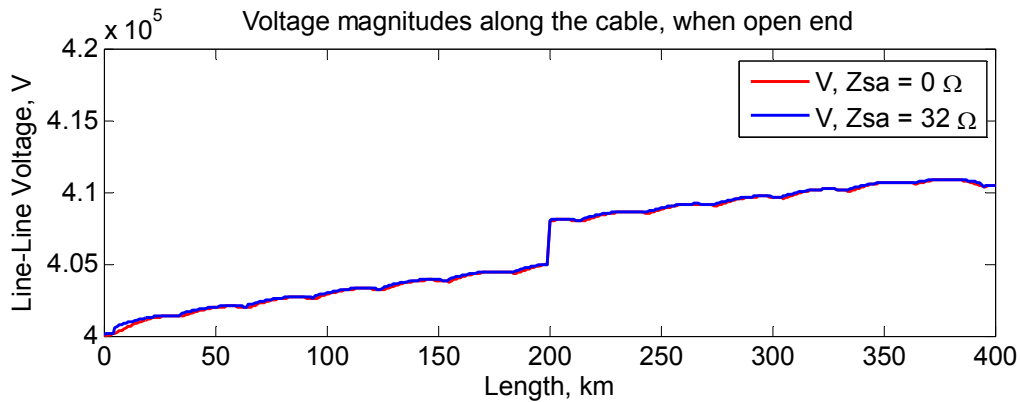


Figure 5.3: Voltage magnitudes when energizing the cable

Figure 5.3 displays the voltage magnitudes along the cable on energizing; the sending end is set to 400 kV. The strength of a connection point can be defined by using short circuit capacity. A connection point with many circuits reduces the short circuit impedance and increases the capacity. This diagram has an infinite strong connection, 0Ω , and a weaker connection, 32Ω , which signifies a capacity of about 5000 MVA. A weaker connection point can not receive that much of reactive power from the cable. In this case there is almost no difference between a strong and a weak connection. This could probably relate to the degree of compensation, k , which is 100%. There is not much reactive power flowing through the connection point. The Hallsberg connection is fairly strong with its four incoming overhead lines; it should be larger than 5000 MVA.

The cable is located symmetrical around the PST which is positioned in the middle. This means that the cable is capable of transferring power in either direction. It could be useful to be able to import larger amounts of power from the south, from Denmark and Germany.

Figure 5.4 describes the Sydlänken case with a load of 4000 MVA at a lagging power factor of 0.99. The voltage magnitudes are below 420 kV, which is the highest voltage for equipment.

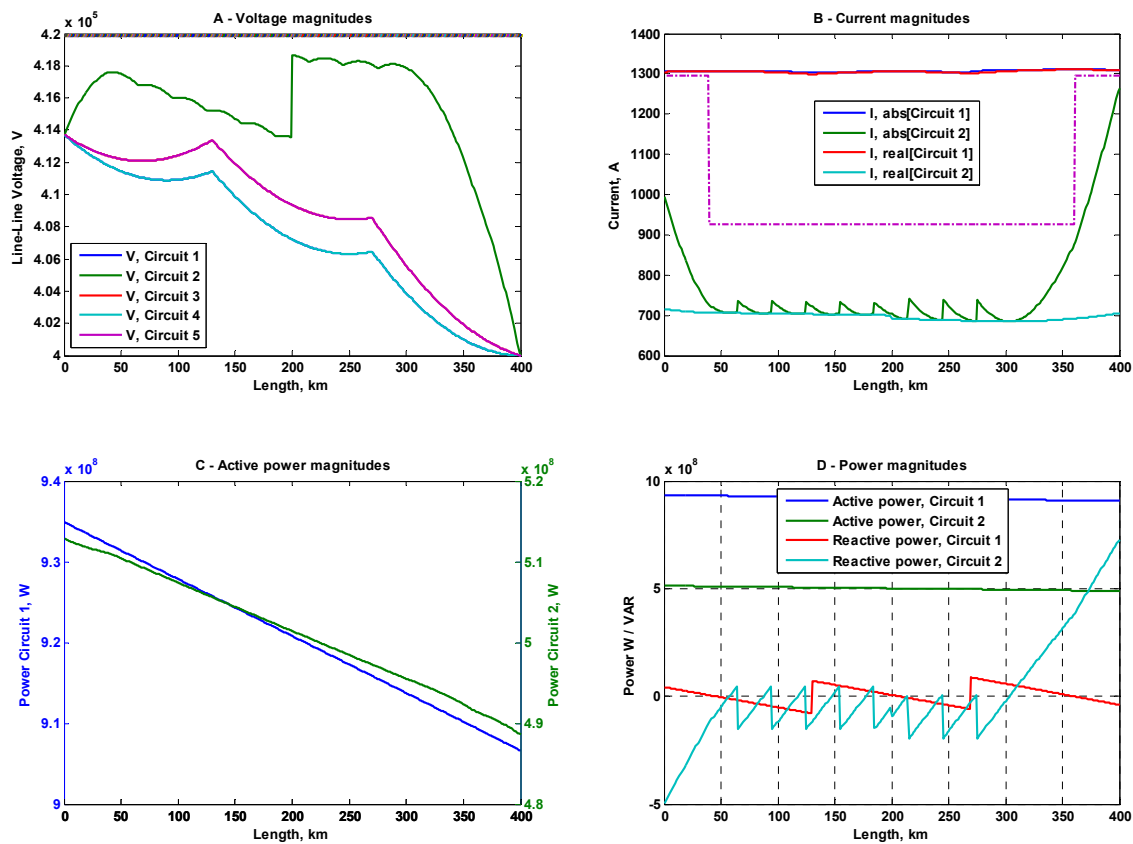


Figure 5.4: Data from Sydälänken example at 4000 MVA load point

Figure 5.4-D confirms that the cable, circuit 2, delivers 500 MW and well above 700 Mvar of reactive power to the receiving end. The delivery of reactive power to the sending end is 500 Mvar. The load point consumes 600 Mvar at a power factor of 0.99. All reactive power needed at the receiving end is provided by the cable, there is also some reactive power left to feed the overhead lines as well. There are only 8 shunt reactors connected at the simulation. This means that a lot of reactive power is being transferred out through the cable ends. The cable is constructed to transfer a little bit over 500 MW, from one end to the other. The larger conductor at the last 40 km of both cable ends makes it possible to disconnect shunt reactors and thereby injecting reactive power into the rest of the system. The compensation is disconnected from the ends and inward, this makes the transport of reactive current as short as possible. Losses are kept to a minimum by transporting current in as short distances as possible. The ejected reactive power can be controlled by connecting or disconnecting shunt reactors.

The PST has the phase angle -22° . This is the maximum angle needed in the system, the simulation runs at the maximum load condition of 4000 MVA. The phase angle must be able to switch to $+22^\circ$, when transferring power in the opposite direction. The angle of $+22^\circ$ seen from the other end becomes -22° . The

PST in this case will have to manage angles from -25° to $+25^\circ$ and have the rating of approximately 550 MVA, because there is always some reactive power flowing in either direction in the cable.

5.3.1 Losses

The transfer losses in the new circuit are an important factor when deciding which alternative to use. A comparison of the three different types of circuits used in the simulation is shown in Table 5.2. Circuit 1 is the overhead line that is suggested in the Sydlänken project. Circuit 3 is the older type of overhead line used in Sweden. Circuit 1 has lower losses than the cable; this is of course due to the larger conductors (equals 1293 mm^2 of copper). The losses in the grid are probably somewhere in between circuit 1 and circuit 3, because the load sharing is almost equal. Average losses for the overhead lines then become $\frac{906 \cdot 3.1\% + 829 \cdot 5.7\%}{906 + 829} = 4.3\%$. The losses per transferred watt is based

on real power only, the cable delivers more reactive power than real power in this example. Reactive power contributes to the losses; current of both active and reactive loads the conductor. More current means more losses.

The losses in the shunt reactors are not taken into account. The losses are approximately 0.4 % for a shunt reactor, which means 0.8 MW per reactor.

Table 5.2: Losses in the simulation

Resistive losses	Circuit 1, New type 3x774 mm ²	Circuit 2, Cable	Circuit 3, Old type 3x593 mm ²
Total losses (MW)	28.2	22.1	47.3
Transferred power (MW)	906	489	829
Losses/transferred W (%)	3.1%	4.5%	5.7%

The PST introduces controllability to the system. Another useful feature of this controllability is to minimize losses. By varying the phase angle different load situations arises. An iteration made in this case with two shunt reactors at each end disconnected is shown in Figure 5.5. This iteration varies the phase angle of the PST between -10 to -30 degrees. The optimum point in this iteration is -21 degrees. The angle set by this case is 22 degrees; this angle was chosen in respect to the power throughput of 500 MW. A rough estimate of the annual savings for each mega watt of reduced losses is: $1 \text{ MW} \cdot 5000 \frac{\text{operation hours}}{\text{year}} \cdot 300 \frac{\text{SEK}}{\text{MWh}} = 1.500.000 \frac{\text{SEK}}{\text{year}}$. There is a lot of money to save by investing in a PST. The savings alone will probably not return the invested money, but it certainly makes the PST a more attractive option.

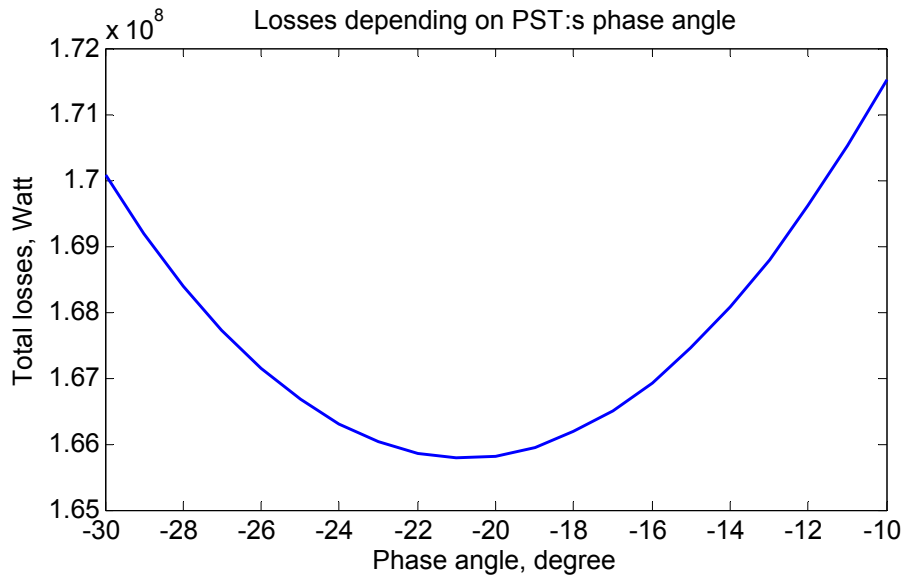


Figure 5.5: Losses in the complete circuit depending on the PST:s phase angle

5.4 Discussion

The cable alternative is a feasible option in the range of 400 km from a steady state perspective. There are higher losses in the cable compared to the newer overhead line (circuit 1), but the overhead line was based on DC resistance. The choice of cable dimension could be larger, the 630 mm² cable was chosen in respect to the transfer capabilities of 500 MW. The existing power grid used today is limited by the older overhead lines. The power transfer capabilities in new overhead lines are thereby far from fully utilized. A cable transfers to much power, which is the opposite of the new overhead lines. A PST could also be interesting for the new overhead line; it could increase the power throughput and thereby reduce losses.

The cable has to be compensated with 14 shunt reactors; these reactors cost about 20 MSEK each. It sums up to 280 MSEK, probably less because of the quantity. The PST probably costs at least 100 MSEK, a 1000 MVA PST costs about 200 MSEK. A rough estimation could be that the compensation needed costs about 400 MSEK. This is quite a lot, but a PST is a good investment both in terms of extra controllability and loss reduction.

6 Sub transmission grid, tree-phase cables

This case is simulated in the steady state program Powerworld. It is much easier to set up a case in a simulation program; it can even be done without that much prior knowledge about the calculations. The reason behind solving it through equations is to build up a basic comprehension about long distance calculations of transmission lines and cables. Without the basic comprehension it is more difficult drawing any conclusions about the results.

This case illustrates how a cable can affect the load flow in a smaller city network. The city has four main transformer stations to feed the city. These transformer stations are feed by a set of 130 kV overhead lines, see Figure 6.1. The network shall be reinforced by adding a new circuit, the dashed one in the figure. This circuit closes the loop in the city ring which makes the network more reliable in case of a fault. The network has a local power generation plant up in the northeast corner; this generator produces 25 MW of power into the grid. The southwest corner is connected to the 400 kV power grid through a 250 MVA transformer.

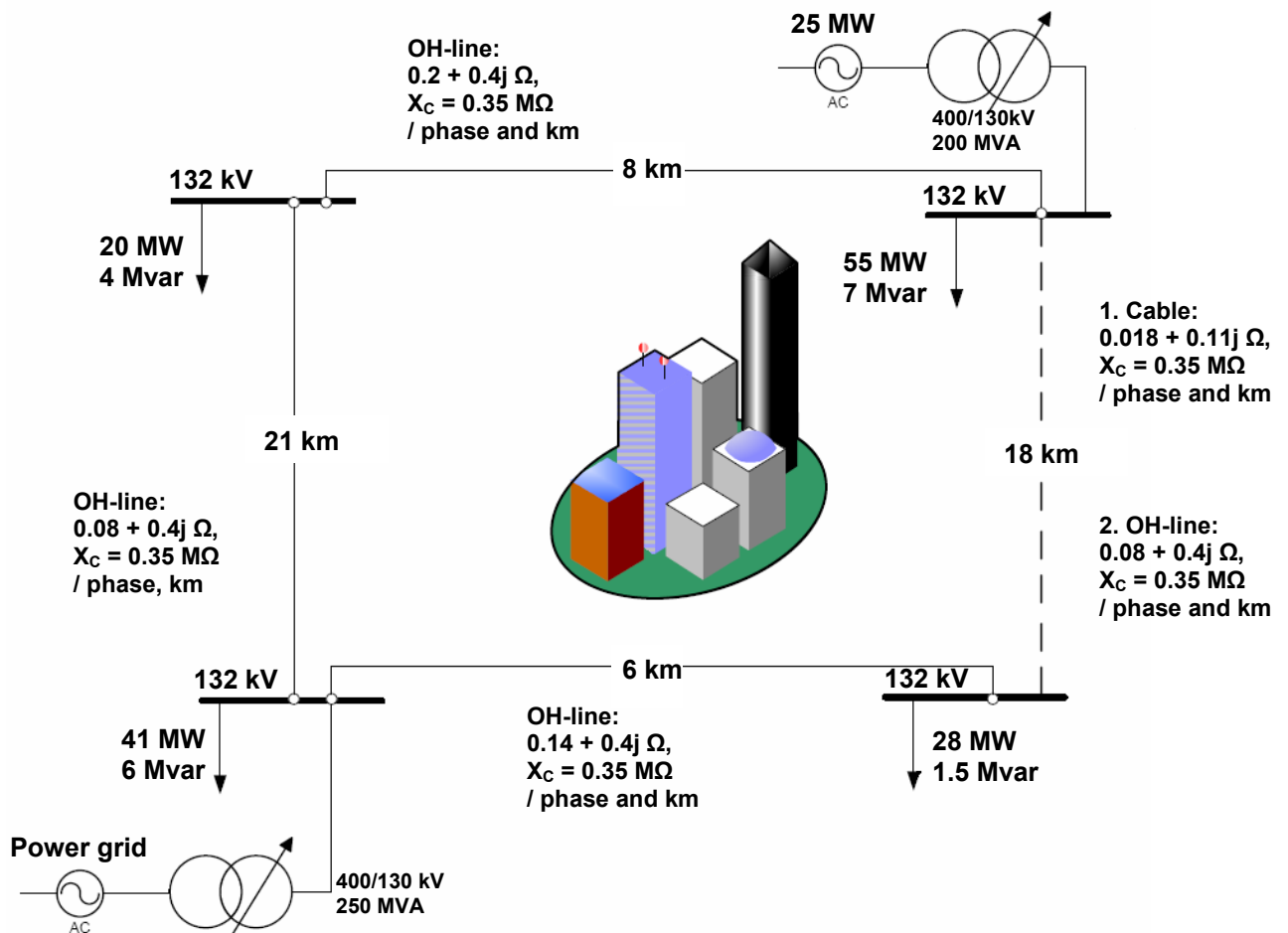


Figure 6.1: Layout of the 130 kV city network

The new circuit can either be an overhead line or an underground cable. The overhead line parameters are $0.08 + 0.4j \Omega$ with the shunt capacitance $350 \text{ k}\Omega$ per phase and km. The cable is suggested to be a 1000 mm^2 with the parameters $0.018 + 0.11j \Omega$ with the shunt capacitance $12.7 \text{ k}\Omega$ per phase and km.

Let us assume that the generation plant up in the northeast corner has a fault. The northeast bus has to increase its load from the other two busses. The load flow over this system without the new circuit is shown in Appendix A. The southern line in this example is a 127 mm^2 and has a maximum current throughput of about 2 A/mm^2 , this line can then transmit about 60 MVA. The transmitted power on this link depends on which alternative that is used for the eastern link, Appendix B and Appendix C.

The power through the southern link in the overhead line and cable alternative is 63 MVA and 73 MVA. Let us assume that the southern link can handle the load of 63 MVA. The cable has to be series compensated in some form. The simplest solution is to add a series reactor to the new eastern cable which reduces the power throughput. A PST can also be used but it is a bit more expensive. The series reactor of 9Ω reduces the power through the southern to less than 60 MVA.

A cable generates a lot of reactive power; this power is needed at the loads and transformers. The cable case feeds the 130 kV grid with reactive power, there is also 5 Mvar going back through the feeding 250 MVA transformer. The transformer consumes about 21 Mvar; this means that the city only has to buy 16 Mvar of reactive power from the 400 kV grid. In the overhead line alternative the city would have to buy 39 Mvar of reactive power. This is a significant difference and there could be money to save by having a cable that generates reactive power.

Table 6.1: Power transmitted from the grid

Power transmitted from the grid	Before	Cable with a series reactor	Overhead line
MW	144.90	144.45	144.49
Mvar	41.53	15.76	38.68
MVA	150.73	145.31	149.58

Table 6.1 describes the difference between the three options. The overhead line alternative saves 410 kW while the cable saves 450 kW. As said before, the big difference lies in the amount of consumed reactive power where the cable alternative is the most favorable. There is a quite large difference in the total amount of complex power drawn from the grid, where the cable draws about 5 MVA less.

A real example is that the city of Lund in Sweden has two 130 kV cables connecting their three substations together, all of the substations has a primary connection from the grid. The cables works as backup in case of a fault and instead of shunt capacitors (provides reactive power).

7 Conclusion

Cables has much lower impedance than overhead lines, this makes it necessary to investigate the power flow in some detail. Low impedance is better in terms of stability and power transfer, but the existing power grids used today consists of overhead lines. The cable may take on too much load in an interconnected power system. Some series compensation is always needed in order to balance the load sharing. The compensation can be a series capacitor or reactor in order to decrease or increase the impedance of the circuit. A better alternative is to use a PST as compensation, it can control and alter the power flow in real-time. The PST increases stability and can also be used for minimizing losses in a system.

The shunt capacitance of a cable can be both an advantage and a disadvantage. Power systems need reactive power in order to feed lines, transformers and loads. The amount of reactive power needed differs a lot. An overhead line consumes reactive power at high loads, but at low loads it can produce excess reactive power. In a long cable circuit, i.e. Sydlänken, the cable produces too much reactive power; this reactive power has to be taken care of in shunt reactors. The amount of shunt compensation needed becomes expensive; this is the price for using a cable. The price should be set in relation to the fact that cables affect the surroundings less and the magnetic fields are greatly reduced.

In a smaller network, i.e. the 130 kV example, a cable can be a good way of decreasing the amount of reactive power needed. The smaller grid don not need to buy reactive power from the power grid. Decreasing the reactive power also decreases the complex power drawn from the power grid.

8 Future work

This thesis introduces the idea of a longer cable in an interconnected power system. This is not a complete solution, further calculations have to be made in order to have a complete due able option, calculations like stability, short-circuit, etc.

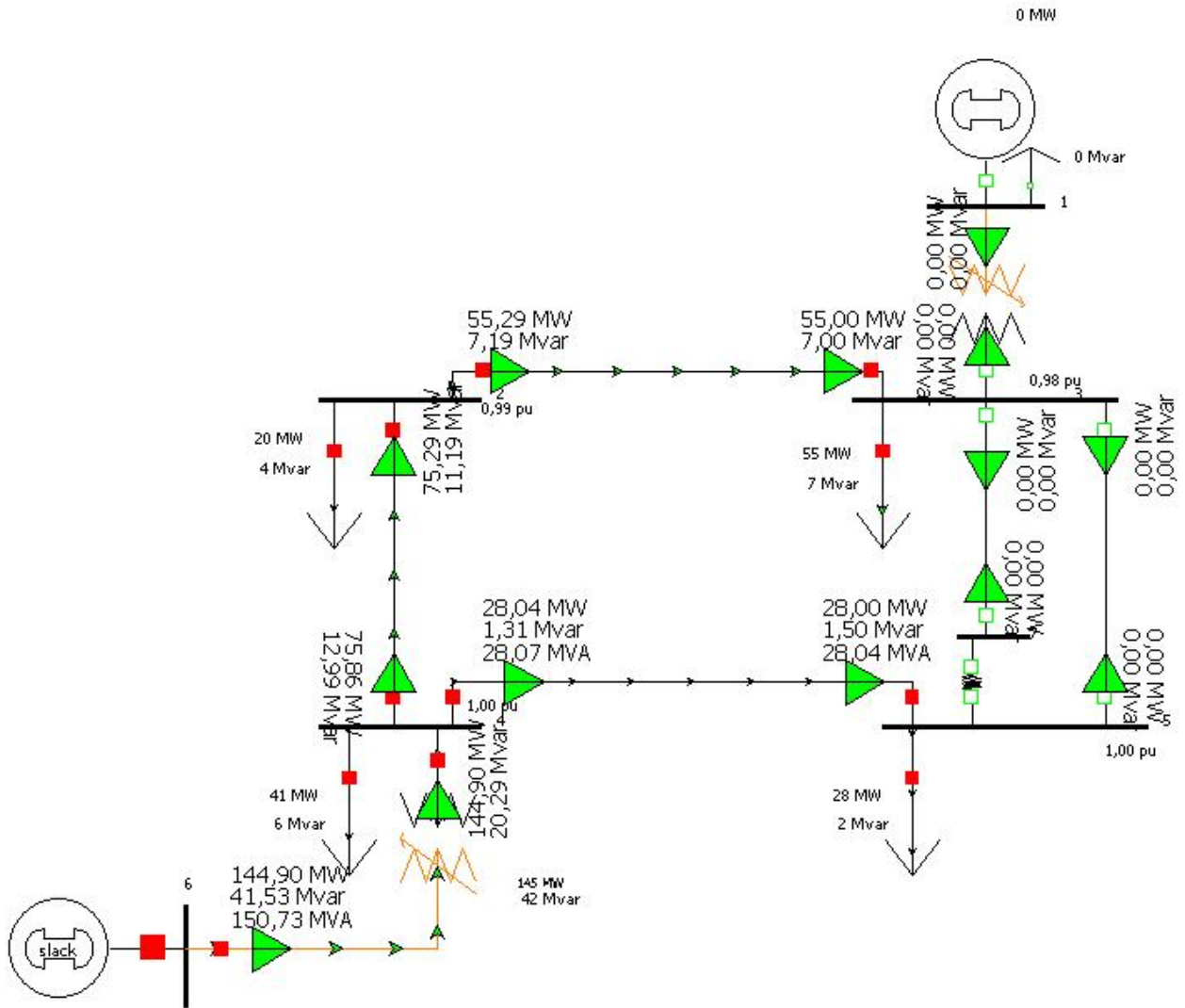
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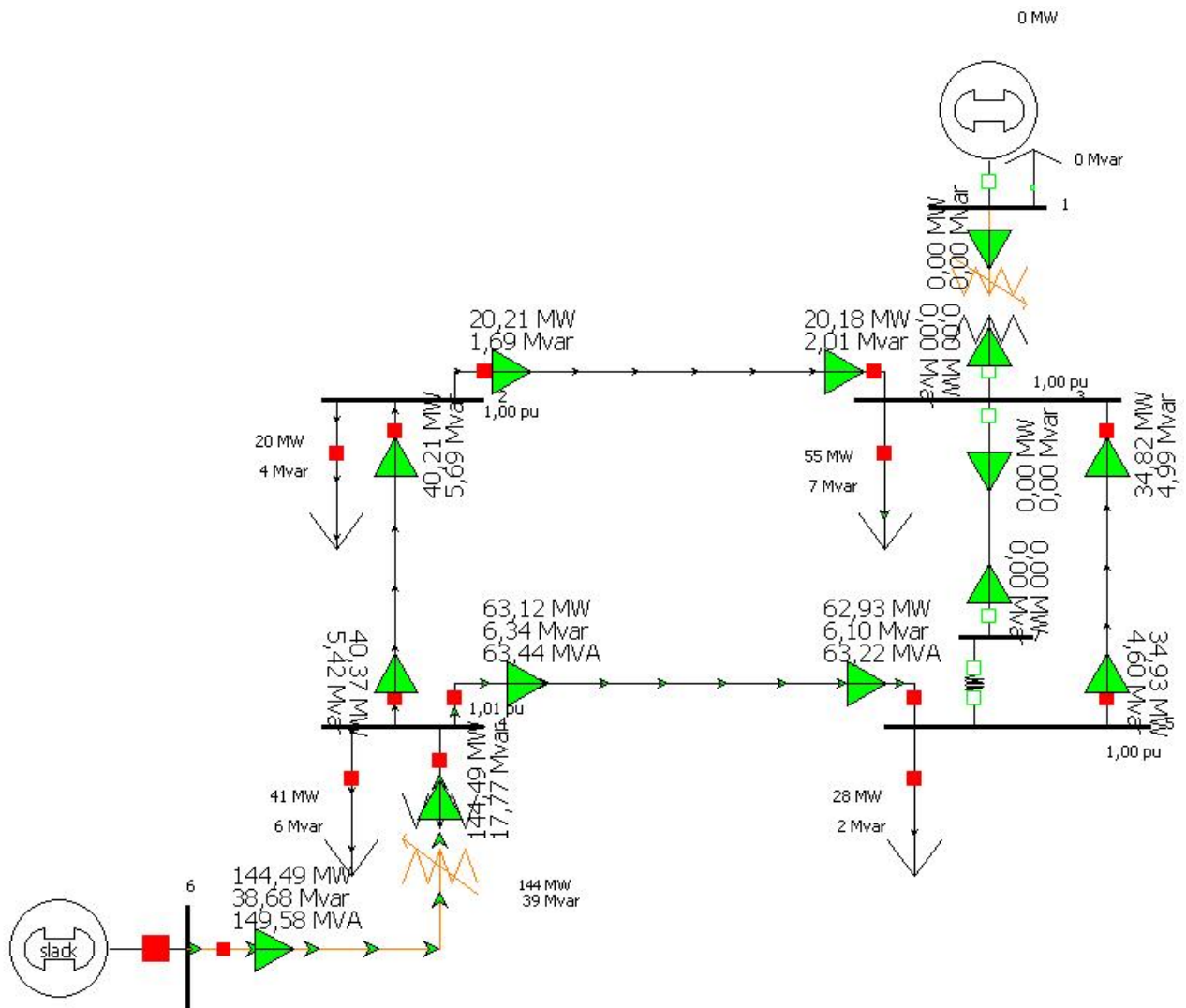
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10 Appendix

10.1 Appendix A – Power flow before eastern link



10.2 Appendix B – Power flow with an overhead line in the eastern link



10.3 Appendix C – Power flow with a cable in the eastern link

