Doctoral Thesis

Increased Transmission Capacity by Forced Symmetrization

Author(s):
Karpatchev, Andrei

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Increased Transmission Capacity by Forced Symmetrization

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH
for the degree of
DOCTOR OF TECHNICAL SCIENCES

presented by
ANDREI KARPATCHEV
Master of Science, Moscow Institute of Physics and Technology
born on 17.07.1973
citizen of Russian Federation

accepted on the recommendation of
Prof. Dr. Göran Andersson, examiner
Prof. em. Dr. Hans Glavitsch, co-examiner and supervisor
Prof. em. Dr. Dusan Povh, co-examiner

Zurich 2003
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Andrei Karpatchev
Zurich
December 2003
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Abstract

The electrical power industry experiences nowadays a significant need in modern techniques for increasing the capability of power transmission systems. The reason for this lies in growing power flows, caused by rising power consumption, and in the deregulation of the electrical market, where power flows should be more flexible. These factors demand more transmission capability from the existing networks. The conservative expansion of the high voltage grid is often not desirable or not possible, because the approval of new overhead transmission lines meets strong opposition in society. Furthermore, it takes a long time and is generally a risky long-term financial investment. New technological solutions are sought to meet the capability needs under consideration of modern environmental requirements.

The presented work considers possibilities for ensuring power transmission through an AC transmission line with a damaged phase conductor. The disturbance of the symmetrical pattern of currents and voltages in the surrounding network can be eliminated by active measures for symmetry. The utilization of two remaining healthy phases of a three-phase transmission line with a damaged phase in this way can be an economical way to enhance the system reliability.

The present planning procedure of the high voltage networks mostly respects the (n-1) criterion. This means that the network should not be subject to any overload or voltage drop below a strictly given limit when any network element is disconnected. Based on statistics, single phase-to-ground faults are the most frequent faults in transmission systems,
typically approximately 2/3 of all line faults at voltage level 220-380 kV. Present planning procedures are often based on single outages of three-phase circuits, which do not take into account the actual fault pattern. For the single-phase faults it is necessary to avoid unsymmetrical conditions or unsymmetrical currents in the network. The reason for this is that the currents in the zero sequence system mean earth currents, and those can be dangerous for people and cause adverse interactions with other systems. The currents and voltages in the negative-sequence system are of concern to rotating synchronous machines like generators and motors, but if no such machines are connected to a network part, negative-sequence voltages can be tolerated in that part.

Symmetrization means the suppression of both zero- and negative-sequence currents on the network side of both line circuit breakers so that the network does not experience any unsymmetrical conditions. This can be performed by the installation of special equipment as shunt or serial elements at the line terminals.

Different arrangements and strategies are considered in this work. In order to be able to try all the different arrangements a special system simulator has been developed. It is based on power flow calculations with multiple symmetrical system representations and allows simulation of the symmetrization effect in a complex meshed network. The fault currents in the negative and zero sequence systems can be studied directly. Different symmetrization topologies, both concentrated and distributed, are investigated and discussed.

Modern power electronics devices and measurement technology provide the hardware basis for the practical implementation of different modern symmetrization techniques. The present work considers impact on the whole grid, in case symmetrization techniques are applied. The achieved rest transmission capacity of the damaged line and other "system" characteristics are in focus of interest. Different methods of symmetrization are considered and compared. A possibility of distributed compensation is also one item of interest, which is very promising for the protection of several lines.

Symmetrization methods, which are examined in this work, increase considerably the system reliability and can be seen as competitive solutions for an extensive grid expansion on the existing congestion routes. The installation of the necessary additional equipment can be done in shorter terms than the construction of a new transmission line. The environmen-
tal and aesthetic impact is then very small too. Modern power electronics devices, which are needed to achieve these advantages, introduce more operational flexibility and can be used also in non-disturbed operation of the network.
Kurzfassung


Moderne Leistungselektronik-Geräte und Messtechnik liefern die Basis für die praktische Implementierung verschiedener Symmetrierungstechniken. Die vorliegende Arbeit berücksichtigt Auswirkungen der Anwendung von Symmetrierungstechniken auf das ganze Netz. Der Fokus des Interesses liegt in der erreichbaren Übertragungskapazität der defekten
Leitung und in anderen Systemcharakteristiken. Verschiedene Symme-
trierungsmethoden werden untersucht und verglichen. Die Möglichkeit
verteilter Kompensierung ist ebenfalls Gegenstand des Interesses, was
vielversprechend ist für den Schutz mehrerer Leitungen.

Die in der vorliegenden Arbeit geprüften Symmetrierungsmethoden
erhöhen die Systemverfügbarkeit erheblich und können als konkur-
renzfähige Alternative zum extensiven Ausbau überlasteter Leitungen
betrachtet werden. Die Installation der nötigen zusätzlichen Geräte
cann in kürzerer Zeit realisiert werden als der Bau einer neuen Übertra-
gungsleitung. Zudem ist der Einfluss auf Umwelt und Ästhetik ebenfalls
sehr klein. Die modernen Leistungselektronik-Geräte, welche zur Erlan-
gung dieser Vorteile nötig sind, bringen mehr Betriebsflexibilität und
können auch bei normalem störungsfreiem Betrieb benutzt werden.
1.1 Changes in the Electricity Industry

Worldwide the electrical power industry is undergoing profound changes today. In addition to the classical changes drivers, such as energy consumption rise and equipment technology advances, the electricity industry now meets deregulation and the competitive electricity market as new challenges. A distinguishing feature of the emerging industry structure is the separation, or unbundling, of power production from power delivery. The primary motivation for this separation, particularly in developed countries, is the desire of governments and energy policy makers to foster competition in power generation in order to drive the cost of electricity down, while keeping or even enhancing supply quality and reliability. In this new paradigm, transmission has no direct role in deciding generation and transmission patterns, because generating companies are free to choose both the technology and location of their generating facilities. Coordination of transmission and generation investment as done in vertically integrated power utilities becomes a thing of the past [1]. This is one source of new congestions on the high voltage grid.

On the other hand a slow, but steady electrical power consumption rise in developed countries brings the existing transmission infrastructure to its limits. Increase of consumption of the electrical energy can still be observed in all countries, even in spite of efforts of governments and
"green" organizations to stabilize the energy consumption. In this way, the electrical grid is stressed by two forces: hardly predictable, varying power flows and overall increase in power throughput. These factors represent a challenge, which can be solved in different ways. One way can be a traditional extensive grid capability upgrade by construction of new transmission capacities. Another way can be an optimized usage of the existing transmission lines by involvement of new techniques and technologies.

This work elaborates a small piece of the second way. Particularly, new possibilities for enhancing the reliability of the existing transmission lines are studied. The progress in high voltage equipment, like controllable power electronics devices, open a wide range of new possibilities in the grid operation. It will be shown that with the aid of additional equipment at substations an AC transmission line can safely operate also during fault conditions, such as a single-phase line fault. This means a better overall system reliability, because even during fault conditions some remaining transmission capacity of the line can be used.

1.2 Fault Statistics

The ignition idea for the research work arises out of knowledge of fault statistics for the overhead transmission lines. It is commonly known that single-phase faults are the most common faults in the high voltage grid. Detailed statistics studies confirm this fact. This basic fact lies at the base of the whole work.

Selected publicly available Swiss, German and North American statistics sources have been studied. Focus of the analysis was devoted to the frequency and sort of faults on high voltage AC transmission lines. A clear majority of the single-phase faults justifies the emphasis of the presented research on that type of faults. The percentage of faults due to the phase-to-phase and three-phase faults is considerably smaller. Reliability of a transmission line will increase remarkably, if the line can stay in operation and transmit some power even with disconnected single phase conductor.
1.3 Field of Research

This work focuses on a more effective usage of the existing overhead transmission lines by utilization of remaining transmission capacities of a line in a faulted state. Under the more effective usage will be understood additional equipment and financial investments, but no additional right of ways or transmission corridors for the overhead lines. The utilization of the remaining transmission capacity of the line can be an alternative to the extensive grid expansion.

The present planning procedure of the high voltage networks mostly respects the (n-1) criterion. That means that the network should not be subject to any overload or voltage drop below given limits when any single network element is disconnected. Present planning procedures mostly do not take the actual fault pattern into account and suppose a single outage of the three-phase circuit, even if only a single phase is damaged. The explanation for this lies in the necessity of avoiding unsymmetrical conditions or unsymmetrical currents in the network. Currents in the zero sequence system\(^1\) (ZSS\(^2\)) mean earth currents, and those can be dangerous for people and force equipment corrosion. In Swiss practice no zero sequence currents are tolerated in the high voltage overhead grid. As soon as a zero sequence current is detected on some line section, the section has to be taken out of operation. The currents and voltages in the negative sequence system (NSS) are a danger to rotating synchronous machines like generators and motors [2], but if no such sensitive equipment is connected to a network part, the NSS voltages can be tolerated in that part.

This work discusses a three-phase transmission line in case of damage of a single phase conductor. A new proposed approach is to leave the two remaining sound conductors in operation and simultaneously to provide special measures for symmetrization of non-symmetrical currents. Symmetrization means suppression of zero and negative sequence currents on the network side of both line circuit breakers so that the network does not experience any unsymmetrical conditions, even if non-symmetrical currents flow through the transmission line section.

The symmetrization can be performed by the installation of special devices at the ends of the faulted transmission line section. These devices

\(^1\)More to symmetrical sequence systems see in section 3.5
\(^2\)See Appendix C for the abbreviation list
will be called symmetrization compensators or simply compensators in the following. It is schematically illustrated in figure 1.1, where compensators are shown as black boxes. The compensators can be both series and shunt devices. They can be implemented on the basis of power electronics elements, like FACTS (Flexible AC Transmission System) devices, and/or on the basis of traditional equipment like fixed series capacitors or power transformers. An additional highground wire with a low insulation level provides a secure path for zero sequence currents. The wire can be integrated into the existing tower layout.

![Figure 1.1: General symmetrization scheme](image)

The goal of the presented research project is to investigate the possibilities of the symmetrization, when two non-affected phases stay in operation and only the faulted phase is disconnected. Different arrangements and strategies are studied in order to find technically and economically reasonable solutions. The symmetrization techniques can be also applied at double phase faults, when only one sound phase stays in operation. This possibility is theoretically considered without detailed modelling.

### 1.4 Research Approach

The possibility of the symmetrical compensation has been studied in classical symmetrical components systems representation (see also [12], [13] and [14] and section 3.5.1). This approach has proved to be very practical for analysis of the symmetrization strategies. Simple network topologies can be calculated very easily and new compensation techniques can be analyzed with minimum effort. For the complex network
1.4. RESEARCH APPROACH

analysis the approach of symmetrical sequence systems is also very practical, because the non-symmetrical currents and voltages (currents and voltages in the negative and zero sequence systems) are directly presented in the analysis results.

Most of the high voltage networks are designed in such a way that they can conduct zero sequence currents. It helps to limit overvoltages in the system at single phase earth faults. It has been reflected in the assumptions about the considered network. Generally it has been supposed that zero sequence and earth currents can flow in the system as long as no countermeasures are undertaken. The earth currents have to be avoided, so for compensation topologies, where zero sequence currents can flow in the faulted section, an additional wire, the highground (HG) wire, is foreseen for bypassing the earth currents. The difference between the highground wire and a spare phase wire, which is used nowadays on some important routes, lies in its insulation level. The HG-wire is supposed to carry the return zero sequence current, but no power. It needs only a low insulation level in comparison to the phase wires. It can even be grounded at one point to provide a voltage reference and to ensure a low voltage level, figure 1.1. It should thus be no problem to integrate the wire in the existing tower topology with minimum investments, figure 3.5.

The three phase wires, which are convenient to be considered in the symmetrical sequence systems, combined with additional highground wire have inspired the introduction of a new mathematical basis, the extended symmetrical components system, see section 3.5. This basis comprises all advantages of the classical symmetrical components systems for analysis of conditions at the phase conductors. It also allows a direct representation of the voltages and currents at the highground wire as they can be directly measured. Aside from this, three of four sequence systems of the extended symmetrical components system are completely compatible with the classical symmetrical components system. In system modelling this compatibility allows easy integration of the four-wire (three phases plus a highground wire) transmission lines into a three-phase network. Representation of the network in the classical and extended symmetrical components systems have helped to develop and analyze several methods for avoiding the non-symmetrical currents in the system in case one phase conductor is taken out of operation.

Basic properties of different compensation schemes have been directly analyzed with the aid of very simple models. For deeper analysis of the
most promising methods, the compensation schemes have been analyzed on a specially developed simulator, see chapter 4. The compensated faulted line has been simulated with consideration of all inductive and capacitive interactions between all four conductors, because these interactions are very important for the calculation of the non-symmetrical currents in the grid and in compensators.

The simulation allows the investigation of the distribution of non-symmetrical currents and voltages in the network. Different compensation schemes can be tried out in a complex meshed environment. Symmetrization methods influence parameters of the considered transmission line as these parameters are seen from the rest of the network. The impedance of the transmission line significantly changes, thus changing the power flow in the line section and in the network. The simulator allows the analysis of all these impacts on the network.

It has been proposed to distinguish between local and distributed compensation schemes. The schemes differ from each other in the scope of the network, where the non-symmetrical currents will flow, and in the number of locations, where compensators will be placed.

**Local symmetrization**

The idea of the local symmetrization is that the symmetrization compensators are located at the ends of the faulted transmission line. The compensated line, although carrying non-symmetrical currents, is seen as a symmetrical component from the surrounding grid. It is the task of the compensators to re-configure the currents and voltages at the ends of the damaged line section. The line will expose symmetrical properties to the rest of the network, which can differ from the properties of the same line in healthy operation. Different compensation strategies and configurations were tried out at different system layouts.

**Distributed symmetrization**

The distributed symmetrization supposes that the compensation equipment is distributed over larger network parts. The idea is based on the fact that transmission lines can carry negative sequence currents without danger. If no sensitive equipment is connected at some network part, the negative sequence currents can be tolerated there. In this case only the zero sequence system current has to be locally compensated to guarantee
that no current flows through the earth. The negative system currents can be compensated at other substations. Such a solution will lead to the installation of compensation equipment at different locations in the network. The rated power of the compensating equipment per location can be kept low. The negative sequence compensators, distributed over larger network parts, can be used for the power flow and power quality control during the normal operation and/or serve as a part of the infrastructure for the compensation of faults at other lines.

Several compensation schemes have been applied to selected lines at two IEEE test networks, see section 3.11. The most important factors, which were investigated during the simulation, are the relation of the transmitted power through the faulted and healthy lines, the loading of each conductor and the needed rating power of the compensators.

1.5 Advantages

The analysis of selected compensation schemes has shown that symmetrization techniques allow to preserve a substantial part of the transmission capacity of the transmission line in case of a fault at only one or two phases. Up to two thirds of the original transmission capacity can be reached in case of a single phase fault. This can be achieved without big changes in the network structure. Partially the existing network components like power transformers can be used for the symmetrization purposes. The environmental impact of the proposed techniques is minimal, because the equipment is mostly located at substations. The highground wire can be integrated into existing towers, so no new rights of way are needed. This simplifies remarkably the implementation and makes the network upgrade possible during short times.
Chapter 2

Fault Statistics

The most important basis for this research work was the fact that most of faults on the high voltage overhead lines affect only one phase. Knowing that, a natural question arises: "Is it possible to operate the grid in case one phase wire at a transmission line is disconnected?" So the knowledge of statistics was crucial for the presented project.

Several public statistics sources have been studied. That are Swiss sources from the Association of Swiss Electrical Utilities (VSE - Verband Schweizerischer Elektrizitätswerke) [3, 4, 5, 6], German sources from the Association of German Power Utilities (VDEW - Vereinigung Deutscher Elektrizitätswerke) [7, 8] and a North American (U.S. and Canadian) source [9]. The statistics sources come from different countries and from different dates as shown below. All of them confirm that one phase damages are the most frequent ones at high voltage overhead transmission lines at rating voltages over 110 kV.

Extractions from the studied sources are presented in the tables below (tables 2.1-2.3). The tables have different structures, reflecting the original source data. The representation has been specially left as it is and not further simplified, because the information of interest can already be obtained and because a little bit of detailed statistics data can also be of interest to the reader. In table 2.3 information about circuit exposure for the North American statistics has also been included, which allows a direct comparison with Swiss and German sources.
Fault Type | VSE, 220 kV | VSE, 380 kV | VDEW, 220 kV |
--- | --- | --- | --- |
Self-extinguishing EF | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
Lasting EF | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
Earth short circuit | 3.3 | 2.9 | 3.1 | 5.8 | 3.7 | 4.75 | 2.08 | 2.18 | 2.13 |
Double or multi-EF | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
Deact. of one resource | 1.6 | 1.0 | 1.3 | 0.9 | 0.2 | 0.55 | 0.51 | 1.04 | 0.78 |
Feeder loss | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.02 | 0.06 |
Other | 0.1 | 0.2 | 0.15 | 0.1 | 0.0 | 0.0 | 0.5 | 0.02 | 0.04 |
One-phase faults (%) | 60% | 63% | 61% | 83% | 80% | 83% | 65% | 82% | 52% |

Results are given per 100 km of line length.

Table 2.1: Line faults by fault type, VSE and VDEW, older data.
<table>
<thead>
<tr>
<th>Fault Type</th>
<th>VSE, 220 / 380 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1998</td>
</tr>
<tr>
<td>Earth Fault (EF)</td>
<td>0.15</td>
</tr>
<tr>
<td>Earth short circuit</td>
<td>1.7</td>
</tr>
<tr>
<td>Short circuit</td>
<td>0.63</td>
</tr>
<tr>
<td>Other</td>
<td>0.32</td>
</tr>
<tr>
<td>One-phase faults (%)</td>
<td>66%</td>
</tr>
</tbody>
</table>

Results are given per 100 km of line length

*Table 2.2: Line faults by fault type, VSE, newer data*
<table>
<thead>
<tr>
<th>Fault Type</th>
<th>230 kV</th>
<th>345 kV</th>
<th>500 kV</th>
<th>765 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fault or no open</td>
<td>21.14%</td>
<td>18.01%</td>
<td>2.27%</td>
<td>11.02%</td>
</tr>
<tr>
<td>Single phase to ground</td>
<td>52.89%</td>
<td>24.57%</td>
<td>17.29%</td>
<td>38.41%</td>
</tr>
<tr>
<td>Phase to phase</td>
<td>5.36%</td>
<td>6.99%</td>
<td>0.64%</td>
<td>2.23%</td>
</tr>
<tr>
<td>Double phase to ground</td>
<td>3.61%</td>
<td>2.51%</td>
<td>0.20%</td>
<td>0.74%</td>
</tr>
<tr>
<td>Three phase</td>
<td>1.14%</td>
<td>1.27%</td>
<td>0.30%</td>
<td>0.17%</td>
</tr>
<tr>
<td>Three phase to ground</td>
<td>0.00%</td>
<td>0.97%</td>
<td>0.15%</td>
<td>1.60%</td>
</tr>
<tr>
<td>Open phase</td>
<td>0.06%</td>
<td>0.30%</td>
<td>0.00%</td>
<td>0.06%</td>
</tr>
<tr>
<td>Unknown</td>
<td>15.18%</td>
<td>45.09%</td>
<td>1.93%</td>
<td>5.02%</td>
</tr>
<tr>
<td>Not classified</td>
<td>0.60%</td>
<td>0.30%</td>
<td>77.22%</td>
<td>40.75%</td>
</tr>
<tr>
<td>Total number of faults</td>
<td>1'660</td>
<td>2'992</td>
<td>2'024</td>
<td>1'752</td>
</tr>
<tr>
<td>Circuit Exposure, Mile-Years (km-Years)</td>
<td>232'454 (374'142)</td>
<td>232'949 (374'938)</td>
<td>78'364 (126'129)</td>
<td>39'945 (64'293)</td>
</tr>
<tr>
<td>100% of faults, per 100km and year</td>
<td>0.44</td>
<td>0.80</td>
<td>0.54</td>
<td>0.47</td>
</tr>
</tbody>
</table>

*Table 2.3: Primary Automatic and Forced Manual Outages by Fault Type, Duration Class and Voltage Level, North America, 1965-1985*
Table 2.1 shows that a single phase earth short circuit fault is clearly the most frequent fault type in the transmission grid. This kind of faults occurred with a frequency of 2.13 to 4.75 times a year per 100 km of the high voltage line length. That corresponds to 43% up to 83% of all registered faults on transmission lines in the considered statistics sources. It should be noted that the higher the rating voltage is, the higher is the percentage of one-phase faults. The reason for this lies obviously in the physical implementation of carrying towers.

Here it is important to note that the Swiss statistics from the years 1982-1983 do not exhibit double or multi-earth faults. That was the reason for interpreting terms Earth Fault and Earth Short Circuit from table 2.2 also as single phase faults. This interpretation was necessary, because the statistics from the years 1998-1999 are less detailed than those from the years 1982-1983.

During the years 1998-1999 the single-phase faults, which are of interest to us, have approximately happened two times a year at each 100 km of line.

The North American statistics [9] show the situation at four extra high voltage levels. Even there the most frequent faults concern only single phase conductors. The sustained or permanent single phase to ground fault can do up to about half of all faults. The picture is very similar to the Swiss and German sources, except that the number of line faults per 100 km is lower than in Switzerland and Germany.

The important conclusion from the study of statistical fault reports is the evidence of the majority of single phase faults on the high voltage electrical lines and not the absolute number of the faults. The absolute number depends on particular weather conditions, particularly installed equipment and other factors ([10]). Compared with it, the percentage of faults of particular types shows the importance of measures against that kind of faults in order to increase the overall system reliability. In this work possible measures against line faults on a single phase are investigated in detail.
Chapter 3

Principles of Symmetrization

This chapter considers general principles of the symmetrization. Some ideas of possible configurations for the symmetrization are introduced and explained. A convenient mathematical system of coordinates, based on the classical symmetrical decomposition, is introduced. This introduces an understanding background for simulation models and results as well as a mathematical basis for the simulator, which will be introduced in following chapters.

3.1 Possibility of Symmetrization

The general idea of symmetrization is as follows: to install special devices on both ends of the faulted transmission line section, which will provide symmetrical conditions, that is symmetrical currents and voltages, in the rest of the network. Such devices will be called symmetrization compensators or simply compensators in the following. The compensators can be both series and shunt devices, their particular structure is not specified at the beginning. The symmetrization can be achieved by different compensator configurations, which will be discussed later in this chapter.

Methods considered here presume that sound phases still operate with alternating current. The idea is to keep the modification of the system
for the symmetrization purposes as small as possible. For instance, an obvious symmetrization method would be a transformation of the faulted three-phase AC transmission line into a two-wire DC transmission system. Additional switching equipment can provide the adjustment to particular sound phases. This case is not a subject of investigation in this work. All methods discussed below work with alternating currents and voltages.

The possibility of symmetrization and one possible configuration of the symmetrization have been presented in [11]. A general configuration scheme for the symmetrical compensation is shown in figure 1.1. An additional highground or HG wire with low insulation level provides a secure path for the return zero sequence currents. The wire can be integrated into an existing tower layout and it carries the return zero sequence current, which would otherwise flow through the earth. The highground wire is needed in all cases, when zero sequence currents can flow in the system and are not blocked by other measures like transformers with delta-connected windings. A common situation in high voltage transmission systems, which is considered in this research, is that transformers are grounded at the star point of the star-connected windings and therefore are able to carry the zero sequence currents.

A simple example will visualize the possibility of symmetrization, see figure 3.1. A symmetrical network feeds a transmission line, in which phase R is disconnected. The symmetrization compensator at the input end of the line injects equal currents into all three phases in such a way that each current being opposite to the current R from the feeding network (upper part of fig. 3.1). The sum of currents from the feeding network and from the compensator drive currents into the transmission line (lower part of fig. 3.1). In this way, the current into the R phase of the damaged line, which is the sum of currents from the feeding phase and from the compensator, will become zero. This is in exact accordance to the fact that this phase is out of operation and transports no current. Currents in phases S and T of the transmission line will also change their magnitudes and phase angles as shown in the picture. To provide such compensating phase currents, a three times greater current should flow through the highground wire, giving a sum of all currents through the system of three phase conductors plus HG-wire equal to zero. As a consequence no earth current will occur in such an operation mode and the feeding system will stay in a symmetrical state.

If the transmission line has no impedance, the compensation at its output
end can be achieved by an identical compensator with only the difference that all currents change their direction to the opposite. How this compensation method works is illustrated in figure 3.3. The current, which should flow through the phase R, is bypassed through the HG-wire. The compensators feed the same currents into all three phases, their currents in phases S and T do not flow into the surrounding network, but circulate at the section of the damaged line. The highground wire carries the triple current of phase R.

The condition that the impedance of the transmission line equals zero

Figure 3.1: Vector diagram for configuration of currents

Figure 3.2: Zero sequence compensation transformer
is important in this example. Otherwise the circulating currents in the phases S and T would cause some negative sequence voltage over the line, which should be avoided. This idealization is taken into account for the sake of simplicity of the example.

![Diagram](image)

Figure 3.3: Possible compensation of a disconnected phase

The task of the compensators in the example is to control the highground current and to distribute equally the highground current between the three phases. It can be done completely by power electronics or by a mixed technology with the aid of a special transformer, as shown in figure 3.2. In the picture three single phase transformers inject the same currents into all phases. The value of the injected current is controlled by a single current source. In case of the usage of transformers with transformer ration of unity, the injected phase currents are equal to the controlled current $I_c$ of the source. The HG current is three times of the single phase current or of the current source. If no zero sequence voltage is present on the phase wires, the voltage over the current source is three times the voltage HG-wire to earth.

Figure 3.1 allows to estimate the effectiveness of the proposed compensation method. If voltages and currents at the feeding side of the network are 1 p.u., the transferred power is also 1 p.u., both at the network side and at the side of the transmission line. The currents through the sound phase conductors are $\sqrt{3}$ p.u., this fact sets a thermal limit to the proposed compensation scheme. The compensated line has transmission capacity of a factor $1/\sqrt{3}$ or approximately 58% compared with
the healthy three-phase operation. The limit is caused by the thermal limit of the phase conductors.

3.2 Existing Transformers as Zero Sequence Compensators

Being considered in symmetrical components representation, the task of the symmetrization is the elimination of the negative and zero sequence currents from the network surrounding the damaged line section. It will be discussed in detail in section 3.6. In this section it will be discussed, how existing network apparatus can be utilized for the purpose of elimination of the zero sequence currents. Namely, under certain circumstances, existing power transformers can be used as zero sequence compensators. This brings a big potential for savings in money, in equipment and in erection time.

An already installed transformer can be employed as a ZSS compensator according the scheme in figure 3.2. From that scheme it can be derived an equivalent one, with the same currents, as shown in figure 3.4(a). Three current sources are placed in circuits connected to the phase conductors. The scheme would have the same currents with only one current source too, because the loop connection of secondary windings of the transformer guarantees the same currents in all transformer legs. The next transformation step leads to the scheme from figure 3.4(b). Only one current source with three times\(^1\) the current of source from figure 3.2 is needed. The equality of currents in the transformer legs is provided by loop connection of secondary transformer windings.

The loop of secondary windings, figure 3.4(b), brings the sum of phase voltages against point \(O\) to zero. If the sum of phase voltages against earth (zero sequence voltage) is also zero, then point \(O\) has the earth potential. The star point can be grounded in this case, as shown by the dotted line in the picture.

The scheme 3.4(b) is a standard transformer with \(Y\)-\(\Delta\) windings configuration, where the HG-wire is connected over a current source to the star point of the \(Y\)-connected windings. As concerns to the purpose of zero sequence compensation, it does not matter, whether the star point

\(^1\)It is assumed here that we work in "per unit" system. We would get the same results, if the transformer ratios were unity.
O is grounded or not. In both cases, the current source at the HG-wire should be controlled in such a way that no current flows through the earth link and that zero sequence voltage on the phase wires is zero.

If an existing transformer has Y-Δ configuration or Y-Y configuration with a balancing tertiary Δ-winding, it can be used as a transformer part of ZSS compensator from scheme 3.4(b). Zero sequence voltage on the Y side(s) of the transformer can be brought to zero. The only limiting factor in this case is the maximal current. Tertiary Δ-windings are normally designed for 1/3 of the transformer nominal power. In simulations presented in subsequent chapters this was sufficient for zero sequence compensators, but the limit should be checked in every particular case.

It is less obvious, but scheme 3.2 can be also used directly at an existing transformer for the zero sequence system compensation. For this purpose a transformer should have only one Δ-winding, either secondary or tertiary, and a Y-winding on the side, where ZSS will be compensated. The Δ-connection has to be open and a current source has to be inserted in that gap. The star point of the Y-windings has to be isolated from the earth and connected to the HG-wire. Then the zero sequence current from the phase conductors into the HG-wire can be directly controlled by the current source. The voltage over the current source is three times of the HG-wire voltage over earth, in case ZSS voltage is zero at the phase conductors.
This ZSS compensator scheme has a disadvantage that not only ZSS currents are absorbed, but also some negative sequence voltage is generated by the distortion of the Δ-connection. It can be shown that the magnitude of the arising NSS voltage lies under \((\frac{2}{\sqrt{3}} \cdot U_{\text{gap}})\) for small \(U_{\text{gap}}\), where \(U_{\text{gap}} = 3U_{HG}\) is the voltage over the gap in the open Δ-connection. This NSS voltage have to be compensated at other locations. For simulated cases presented later, the generated NSS would lie in 1-4% range, and can be kept even lower by changing parameters of the HG-wire and by re-location of the earthing point of the HG-wire (see later). A possible advantage for this compensator configuration can be seen under certain circumstances in a favorable current transformation ratio between the compensated zero sequence system and the controllable current source.

### 3.3 Highground Wire

Single or double phase interruption causes non-symmetrical currents and voltages at the interruption place, Appendix A. Zero sequence system currents can normally flow in the high voltage networks. In some grid topologies the ZSS currents can be blocked by power transformers with Δ-connected windings, what is more typical for medium and low voltage networks. The ZSS current means the same currents simultaneously in all three phases. To close the current loop, according to Kirchhofs law, a triple phase current should flow into the opposite direction. In the high voltage (HV) grid in most cases the return current, or at least a portion of it, flows through the earth. Another possibility is that the zero sequence current is looped by the zero sequence currents in parallel lines in the meshed grid. A third path for the return ZSS currents is the cable shield or a neutral wire in the cable networks.

This work considers the most general case of the overhead HV lines, when the return ZSS current can flow through the earth. The return zero sequence current through the earth should be avoided. An effective mean to achieve this is the installation of an auxiliary highground wire along the concerned line section. The highground wire serves as a bypass for all possible earth currents, which arise as a consequence of the phase interruption. Zero sequence compensators direct the zero sequence current from the phases of the damaged line section into the HG-wire.

The potential of the HG-wire can be kept very close to the earth potential
and the wire can (should) be grounded at some point, figure 1.1. Because of the low insulation level the wire can easily be integrated into the existing tower layout. Examples of possible tower layouts with HG-wires are shown in figure 3.5. The isolation distance to the phase conductors should be respected, the distance to the tower armature is less critical.

The point of the earth connection of the HG-wire is not important to the symmetrization scheme, but it is important to the maximum voltage at the HG-wire and to the characteristics of the current sources, and even to the number of current sources.

If zero sequence compensators are implemented according to the scheme 3.4(b), one current source can be eliminated, if the star point $O$ of one compensator is solidly grounded. The single current source in the HG-wire should be controlled in the way to keep the star point voltage at the second compensator at zero. The second star point can also be grounded. On a real transmission line some small residual earth currents will flow in any case because of capacitive losses on the line, but it normally is not significant.
For zero sequence or universal compensators implemented on the basis of power electronics converters, the voltage at the HG-wire can be controlled directly by those converters. In that case the minimal value of the maximum voltage of the HG-wire is reached if the HG-wire is grounded in the middle.

If there is some freedom in the isolation level for the HG wire, the wire can be designed for transmission of some active power. It is needed that the existing towers allow the integration of an additional wire with some higher insulation level, both against earth and against other phase conductors. An opposite case to the HG-wire with earthing is a spare phase conductor, which is a common mechanism to guarantee the operation of the line with a single-phase fault nowadays. The spare phase conductor can simply overtake the function of the faulted phase. It is achieved by additional switching equipment. The transmission line keeps the characteristics of the healthy line, it can transmit the same power. If the high insulation level of the phase conductors can not be provided for the HG-wire, it can still be operated under some voltage and transmit some useful power, not only the return zero sequence current. Let us call this not grounded HG-wire configuration *hot highground wire*. The voltage of the hot HG wire can be controlled by power electronics converters-compensators. Compensation concepts with usage of a hot HG-wire are quite similar to the usage of an grounded HG-wire. The power, which is transmitted through the hot HG-wire, extends the operation range of the compensated line. This hot HG-wire concept is not considered further on in this work, because no realistic assumptions could be laid down about the possible isolation level for the HG wire. The concept with an grounded HG wire has a wider application range because of easier integration into existing HV towers. The following discussion considers only cases, in which the HG wire is grounded at some point and serves only for current transfer, not for power transmission.

### 3.4 Intervention Points

There is a certain freedom in the placement of the compensating devices. Compensators can be either series or shunt devices. It should be emphasized here that due to resistive losses in a real transmission system any compensation scheme has some active components. The controlled active voltage or currents sources can sometimes be installed at different
locations to achieve the same results. Most of the compensation schemes can be implemented with aid of the following main placement options:

- Complete shunt compensation by two shunt compensators, figure 3.6. The compensators compensate both the zero and negative sequence systems. They can be implemented as power electronics converters. The HG-wire current and, as a possibility, the voltage of a hot HG-wire are controlled directly by the converters. The converters can be controlled in a very flexible way, but they are expensive.

- If the zero sequence system compensation is done with aid of power transformers, section 3.2, there are several possibilities for the control of the current through the HG-wire.
  - The current can be controlled by current sources in the $\Delta$-loop of the transformer, like in figure 3.2.
  - The current can be controlled by current sources at the star point of the $Y$-connected windings, like in figure 3.4(b).
  - The current can be controlled by a current source at the earthing point of the HG-wire, figure 3.7(a). The secondary windings of the compensating transformer are drawn very schematically in the picture. The symbol of the transformer emphasizes that the secondary windings are connected in a loop.
  - If the power transformer is used for the zero sequence compensation only at one end of the line section, a shunt compensator, based on power electronics converter, at the other end
can be used for the current control for the whole HG-wire, figure 3.7(b).

Figure 3.7: Possible configurations for zero sequence compensation

The voltage profile over the HG-wire is directly dependent on the position of the current sources for the HG current control. Choosing a proper current source, the number of sources, either one or two, can be influenced, and also their power per unit.

Negative sequence compensation in this case has to be done by shunt negative sequence compensators based on power electronics converters. These converters can normally be dimensioned for
lower currents, than in a case where they compensate the zero sequence system as well. The circuit for the HG-wire control is neither needed for these converters. Under some circumstances, section 3.7, it is possible to employ the intrinsic property of the HV grid to damp the NSS for keeping the needed NSS currents low.

- Series compensators for the negative sequence system can be installed at the phase wires at any side from the shunt zero sequence compensator: at the outer loop side, i.e. at the side of the feeding network, figure 3.8(a), or at the internal loop side, i.e. at the side of the damaged line section, figure 3.8(b). Series compensators are shown as black squares in the pictures.

![Diagram](image)

Figure 3.8: Placement of series compensators

If the series compensators are placed in the internal loop, it is sufficient to have one NSS series compensator only at one end of the line. A small portion of negative sequence currents will appear at the other end of the line, caused by inductive coupling between
the wires. This small non-symmetry can mostly be tolerated.

The placement possibilities listed above and their combinations cover the full spectrum of locations for the intervention into the network for the symmetrization purposes. Shunt compensators should be dimensioned for the full network voltage. Series compensators should work at grid voltage or be decoupled from the grid voltage by series transformers. At some configurations it is possible that the task of series compensators can be fulfilled by fixed series capacitors. This possibility will be shown in the next sections. In general, there is no simple criterion to decide which configuration is cheaper or easier to install.

3.5 Extended Symmetrical Components System

An electrical three phase grid can be analyzed in various mathematical bases. The simplest basis is the natural basis which consists of physical values, as measured, without any transformation. For a three phase network with equal components in its phases this basis is not the most convenient. At a normal grid operation the voltages and currents at different phases differ from each other only in 120° phase angles. Even in such a case the natural basis demands three complex non-zero values to represent the voltages or currents. There are possibilities to employ some system properties, such as the normal configuration of generator phase voltages and the far reaching symmetry of the system impedances in order to simplify the analysis of the network by transforming the natural physical values into another mathematical basis.

3.5.1 Classical Symmetrical Transformation

The classical symmetrical components system (see also [12], [13] and [14]) is a widely used representation basis for the analysis of three phase power systems. Most of the power flow calculation results in this dissertation have been obtained with aid of this classical transformation. The classical symmetrical components representation is a linear transformation of natural physical values of the three phases into a coordinates system of three symmetrical sequences: positive, negative and zero sequence system. The transformation rules look as follows:
\[
\begin{bmatrix}
I_+ \\
I_- \\
I_0
\end{bmatrix} = S \cdot \begin{bmatrix}
I_R \\
I_S \\
I_T
\end{bmatrix} \quad \begin{bmatrix}
I_R \\
I_S \\
I_T
\end{bmatrix} = T \cdot \begin{bmatrix}
I_+ \\
I_- \\
I_0
\end{bmatrix}
\]

(3.1)

where indices "+", "-" and "0" stand for the positive, negative and zero sequence system correspondingly and indices "R", "S" and "T" denote the corresponding phases. The matrices of the classical symmetrical transformation are:

\[
S = \frac{1}{3} \begin{bmatrix}
1 & a & a^2 \\
1 & a^2 & a \\
1 & 1 & 1
\end{bmatrix} \quad T = \begin{bmatrix}
1 & 1 & 1 \\
a^2 & a & 1 \\
a & a^2 & 1
\end{bmatrix}
\]

(3.2)

where \( a = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \quad a^2 = -\frac{1}{2} - j\frac{\sqrt{3}}{2} \)

This classical symmetrical system is a convenient and widely accepted basis for analyzing the conditions at the three-phase AC system. In a first approximation this classical transformation decomposes interdependent phase systems into three independent sequence systems. During the normal, or symmetrical, grid operation it is only the positive sequence system, which is energized. That means there are (non-zero) currents and voltages only in the positive sequence system and the system analysis can be reduced only to an analysis of that sequence system.

There is a class of so called cyclic symmetrical matrices. A matrix of this class has a property, that any row of the matrix is a copy of the previous row, cyclic shifted right by one element. Any cyclic symmetrical impedance matrix \( Z_{nat} \) with elements as follows

\[
Z_{nat} = \begin{bmatrix}
\alpha & \beta & \gamma \\
\gamma & \alpha & \beta \\
\beta & \gamma & \alpha
\end{bmatrix}
\]

(3.3)

can be transformed into a diagonal form \( Z_{symm} \) by applying the classical transformation:

\[
Z_{symm} = S \cdot Z_{nat} \cdot T = \begin{bmatrix}
\lambda_+ & 0 & 0 \\
0 & \lambda_- & 0 \\
0 & 0 & \lambda_0
\end{bmatrix}
\]

(3.4)
where
\[ \lambda_+ = \alpha + \beta \cdot a^2 + \gamma \cdot a \]
\[ \lambda_- = \alpha + \beta \cdot a + \gamma \cdot a^2 \]
\[ \lambda_0 = \alpha + \beta + \gamma \] (3.5)

This is the main strength of the classical transformation. Most of the components in the high voltage grid possess impedance matrices, which in the first approximation are cyclic symmetrical. That is why most of the network components can be represented by three independent sequence systems, which is a very convenient way for the analysis purposes.

Transmission lines mostly have a non-symmetrical space arrangement with different inductive and capacitive coupling between the phase conductors and between the conductors and the earth. Long transmission lines can cause remarkable unsymmetrical conditions. An effective method to avoid these non-symmetrical impedances is transposition of the phase conductors. Transposition, or consequential exchange of space positions of the phase conductors, can force the impedance matrix for the whole transmission line to a nearly symmetrical form.

The classical symmetrical components are a convenient mathematical basis. The basis has fixed axes, independent from the particular physical impedances of the grid components. Being considered in detail, a real overhead transmission line has an impedance matrix which is not exactly cyclically symmetrical. The presentation of the matrix in the classical symmetrical components results in slightly interdependent impedances in the three sequence systems. This small interdependence is normally neglected in power flow calculations. It is essential that the mathematical basis is the same for the whole network.

**Example 1**

A system of three parallel wires is considered. The wires possess equal self-impedances \(2i \Omega\) and equal mutual impedances between each other \(1i \Omega\). The case is illustrated in figure 3.9. The application of the classical symmetrical transformation will be demonstrated here.

The initial natural impedance matrix \(Z_{nat}^{(3)}\), which is symmetrical, is transformed into impedance matrix \(Z_{symm}^{(3)}\), the imaginary factor \(i\) has been omitted:
Matrix $Z_{symm}^{(3)}$ is diagonal. It means that the impedances in the positive, negative and zero sequence systems are independent from each other. This is the well known property of the classical symmetrical transformation.

In fact, the classical transformation represents in this case an eigenvalue decomposition. The vectors, which compose the columns of the matrix $T$:

$$
v_+^{(3)} = \begin{bmatrix} 1 \\ a \\ a^2 \end{bmatrix}, \quad v_-^{(3)} = \begin{bmatrix} 1 \\ a \\ a^2 \end{bmatrix}, \quad v_0^{(3)} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}
$$

are eigenvectors of the symmetrical matrix $Z_{nat}^{(3)}$ with eigenvalues 1, 1 and 4 corresponding.

A mathematical transformation, which decomposes original interdependent impedances into several simple independent impedances facilitates the analysis of the system. It is important to emphasize that for any
3.5. EXTEDNED SYMMETRICAL COMPONENTS SYSTEM

full impedance matrix it is possible to find a mathematical transformation, which brings this particular matrix to a diagonal form. The way to do it is the eigenvalue decomposition of the original matrix. The new representation basis will be different for different initial impedance matrices. For calculation of complex networks it is important to have the same mathematical basis for the whole network. Otherwise the calculation of interfaces between the different mathematical representations will annihilate all advantages of the decomposed calculation.

The classical symmetrical transformation forces most of the impedance matrices of real three phase components to a diagonal form or to a form with prevailing diagonal elements. That is why in most cases this transformation facilitates the calculation of the three phase networks.

3.5.2 An Additional Wire

In this work there are some special cases, in which it is necessary to analyze four-conductor systems, in particular systems of three phase conductors plus a highground (HG) wire. This blows up the possibilities of the classical symmetrical transformation, because it can handle only three wires or three physical values at once. The question arises: Is it possible to integrate four-wire components into a network, in which all other components are represented in the classical decomposed way?

One solution would be to decompose the impedance matrix of the four-wire element into four independent impedances with the aid of the eigenvalue decomposition and to re-calculate the currents and voltages at the ends of the four-wire element bringing them in compliance with the classical symmetrical sequence systems. The mentioned re-calculation, or an additional transformation, is necessary, because it is normally not possible to find a decomposing mathematical basis for the four-wire element, which has three systems identical with the classical positive, negative and zero sequence systems. Example 2 illustrates this case:

Example 2

A system of four parallel wires is considered, similar to Example 1 on page 29. The wires possess equal self-impedances ($2\Omega$) and equal mutual impedances between each other ($1\Omega$). A similar case, but with only three wires is illustrated
in figure 3.9. The eigenvalue decomposition brings the initial full impedance matrix to a diagonal form (the imaginary factor $i$ is omitted):

$$Z_{\text{nat}}^{(4)} = \begin{bmatrix} 2 & 1 & 1 & 1 \\ 1 & 2 & 1 & 1 \\ 1 & 1 & 2 & 1 \\ 1 & 1 & 1 & 2 \end{bmatrix}$$

$$Z_{\text{eigen}}^{(4)} = (T_{\text{eigen}}^{(4)})^{-1} \cdot Z_{\text{nat}}^{(4)} \cdot T_{\text{eigen}}^{(4)}$$

where $T_{\text{eigen}}^{(4)}$ is the matrix composed from eigenvectors of the matrix $Z_{\text{eigen}}^{(4)}$. These basis eigenvectors look as follows:

$$v_+^{(4)} = \begin{bmatrix} 1 \\ a^2 \\ a \\ 0 \end{bmatrix}, \quad v_-^{(4)} = \begin{bmatrix} 1 \\ a \\ a^2 \\ 0 \end{bmatrix}, \quad v_{01}^{(4)} = \begin{bmatrix} 1 \\ 1 \\ -3 \end{bmatrix}, \quad v_{02}^{(4)} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

the corresponding eigenvalues are 1, 1, 1 and 5.

The transformation matrix, composed from these vectors:

$$T_{\text{eigen}}^{(4)} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ a^2 & a & 1 & 1 \\ a & a^2 & 1 & 1 \\ 0 & 0 & -3 & 1 \end{bmatrix}$$

Vectors $v_+^{(4)}$ and $v_-^{(4)}$ are identical with the classical positive and negative sequence system basis vectors. Vectors $v_{01}^{(4)}$ and $v_{02}^{(4)}$ can be seen as two special "zero sequences" (Zero 1 and Zero 2) of this decomposition, because in both of them equal currents flow through the first three wires. None of these two special systems is compatible with the classical zero sequence system. Because of this the integration of the four-wire components into a three-wire system is complicated.
Figure 3.10 illustrates the compatibility problem. It shows a four-wire component, which is connected between two three-wire components. The three-wire components are calculated in the classical symmetrical representation. The four-wire component with the symmetrical impedance structure is decomposed by the eigenvalue decomposition. By choosing proper eigenvectors, it is possible to make the positive and negative sequence systems for all components compatible, if the four-wire component has a symmetrical impedance structure like in Example 2. The dotted lines between the corresponded boxes in figure 3.10 illustrate that the systems can be directly connected. In contrast to this, it is normally not possible to find an eigenvector for the four-wire component, which would be the same as the classical zero sequence system base vector. The two independent systems "Zero 1" and "Zero 2" can not be directly connected to the classical zero sequence system of the neighbour elements, as it is emphasized by two question marks in figure 3.10. An additional transformation is needed to interconnect the zero sequence systems.

![Figure 3.10: Compatibility of the diagonal decomposition with the classical symmetrical system](image)

There is another important disadvantage, if a larger network is analyzed with aid of such decomposition: The basis vectors for the "Zero 1" and "Zero 2" systems are dependent on particular line impedances. They are different from line to line, even if the line impedances have a symmetrical structure. The diagonal decomposition of the impedance matrix for each line has its own unique basis. The combination of different bases
for every line makes the idea of the sequence splitting hardly applicable for the system analysis. The combination with three-wire components, represented in classical symmetrical components, is always tricky. Not only the two new zero sequence systems are not identical to the classical definition of the zero sequence system, but also two other basis vectors of the diagonal decomposition can differ from the classical definition of the positive and negative sequence systems if the line impedance matrix is more complex than in Example 2. Each line would have an own definition of the symmetrical sequence systems. A human overview of real physical parameters of the system would be hardly possible without a transformation to some fixed basis common for the whole system.

In order to avoid the mentioned incompatibility problems it was proposed to use a fixed mathematical four-component basis for all four-wire network elements. The basis is defined in such a way that three of its four sequence systems are identical with the classical symmetrical systems. The new system has been called extended symmetrical components system, though it not only contains symmetrical components. The new system is thought to be a convenient basis for the work with three phase wires plus an auxiliary wire.

The extended system can be understood as three classical symmetrical systems plus a system, which represents the highground wire, the high-ground system. The three classical systems, which are positive, negative and zero sequence systems, allow a comfortable way of calculating the conditions in the three-phase transmission systems. These symmetrical systems have been left untouched to preserve all analytical instruments, which are developed for the symmetrical components analysis. This is one of the main advantages the extended symmetrical components system introduces in comparison with the diagonal decomposition of the impedance matrices of the four-wire components. A detailed illustration of the advantages is presented in Example 3 below in this section.
Transformation rules of the new extended basis look as follows:

\[
\begin{bmatrix}
I_+ \\
I_-
\end{bmatrix}
= S_{ext} \cdot
\begin{bmatrix}
I_R \\
I_S \\
I_T \\
I_{HGS}
\end{bmatrix}
\]

\[
\begin{bmatrix}
I_R \\
I_S \\
I_T \\
I_{HGW}
\end{bmatrix}
= T_{ext} \cdot
\begin{bmatrix}
I_+ \\
I_- \\
I_0 \\
I_{HGS}
\end{bmatrix}
\]

(3.8)

Indexes ”+”, ”-”, ”0” and ”HGS” stay for the positive, negative, zero and HG sequence systems correspondingly. Indexes ”R”, ”S”, ”T” and ”HGW” stand for the corresponding phase- or HG- wires. A detailed view of the extended transformation matrices is as follows:

\[
S_{ext} = \frac{1}{3} \cdot
\begin{bmatrix}
1 & a & a^2 & 0 \\
1 & a^2 & a & 0 \\
1 & 1 & 1 & 0 \\
0 & 0 & 0 & 3
\end{bmatrix}
\]

(3.9)

\[
T_{ext} =
\begin{bmatrix}
1 & 1 & 1 & 0 \\
1 & a & a & 1 & 0 \\
a^2 & a & a^2 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

The left upper 3x3 sub-matrices of the extended transformation matrices \(S_{ext}\) and \(T_{ext}\) are classical matrices of symmetrical transformation \(S\) and \(T\) correspondingly. The right down 1x1 sub-matrix, the unity element, of both matrices serves to transfer the HG-values into the new extended basis and back without any changes. Both sub-matrices do not interact with each other if the main matrices are multiplied with each other, because they are placed on the main diagonals of the \(S_{ext}\) and \(T_{ext}\) matrices and the remaining elements are zero.

The auxiliary highground wire introduces the additional independent highground sequence system. The HG sequence system is directly added to the classical symmetrical sequence systems without any transformation and without any interaction with the remaining three systems as a fourth sequence system. All physical values measured at the highground
wire in the natural system preserve their values when transformed into the highground sequence system. That is why the fourth sequence system in the extended transformation is named highground sequence system. It should be distinguished between the physical values at the HG wire and the values in the HG sequence system. The first is a part of the world of natural values, which can be directly measured. The natural HG-wire currents and voltages interfere with similar natural currents and voltages in the phase wires. The second, the highground sequence system, is a part of the artificial system of coordinates. Currents and voltages in the HG sequence system interfere with currents and voltages in the positive, negative and zero sequence systems.

In the mathematical sense, for the four quantities both the natural system and the extended symmetrical components system are full linear spaces. Any four quantities have a unique representation in both systems and both systems are linear. The highground axis is the same in both spaces, whereas the three other axes are transformed according to the rules of the classical symmetrical transformation. Both systems of coordinates are orthonormal.

Such an approach allows to combine the comfort of classical symmetrical systems analysis with the convenience of direct representation of the physical values in the auxiliary highground wire. If no HG wire is present, the representation of currents and voltages is identical with the classical symmetrical representation, what facilitates the model integration into well known algorithms.

Three important observations should be emphasized in this place. First, if we consider a current, which is related to lp.u. in the zero sequence system, it corresponds to 3p.u. in the HG sequence system. This fact is easy to understand if we remember that 1p.u current in the zero sequence represents 1p.u. current in each of the three phases.
Secondly, if we consider the power balance, the 1 p.u. in any of the positive, negative or zero sequence system corresponds to 3 p.u in the HG sequence system. The explanation for this is the same as for the currents, mathematically it can be seen from the consideration of matrix $(T^*_{ext} \cdot T_{ext})$, which is important at energy calculation:

\[ S = I^*_{nat} \cdot U_{nat} = (T^*_{ext} \cdot I_{sym})^* \cdot (T_{ext} \cdot U_{sym}) = I^*_{ext} \cdot (T^*_{ext} \cdot T_{ext}) \cdot U_{sym} \]

\[ T^*_{ext} \cdot T_{ext} = \begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

\[ S = (3 \cdot U_+ \cdot I^*_+ + 3 \cdot U_- \cdot I^*_- + 3 \cdot U_0 \cdot I^*_0) + 1 \cdot U_{HGS} \cdot I^*_{HGS} \]

Thirdly, the extended symmetrical system is not based on an eigenvector decomposition of some configuration of line reactances. The extended basis does not force a full impedance matrix into a diagonal form, as it is the case with the classical symmetrical system. The term "symmetrical" has been preserved for the new four-component system only because of convenience as a reference to the initial classical three-component symmetrical system. The new system is normally not symmetrical. The following example demonstrates this:

**Example 3**

The same system of parallel wires as in Example 2 is considered. The wires possess equal self-impedances ($2i \Omega$) and equal mutual impedances between each other ($1i \Omega$). Considering the same impedance matrix $Z^{(4)}_{nat}$ as in (3.7) and applying the extended symmetrical transformation according to (3.8), we get the following impedance matrix (the imaginary factor $i$ is omitted):

\[ Z^{(4)}_{symm} = S_{ext} \cdot Z^{(4)}_{nat} \cdot T_{ext} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 4 & 1 \\ 0 & 0 & 3 & 2 \end{bmatrix} \quad (3.10) \]

The interdependence of the zero and HG sequence systems is obvious in this example. The interaction between diffe-
rent systems can even be more complicated if the component has not such a symmetrical structure like in the presented example. Then in most cases it is difficult to make simple calculations on paper, but for computer calculations it practically makes no difference, either the systems interact with each other or not. The clear and consistent mathematical basis is of big advantage if conditions at different network points are analyzed.

In contrast to the eigenvalue decomposition, the extended symmetrical components system with transformation rules according to 3.8 provides a direct compatibility with all three classical symmetrical systems. This case is shown in figure 3.11. The positive, negative and zero sequence systems of all components can be directly interconnected without any additional transformation. One important advantage of this approach is the possibility to incorporate four-wire components directly into a three-wire network. Three of four sequence systems of the four-wire component are fully compatible with the three classical symmetrical sequence systems. The additional HG-sequence system does not influence the compatibility at the phase wires or at the positive, negative and zero sequence systems. The extended transformation does not decouple the zero and HG sequence systems, but the mathematical basis is fixed or independent from the component, to which it is applied.

![Figure 3.11: Compatibility of the extended symmetrical transformation with the classical symmetrical system](image)

Figure 3.11: Compatibility of the extended symmetrical transformation with the classical symmetrical system
The extended symmetrical system, as defined above, has proved to be a useful tool for analyzing currents and voltages in the four conductor systems. The positive, negative and zero sequence systems are the same as in the classical case for three wires. All measures of the non-symmetry, expressed in terms of negative and zero sequence components, are simple to analyze in the new basis and can easily be understood by power engineers, well-acquainted with the classical symmetrical transformation. The representation basis for values at three phase conductors is common for the whole network. The integration of four-conductor components into a network, which is calculated in classical symmetrical components, is quite obvious and easy, using the proposed extended symmetrical components system.

Example 4

It is interesting to look at the impedance matrix for a real line in the introduced extended symmetrical basis. In order to illustrate a calculated line model has been taken, as described in section 4.1.1. The HG-wire is grounded in the middle of the line, phase conductors at sections before and after the earthing point are transposed three times to make interaction between phase conductors symmetrical as far as possible.

The following parameters for the line have been assumed:
Length $= 100$ km, Scaling factor $= 1$.

Matrices $M_U$ and $M_I$, as in section 4.1.1, are full for the calculated line. To win the impedance matrix, output voltages have been supposed to be zero. The impedance matrix $Z$ couples input currents with input voltages: $U = Z \cdot I$. The following impedance matrix $Z$ has been calculated in this way:

$$
Z = \begin{bmatrix}
12.2 + 41.7i & -0.0 + 0.0i & -0.0 + 0.0i & 0.0 + 0.0i \\
0.0 - 0.0i & 12.2 + 41.7i & 0.0 - 0.0i & 0.0 + 0.0i \\
0.0 - 0.0i & -0.0 + 0.0i & 27.4 + 133.8i & 2.5 + 17.2i \\
0.0 + 0.0i & 0.0 + 0.0i & 7.5 + 51.6i & 12.2 + 40.4i
\end{bmatrix}
$$

(3.11)

Rows correspond to the voltages over positive, negative, zero and HG sequence systems, columns correspond to currents.
through the same sequence systems, similar to the matrix $Z_{\text{symm}}^{(4)}$ from Example 3.

It can be seen that the structure of the elements in matrix $Z$ is essentially the same as that in the matrix $Z_{\text{symm}}^{(4)}$ from Example 3. The positive and negative sequence systems are independent in the shown precision. Their own impedances are much bigger than interaction impedances with other sequence systems. Zero and HG sequence systems strongly interact with each other.

The extended system is a fixed mathematical basis, independent from particular impedances of the network components. The purpose of the extended symmetrical components system is to establish a convenient framework for analyzing non-symmetrical currents and voltages rather than decoupling of the interfering line impedances. The situation is the same with the classical symmetrical components. The classical system is also a fixed mathematical basis. The difference is that the classical symmetrical system can bring a certain (cyclically symmetrical) class of full impedance matrices to the diagonal form or to decouple the impedances into three independent sequence systems. To a first approximation most of the network components can be represented in three independent sequence systems by applying the classical symmetrical transformation. At more precise modelling of real network components the classical symmetrical transformation gives symmetrical sequence systems, which interfere with each other as well. The extended transformation does not bring a general impedance matrix class to a diagonal form. That means that also simple configurations of four interfering impedances will not be decoupled by applying this transformation. Example 3 shows that normally some coupling between the zero and highground sequences will exist. This coupling has been considered a non-disturbing factor in contrast with advantages of the preserving the well-known definition for the positive, negative and zero sequence systems.

3.6 Methods of Local Compensation

In the example considered in section 3.1 the surrounding network does not experience any non-symmetrical conditions caused by the faulted line section. Such a type of the symmetrical compensation, in which the non-
symmetrical systems are kept localized only at the faulted line section, is called local compensation. It is the local compensation that has been shown in figure 1.1. The kind of compensators and their locations are not fixed. The compensators can be both series and shunt devices and their characteristics can be arbitrary. With such assumptions a lot of different compensation schemes can be proposed, which represent different configurations of currents and voltages at the damaged transmission section. The complement to the local compensation builds distributed compensation, which is discussed in details in section 3.7.

3.6.1 Representation in Symmetrical Sequence Systems

The compensation possibilities can be studied better, if the electrical scheme of the system is studied more detailed. Let us consider two networks, which are interconnected by a single three phase link, see figure 3.12. If one phase conductor is interrupted, as shown in the picture, non-symmetrical currents and voltages arise. A simplified scheme for the analysis of this case, represented in symmetrical systems, is introduced in figure 3.13. Both networks are represented by a substitution scheme, a kind of Thevenin substitution scheme, which contains network impedances in all symmetrical systems and a voltage source in the positive sequence system.

The fault location, the interrupted phase, is represented by the shown interconnection between three symmetrical systems. From figure 3.13 it is seen that at the fault location the positive sequence current is directed into the negative and zero sequence systems. The condition for zero current in the damaged phase $R$ is: $I_R = I_+ + I_- + I_0 = 0$.

A current only in phase $R$, represented in the symmetrical components, corresponds to equal currents in all three symmetrical systems:
where indexes \( R, S \) and \( T \) stand for the different phase conductors, and indexes \(+, -\) and 0 stand for positive, negative and zero sequence system correspondingly. That means the interruption of a single phase conductor causes currents in all three symmetrical systems, see also Appendix A.

The currents, which flow through the zero and negative sequence impedances of the corresponding networks, cause unsymmetrical voltages in those networks. It is the task of the symmetrical compensation to provide mechanisms, which will guarantee that on both network sides there are no non-symmetrical currents. The location and the type of the compensators are arbitrary, several possible configurations will be shown below.

\[
\begin{bmatrix}
I_R \\
I_S \\
I_T
\end{bmatrix} = \begin{bmatrix}
1 \\
0 \\
0
\end{bmatrix} \Leftrightarrow \begin{bmatrix}
I_+ \\
I_- \\
I_0
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 \\
1 \\
1
\end{bmatrix}
\]

Figure 3.13: One phase fault represented in symmetrical system
Figure 3.14: Compensated fault represented in symmetrical system
3.6.2 Full Shunt Compensation

Figure 3.14 illustrates one method of the symmetrical compensation. There are no restrictions on the properties of the transmission line. Compensators are shown by double concentric circles. They act as current sources with the purpose to bypass currents, which otherwise would flow through the negative and zero sequence systems of the feeding networks [11]. The corresponding zero and negative sequence systems of the feeding networks are represented in dotted lines in order to emphasize that they carry no current. Here the compensators are simply considered as current sources in the corresponding symmetrical systems without discussion of their technical implementation. An unacceptable factor which is present in this compensation scheme is the return earth current. The return earth current is three times of the zero sequence system return current.

The earth current has to be avoided because of security reasons, as it is dangerous for people and causes equipment corrosion. The elimination of the current can be achieved by creating a bypass path for it. It can be a highground wire, which is installed along the phase wires of the transmission line. The zero sequence compensators direct the return zero
sequence current into the HG-wire. Figure 3.15 schematically illustrates this situation and introduces an additional highground (HG) sequence system along with the classical symmetrical systems, see also section 3.5. The highground sequence system is a constituent part of the extended symmetrical components system, explained in section 3.5. This extension of the classical symmetrical system integrates the highground wire into the calculation framework without disturbing the classical symmetrical sequence systems. Physical quantities of the additional HG-wire are considered and calculated in normal natural representation without any transformation. In opposite to it, values for the phase wires are transformed in the classical way of symmetrical components. Such an approach allows the analysis of the non-symmetrical conditions at the network in the classical way, with a common definition of the positive, negative and zero sequence systems. This new mathematical basis is called "extended symmetrical components system" in order to emphasize the fact that it is developed as an extension of the classical symmetrical components system.

Inductive coupling between the zero and HG sequence systems in figure 3.15 is emphasized by wavy dotted arrows. This interaction between two systems is a direct consequence of the fact that the extension of the symmetrical components system has been defined as a simple addition of the HG sequence system to the set of classical symmetrical systems, not by a symmetrical decomposition of the line impedance ma-
trix. Figure 3.15 also emphasizes the fact that HG-sequence can be only used at selected components like at the faulted line in that case. The extended symmetrical components system should be applied only to the four-wire components of the network. The rest of the network, which has only three-phase components can be calculated in classical symmetrical components. The classical symmetrical components system and the extended version with the HG-sequence system (according section 3.5) are compatible with each other at three phases or at three classical sequences. The definition of the positive, negative and zero sequence systems is identical in both mathematical bases, see also figure 3.11. The positive, negative and zero sequence currents and voltages are exactly the same in both definitions, according to the classical definition. The definition is independent whether either the three- or four-wire system is considered or either the classical or extended symmetrical transformation is applied. No conversion is needed at connections between components, represented in the classical and extended symmetrical components systems. In figure 3.15 it is visible at connections between the faulted line with feeding networks. The coupling between the zero and HG sequence systems have to be taken into account at calculations. It can easily be mastered by modern computers.

The HG sequence system is special in several ways compared with the positive, negative and zero sequence systems. One of that specialities is the definition of the currents. One unit of current in the HG system corresponds to 1/3 unit of current in positive, negative or zero sequence system. Current of 1 p.u. in the zero sequence sequence being directed through the HG system gives 3 p.u. in the HG system. The origin of this difference lies in the fact that a current in one of the classical symmetrical systems is defined as current in each of three phases with special phase angle configurations, see also section 3.5.

Figure 3.15 illustrates the symmetrization idea with avoided earth currents. The return earth current is guided through the HG-wire. It is not explicitly shown that the HG-current corresponds to three times the zero sequence current, rather the bypassing of the zero sequence return current through the HG-wire is shown as a direct series connection. The idea of the method is quite straightforward: compensating the negative and zero sequence currents locally at the ends of the damaged line section and directing the possible return earth current through an auxiliary HG wire. In spite of the interference between the HG and zero sequence systems, it is possible to find such parameters for the compensators, which
force the zero and negative sequence currents in the feeding networks to zero. This compensation method indicates good characteristics and has been chosen for later detailed analysis, see Chapter 5. Compensators for the proposed method can be implemented on the basis of power electronics converters. Zero sequence system compensation can be fulfilled with aid of power transformers, see also section 3.2.

A simple estimation of the current loading of the phase conductors under this compensation method can be undertaken. If the relations between phase impedances are as in equations 3.10, the thermal limit of the transmission line will lie at about 65% of the original limit of the sound line. The current through the HG-wire will be twice the phase current. So a thicker HG-wire should be installed to avoid the limiting effect from the HG-wire. The effective line impedance, measured in the positive sequence system rises by factor 5/3. This is a self-regulating effect that in a meshed network a smaller portion of power will flow through the damaged section. Equations 3.11 give a realistic relation between phase impedances of a real line, as was shown in Example 4, section 3.5.2. The estimation shows that the proposed compensation method is extremely effective. There are two conductors of three in operation (or 67%) and the section is able to transport 65% of the original capacity. That is almost the theoretical limit.

3.6.3 Blocking One Sequence System

Another possibility to avoid the earth currents is to utilize the property of certain power transformer configurations to block zero sequence currents. For example, no zero sequence currents can flow into a transmission line, if the line is fed by the \( \Delta \)-connected side of a power transformer. The situation is the same if the line is fed by star-connected transformer windings with isolated star point. If the damaged line is connected at one or both ends to such a type of transformer, no zero sequence currents will arise in the system. Figure 3.16 illustrates this case. Transformer impedances in the symmetrical sequences are not explicitly shown, they are ascribed to the substitution network impedances, only the interrupted zero sequence system is shown in the picture. The damaged phase is disconnected from the rest of the network, no earth currents can flow from the fault place, even if there is an earth connection there. In this case no currents will flow in the zero sequence system and it is needed to compensate only the negative sequence system. The
compensators have to be of shunt type, because blocking of the negative sequence currents by some series compensators would block the positive sequence automatically as well and no energy will flow through the line. Compensators for the proposed method can be implemented on the basis of power electronics converters, as shown in [15]. An inconvenient disadvantage of this method is the zero sequence voltage at the faulted line. This voltage additionally stresses the line insulation. The method can be only applied at lines with rather big security margin at the line insulation level.

A somewhat more elaborate method, which also could be used for the symmetrization, can be realized if the line impedance can be influenced by series compensators [16]. In this method one tries to bring the situation to a case, similar to the example in section 3.1, figure 3.3. In that example no negative sequence compensation is needed, because the zero sequence impedance of the line is zero. To bring the effective zero sequence impedance of a real transmission line to zero, some additional equipment is needed. For instance, if the line impedance is purely inductive, without interaction between the symmetrical systems, then with the aid of series capacitors it is possible to bring the effective zero sequence system impedance to zero. The impedance of the series capacitors should

\[ \text{Network 1} \quad \text{Faulty Line} \quad \text{Network 2} \]

\[ + \quad \text{~} \quad \text{~} \quad \text{~} \quad \text{~} \quad - \quad \text{~} \quad \text{~} \quad \text{~} \quad 0 \]

\[ \text{Inductive Coupling} \]

\[ \text{HG} \]

*Figure 3.17: Symmetrization by line impedance compensation*
simply be opposite to the inductive impedance of the zero sequence of the line. The zero sequence impedance of conductors is considered, without the earth impedance, because the return current is bypassed over the highground wire. The distribution of currents is like in figure 3.3, only series compensators are not shown there.

With aid of series capacitors with different capacitances in each phase, it is possible to apply the described method even for cases where line impedance has some resistive component and where symmetrical systems of the line section interact with each other. This possibility is explained later in section 3.10.2. With aid of the specially adjusted series capacitors it is possible to force all faulty non-symmetrical currents only through the zero sequence system. This possibility will be confirmed later by simulation results. A consequence from this possibility is the opportunity to abandon the shunt negative sequence compensators, see figure 3.17. The adjusted series capacitors are shown in the picture as series compensators in three symmetrical systems. The capacitors produce some voltage not only in zero, but also in negative and positive sequence systems, even if no current flows through the corresponding system. This is the consequence of the interdependence between the
symmetrical sequence systems for non-symmetrical components. In this way the capacitors control the effective impedance of the two sound phases. The capacitors are adjusted in such a way that no current flows in the negative sequence system. On the scheme 3.17 all the points A, B, C and D have the same potential. No currents flow in the negative and zero sequence systems on both network sides. Physically this method means that the current, which otherwise could flow through the phase, which is now disconnected, is redirected into the HG wire. The same currents, which are extracted from the other two phases, are short-circuited within the line and circulate only in the line section. There is no need for active controlled negative sequence compensation, so simpler equipment can be used. The high current loading of the phase conductors of the line section is a drawback of this compensation scheme. The configuration has also been chosen for modelling and numerical results are presented later.

A similar blocking effect for the negative sequence system can be achieved by placing specially adjusted series capacitors outside of the zero sequence loop, as shown in figure 3.18. Like capacitors in only two phases, the voltage induced over the capacitors in each sequence system is dependent on currents in all three sequence systems. It can be shown that it is possible to find such values for the phase series capacitors that

$$U_{A'A} = U_{C'C} + U_{CE}$$  \hspace{1cm} (3.12)

where $U_{XY}$ is voltage between points X and Y in figure 3.18. In fact, condition 3.12 represents one complex number condition, whereas there are three real parameters, the capacitances of the series capacitors in the three phases. That means there is an additional degree of freedom, so an additional real condition can be implied or some real optimization condition can be tried to achieve. At this method it should be not forgotten that there will exist some zero sequence voltage at point C. The corresponding zero sequence compensator should be controlled in such a way that no zero sequence current flows into the surrounding network. The zero sequence voltage at the compensator location is a constituent part of the chosen compensation scheme.

The possibilities of avoiding the negative sequence currents by forcing all the non-symmetrical currents through the zero sequence system has been considered. A mirror symmetrical configuration can be imagined, when zero sequence currents are avoided by forcing all non-symmetrical currents through the negative sequence system. Such a possibility has
been proposed in [17], where a Steinmetz configuration is employed for the reconfiguration of the currents only between the positive and negative sequence systems, figure 3.19. The scheme can not compensate zero sequence voltage drop over the damaged line section, so some blocking measures for the zero sequence currents like Δ-connected transformer are additionally needed. The classical Steinmetz scheme only works with a constant resistive load. For variable loads and for loads with reactive character it is needed to have controllable elements like power electronic converters. The analysis of the symmetrization strategy can be based then again on the general principles, described above. The Steinmetz method implemented with aid of Static Var Compensators (SVC) is successfully used for the compensation of large single phase (railway) loads in Central Queensland, Australia, [18, 19].

\[ \begin{array}{c}
T \\
R \\
S
\end{array} \quad \begin{array}{c}
C \\
L \\
C \\
L \\
R
\end{array} \]

Figure 3.19: Steinmetz scheme

The spectrum of possible configurations for local compensation is not limited by the methods discussed above. It is important to understand that there are some degrees of freedom of currents reconfiguration between the symmetrical systems, which allow the symmetrical condition for the surrounding networks. The configurations discussed above are only several possibilities, how it can be achieved. They have been chosen as demonstrative examples because of their logical simplicity and the evidence, how the reconfiguration of currents can be implemented in hardware.

3.7 Distributed Compensation

Previous sections of this chapter have shown that in some symmetrization techniques it is easy to distinguish between compensations of the
zero and negative sequence system. Schemes like in figure 3.14 make it apparent that the compensation of the both sequence systems can be analytically split. The compensation of the negative and zero sequence systems can be done by different equipment, as it is emphasized in section 3.2 about usage of power transformers for the zero sequence compensation. A further extension of the idea would be to split the compensation of the two sequence systems not only analytically, but also geographically. The compensation of different systems can be done at different locations.

Zero sequence currents, if not specially bypassed, cause earth currents. That is the reason why no zero sequence currents are tolerated in present power systems. The zero sequence system has to be compensated at the ends of the faulted line section.

On the contrary the negative sequence system currents represent normally no danger for the transmission lines and transformers. The negative sequence system currents endanger in a first line synchronous electrical machines, both generators and motors, by causing excessive vibration and heating of the rotor, [2]. The reason for this is that the negative sequence current component rotates in the opposite direction as the rotor. The flux produced by this current as seen by the rotor has a frequency of twice synchronous speed as a result of the reverse rotation combined with the positive rotation of the machine rotor. This flux of double grid frequency causes an excessive heating of the rotor. Most of other types of the grid equipment are not sensitive to the negative sequence currents.

As to the sensitive synchronous machines, their protection against the negative sequence currents is not necessary to be complete. Even the sensitive machines have a certain inherent tolerance against the influence of the negative sequence system. According to [2], it is a general practice today that big synchronous generators and motors are designed to be able to bear permanently at least 5% of the nominal current in the negative sequence system without any overheating. This internal robustness of the system brings additional potential for savings in the compensating equipment.

If no equipment sensitive to the negative sequence currents is connected directly at a substation, it is mostly acceptable to tolerate the negative sequence voltage at that node. If a faulted line is connected to such a node, only zero sequence compensation has to be locally done there. The protection measures against the negative sequence system for the
sensitive equipment can be undertaken at other locations, closer to the sensible loads or generators. That is the background for the distributed compensation.

The name for the method arises from the fact that the compensation equipment is distributed over larger parts of the network. The equipment location is not only limited by substations directly connected to the faulted line. Non-symmetrical currents, in particular only negative sequence currents, flow over larger areas in the network, not only at the faulted line. Figure 3.20 illustrates this situation. The zero sequence system has to be directly compensated at the end of damaged line, at node 1. Compensation of the negative sequence system at node 1 is not crucially needed and can be allocated at neighbour nodes 2 to 4. The compensation equipment is distributed over four nodes. Negative sequence currents not only flow at the section of the faulted line, but also in lines going from the node 1 to other neighbour nodes.

![Figure 3.20: Distributed compensation](image)

The method of the distributed compensation has several advantages. The installed power capacity of compensators at one location can be kept lower than at local compensation, because only a part of the full symmetrization is done at one node. The zero sequence system is compensated at one node, the negative sequence system at several other nodes. The compensation current per node is lower, as if the full symmetrization is done at once.

Another very important advantage lies in the natural attenuation of the faulty negative sequence currents in a real network. Most of the network components, either lines and transformers or loads and generators, have
an inherited resistance in the negative sequence system. So the negative sequence current injected at some point diminishes or attenuates at its propagation over the network. This property of the network has two main consequences for the symmetrization. The portion of the negative sequence currents, which is shunted by internal impedance of loads relieves the loading of the negative sequence compensators. The impedance of the network limits the propagating NSS currents additionally, which leads to a re-distribution of the faulty currents between the negative and zero sequence systems. The negative sequence component becomes smaller, the zero sequence current becomes bigger. Both effects lead to smaller NSS compensators. Negative sequence compensators are probably the most expensive and complex parts in the whole symmetrization infrastructure. Savings on this part are very important. The rising zero sequence current demands a thicker HG wire and more powerful zero sequence system compensators, but it is probably remarkably cheaper.

Another advantage of the compensators being distributed over a larger network region is that the same equipment can be used for the protection of different transmission lines. For instance, the compensator at node 3 (figure 3.20) can be also used for local compensation of lines connected to itself and as a part of distributed compensation at nodes 1 and 4. In such a way different lines can be compensated in case of non-symmetrical faults. The possibility of different compensation patterns depends on particular transmission system configurations and on compensator types.

Apart from the already mentioned benefits, the negative sequence compensators at different substations can be used for a number of other tasks. The fast and flexible power electronics equipment, which is needed for symmetrical compensation, can be used for other tasks during the normal grid operation. These tasks can be reactive power or voltage control, power flow control, oscillation damping, power quality improvement and other specific tasks, which enhance the whole system security and reliability. This added value of the symmetrical compensators, along with the advantages discussed above, are important arguments for the distributed compensation though total costs of the equipment can be higher, than at local compensation.
3.8 Double Phase Faults

Till now it has only been shortly mentioned that it is also possible to compensate faults, where two phases of three are taken out of operation. The double phase faults are also possible to compensate and to utilize a smaller part of the remaining transmission capacity of the line. A possible compensation scheme is shown in figure 3.21. Appendix section A.2 explains the modelling of the double phase interruption, as it is used in the scheme.

![Figure 3.21: Symmetrization of a double phase fault](image)

The compensation principle for the double phase fault is very similar to those for a single phase fault represented in figure 3.15. The negative and
zero sequence systems are short-circuited by shunt compensators. Currents in the positive, negative and zero sequence systems at the section of the damaged line are equal between each other. This is the condition that no current flows in the phases S and T.

An equivalent scheme for calculation of currents in the networks is represented in figure 3.22. Impedances $Z_{N1}$, $Z_{N2}$ and $Z_{LINE}$ stand for the positive sequence impedances of both feeding networks and of the transmission line correspondingly. The influence of the negative, zero and highground sequence systems of the damaged line is reflected by an impedance $Z_{EQUIV}$. For the case presented in the figure 3.21, where the positive, negative and zero sequence line impedances do not interact with each other, the impedance $Z_{EQUIV}$ can be expanded as:

$$Z_{EQUIV} = Z_{Neg} + Z_{(Zero-HG)}$$

where:
- $Z_{Neg}$ is the negative sequence impedance of the damaged line
- $Z_{(Zero-HG)}$ is the total impedance of the interfering line impedances in the zero and highground sequences

If the wires of the transmission line have a configuration like in section 3.5.1, Example 3, the impedance $Z_{(Zero-HG)}$ will be half of the zero sequence impedance with no current in the HG-wire. Both impedances $Z_{LINE}$ and $Z_{EQUIV}$ rise as the length of the transmission line is increasing.

All shunt compensators have to conduct the same current as in the positive sequence system. The negative and zero sequence currents at the line section are essential and none of them can be blocked, as it has been the case with a single phase fault, section 3.6.3. The compensation by the proposed shunt compensators can be fulfilled both by local compensation scheme or by distributed compensation. As for a single phase fault, the zero sequence compensation has to be done at the ends of the faulted line section. The negative sequence compensation can be fulfilled under circumstances at other network nodes.

As for the transmission capacity of the damaged section, it can be estimated as follows. The equal currents in the positive, negative and zero sequence systems force the current in phase R to be three times of the positive sequence current, see transformation rules, equations 3.9. Compared to the normal healthy operation, in which the current through the
phase R is equal to the positive sequence current, it means a three times smaller transmission capacity of the damaged line or 33% of the original transmission capacity. In this case it also is the thermal limit of the line.

Like for the single phase fault compensation, for the compensation of the double phase fault it is possible to apply the distributed compensation topology. In contrast to the single phase case, the increasing negative sequence system impedance will not cause a re-distribution of the currents between the zero and negative sequence systems at the line section. A certain portion of the negative sequence system can still be short-circuited by existing grid components. The increasing effective impedance of the compensated line section has a positive effect on the power flow distribution. The resulting smaller power flow through the damaged line section helps to keep the maximal current through the only sound phase within the thermal limit.

### 3.9 Sensitivity to Compensation

Several compensation methods discussed in this chapter give no general answer, where the compensators should be placed and what type of compensator will be most effective. As help in these questions the analysis of the network sensitivity to the specific control interventions can be supplied. The dependency of the non-symmetrical currents and/or voltages from controlled parameters of the compensator can be studied in advance and give important indicators for the proper type of compensator.

Particular values of interest are different, dependent on the specific compensator type. For instance, for the compensation scheme from figure 3.14 it is valuable to know the following quantities for nodes, where the compensation can be applied:

$$\frac{\partial U_{neg}}{\partial I_{neg}} \quad \text{and} \quad \frac{\partial U_{zero}}{\partial I_{zero}}$$

The quantities show the dependency of the negative or zero sequence voltage at a node from the negative and zero sequence current correspondingly injected into that node. The bigger the partial derivatives are the bigger the influence by a shunt compensator at that node.

For series compensation by controlled series capacitors as in the case
from scheme 3.17, related quantities of interest are:

$$\frac{\partial I_{neg}}{\partial X_{C1}} \quad \text{and} \quad \frac{\partial I_{zero}}{\partial X_{C1}}$$

where $X_{C1}$ is capacitive impedance inserted into one phase. The quantities show how the negative and zero currents react on changes in capacitive impedance in a single phase. It makes more sense to use the series capacitors only at lines, where significant influence on the non-symmetrical currents is expected. The capacitance of the capacitors can be reasonably kept small in such cases.

The sensitivity analysis provides important indicators for studies, what type of compensator will be technically reasonable at any particular line. Dependent on particular available technologies, the specific sensibility values are different. The two cases shown above are only two possible sets of quantities for the chosen compensation methods. Every method can demand its own set of sensitivity values. Numerical algorithms for calculations of the sensitivities, as they are implemented in the simulator, are described in details in section 4.2.

The sensitivity analysis can find another application in the control of the compensators. It is not always possible to win a control parameter directly from the available measurements. The knowledge of the dependency of a measured quantity from controlled parameter can in this case substitute the direct measurement of the controlled quantity. For example, if the shunt zero sequence system compensators inject a controllable zero sequence current, the set point for the current can be derived from the zero sequence voltage on the network by knowing the sensitivity of the zero sequence voltage to the corresponding currents.

### 3.10 Control Algorithms

Previous sections have introduced several possible schemes for the symmetrical compensation. Theoretically it is easy to find compensation currents in order to achieve an optimal compensation. In practical application it is necessary to define the settings for the compensators on the basis of real time field measurements. The number of measurements should be limited. It is practically impossible to provide the same information to the compensator controllers, which we have in solving the complete network power flow. The concrete measurement topology de-
3.10 CONTROL ALGORITHMS

depends on a particular compensation scheme. In this section a possibility will be shown saying that the set points for the compensators can be derived by relatively easy methods.

3.10.1 Full Shunt Compensation

Let us consider the full shunt compensation as in section 3.6.2, figure 3.15. A possible compensation structure is shown in figure 3.23. The compensation equipment is placed at substations A and B, the line between the substation is the subject of the compensation. Zero sequence compensation is done with aid of two zero sequence transformers. The HG wire is grounded at substation A, at point 1. The compensation current in the zero sequence is regulated by a current source in the HG wire at substation B, near point 2. The source is shown as a black box in the figure. Negative sequence compensation is done by shunt power electronics converters at both substations. They are shown as black boxes with letter ”N” in the figure.

\[ I_{\text{neg set}}^{(k+1)} = I_{\text{neg set}}^{(k)} - p \cdot I_{\text{neg measured}}^{(k)}, \quad p = 1 \]
The set point for the negative sequence compensator is decremented at each measurement step \((k)\) by the actual value of measured current. As a positive direction of currents it is supposed here that the compensator injects positive currents into the phase wires and the measured current is positive, if it flows from the compensated section into the surrounding network. The algorithm is the same for compensators at both substations.

Coefficient \(p\) in (3.13) indicates that the reaction speed of the controller can be adjusted according to specific needs. For a case, where the controlled quantity cannot be directly derived from the measurements, \(I_{\text{neg measured}}\) can be substituted by some other dependent quantity, which can be measured. In this case the parameter \(p\) should be replaced by the sensitivity of the controlled quantity from the measured one. For the case of \(I_{\text{neg}}\) as in (3.13) and for an arbitrary quantity \(x\), which can be measured and which is dependent from \(I_{\text{neg}}\):

\[
p = \frac{\partial I_{\text{neg}}}{\partial x}
\]

In real situations the sensitivity of a controlled quantity can mostly be only estimated, because the state of the grid changes continuously. Control algorithms with a feedback loop can solve the task of parameter adjustment.

For the control of the zero sequence compensators at the scheme 3.23 several options are possible. One of them is analogous to the negative sequence system control, the incremental control of the compensator current source on the base of the measured zero sequence current flowing into the feeding network:

\[
I_{\text{HG set}}^{(k+1)} = I_{\text{HG set}}^{(k)} - 3 \cdot p \cdot I_{\text{zero measured}}^{(k)}
\]  
(3.14)

The current source controls current in the HG wire, the black box with letter "Z" in figure 3.23. The positive direction of compensator current is from the HG wire into the star point of the zero sequence transformer. The factor 3 in the formula comes from the fact that zero sequence current flows simultaneous in three phases and appears as three times larger current being re-directed into a single HG wire.

Another control strategy for the HG wire current source can be based on measurements at point 2, the star point of the zero sequence transformer. In case the zero sequence voltage is absent on the grid, at the
measurement points \( b \), the star point of the zero sequence transformer will be also zero. If the star point is not grounded, then the voltage of it can be taken as control signal for the HG current source. If the star point is grounded, the earthing current from the point can be taken as control signal for the HG current source. In both cases the current control should be determined to bring the star point of the zero sequence transformer, point 2 in the figure, to condition, when the point has no voltage against earth and no current into earth.

The HG wire current source can be located at substation A as well, see dotted box near point 1 in figure 3.23. The control of this zero sequence system compensator can be based on the earthing current at point 1. It should be noted, that normally it is not possible to bring both earthing currents at points 1 and 2 to zero. A small earth current will at least flow at one link if both points are grounded. The reason for this lies in capacitive currents from the damaged overhead line, which is under zero sequence voltage. If one star point is not grounded, it will normally be not possible to bring the voltage at the another end of the HG wire to zero.

**Numerical example**

Scheme 3.24 has been used for the illustration of the control algorithm (3.13) and (3.14). All parameters of the scheme are directly denoted in the scheme.

Table 3.1 shows the numerical results. The table contains values of currents in the surrounding network and the corresponding compensator currents. The values are presented in per unit system with \( U_{\text{base}} = 220kV \) and \( P_{\text{base}} = 100MW \). The first column shows the step number in the algorithm (3.13) and (3.14). Parameter \( p \) of the algorithm is set to one.

The results show that already at the third step the compensators compensate approximately 99% of the initial nonsymmetrical currents in the surrounding network.

The graphical representations of the results in figure 3.25 visualizes the convergence of the proposed algorithm.
Figure 3.24: Scheme of the numerical example

<table>
<thead>
<tr>
<th>Step</th>
<th>Network currents</th>
<th>Compensators</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSS</td>
<td>ZSS</td>
</tr>
<tr>
<td>0</td>
<td>0.296</td>
<td>0.111</td>
</tr>
<tr>
<td>1</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>3</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>4</td>
<td>0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Absolute values of currents in p.u.

Table 3.1: Numeric example
Network currents

Compensator currents

Figure 3.25: Numeric example
3.10.2 Symmetrization by Line Impedance Compensation

In section 3.6.3 a compensation method by a line impedance compensation which uses series capacitors for the negative sequence system compensation was described. The zero sequence shunt compensators are identical with those in the method of the full shunt compensation. Their control algorithm is described in the previous section.

The negative sequence current in the line is forced to zero by series capacitors. Series capacitors have to manipulate the line impedance in such a way that no voltage drop happens over the section "line with series capacitors with open phase" in the negative sequence system. That means no voltage between points A and B in figure 3.17. The capacitances of the series capacitors are fixed and not necessary to be controlled. This clearly follows from the fact that the unsymmetrical voltages over the damaged line section are proportional to the current loading of the line. The configuration of currents is independent from the loading, only current magnitudes are proportional to the loading. The voltage drop over the series capacitors is also proportional to the current, whereas the relative influence in the different symmetrical sequences stays the same. The influence of the capacitive losses is normally small and can be neglected, though the capacitive loss currents are not proportional to the current through the line.

For a simple model without interaction between the zero and HG sequence systems, it can be shown that the series capacitors in phases S and T can be determined by the following formulas on the base of the line impedance in the zero sequence system \( Z_{\text{Line zero}} = R_{\text{Line zero}} + jX_{\text{Line zero}} \):

\[
X_S = -\left(\omega C_S\right)^{-1} = -X_{\text{Line zero}} - \frac{1}{\sqrt{3}} R_{\text{Line zero}} \\
X_T = -\left(\omega C_T\right)^{-1} = -X_{\text{Line zero}} + \frac{1}{\sqrt{3}} R_{\text{Line zero}} \tag{3.15}
\]

Series capacitors with these values will cause that no negative sequence current will flow in the line, if phase \( R \) is open and zero sequence currents are bypassed through the HG wire at the ends of the line section.

In a real situation with complex inductive and capacitive interactions between line conductors the value of the series capacitors has to be derived by solving a system of equations describing the phase and HG conductors together with the series capacitors. It should be sought for
capacitors, which force the negative sequence current to zero if the zero sequence currents are short-circuited at the ends of the damaged section through the highground wire. This current is a complex quantity, it can be forced to zero by adjusting two real variables, the capacitances of the series capacitors in the two sound phases. This calculation should be done only once for a particular line section.

In the simulator, which has been used in this work, the parameters of the series capacitors are determined every time by implying a condition that no negative sequence system current should flow through the compensated line section. This is easy to do in a simulator, which solves the whole power flow in the system. It brings flexibility as the system structure is concerned: the parameters of the protected section can be changed, the simulator will find the needed capacitances in any case. If the line section stays the same, the needed capacitors are fixed and not dependent on the actual power flow.

3.11 Test Networks

The discussed symmetrization principles and ideas provide the necessary background for the understanding of the simulation approach. The ideas of the symmetrical compensation have been simulated on two network models. Two well known test networks have been chosen for the illustration of the compensation techniques: IEEE power systems test cases with 14 and 30 buses\(^2\), figures 3.26 and 3.27.

The networks are recognized to be representative examples for the meshed grid. Results, which have been got for these networks, give a good idea of a scope of resources and about benefits, which can be expected from the application of the symmetrization technology.

The results of modelling of the methods of the local and distributed compensation are presented in chapters 5 and 6 correspondingly. Models and assumptions, which have been used at the modelling are described in chapter 4.

Figure 3.26: IEEE power systems test case with 14 buses
Figure 3.27: IEEE power systems test case with 30 buses
The investigation of impact of different symmetrization techniques has been done with aid of an appropriate simulation software. This tool, later called a simulator, has been programmed in Matlab® and successfully employed for experiments described later.

The idea of the simulator is to enable calculation of the state of a meshed power grid. State calculation is understood as calculation of currents in all branches and voltages at all nodes in the network. These calculations are supposed to be able to cope with non-symmetrical conditions as well. A detailed calculation of conditions at all phases is fulfilled. For the calculation of the non-symmetrical conditions an approach of symmetrical decomposition has been chosen, instead of direct calculation of phase voltages and currents. The main consideration behind this decision is to have a clearer picture of the extent of deviation from the symmetrical state of operation. Simulation speed or lower computer resources, which often were the reason for using the symmetrical systems decomposition earlier, were not considered as a reason. Both representations of the grid, in natural physical values or transformed into the symmetrical systems, are equivalent as concerning the computing resources. In both representations the phases or systems are generally considered as interdependent, so no calculation simplifications can be achieved by applying the symmetrical systems transformation. Furthermore, most ideas of the compensation become obvious, considered in symmetrical systems
(chapter 3), so the modelling in symmetrical components representation also seems to be more natural in this case.

The simulator can cope with new types of equipment. It is possible to integrate symmetrization compensators and other special components, mentioned later into the simulated network in an easy way. Such special equipment types have been introduced to represent different special compensation schemes.

A multiple system power flow calculation program has been taken as a solution for the tasks mentioned above. The *multiple system* will be understood in the following as an *extended symmetrical components system*, three classical (positive, negative and zero) symmetrical systems plus a HG-system, as explained in section 3.5. Power flows in the system give a clear picture of the loading of different components and about the transmitted power. The extended symmetrical components system provides both a clear representation of the non-symmetry at three phase conductors and direct representation of physical values at the additional highground wire. Being considered as a part of the four-dimensional transformation basis, the HG-system is an independent axis, orthogonal to the axes of three classical systems.

According to the classical ideas of symmetrical decomposition, the positive, negative and zero symmetrical systems of the extended symmetrical system are independent from each other for symmetrically designed components. Also like in classical symmetrical components, only the positive sequence system is activated for energy transport, if all three phases are identical and the voltage sources on three phases differ from each other only by the phase angle of 120°. All advantages of the classical symmetrical components analysis stay valid, if state of the three phase conductors is considered.

The zero and highground systems of a transmission line with a HG-wire are substantially interdependent, see also examples in section 3.5.1. This interdependence is carefully taken into account by calculating line properties on the basis of space pattern and conductor properties of a realistic transmission line, section 4.1.1.

It should be specially emphasized that the zero sequence system of transmission lines cannot be simulated accurately without field measurements, if earth currents are involved. The reason for this lies in the theoretical impossibility of the exact prediction of the earth currents. The propagation of the earth currents is complex in meshed networks. Field
measurements are needed to make simulation models compatible with reality. The simulator used in this work works only with simple assumptions about the earth impedance and does not consider possible complex current flow topologies in the meshed networks.

The modelling of the earth currents plays no role for simulation of normal symmetrical network operation. It is also not important for simulation of the compensated cases, when the zero sequence system currents are bypassed through the high ground wire. In these cases only small residual capacitive currents flow through the earth. On the contrary, the modelling of the earth currents is important for simulating single- or double-phase faults without zero sequence compensation. These cases cannot be simulated precisely by the simulator. The simulation of such cases should be later understood as only indicative, giving some idea about approximate magnitude of currents. This theoretical weakness of the simulator is not important, because it is assumed that operation conditions with remarkable earth currents are not allowed in real high voltage grids.

The multiple system ability of the simulator demanded the development of multiple system models for all components. That concerns standard equipment like lines, transformers and generators, as well as specific compensation equipment. All models used are described below in this chapter. The support of the multiple system simulation extends the single system simulation ability, but does not disturb it. That means, that single system calculations can be fulfilled on the simulator easily as well.

One of the major emphasis during the simulator development has been put on its flexibility. As basic format for specification of the network configuration the IEEE Common Data Format\(^1\) has been chosen. This format has been extended to allow the specification of multiple system components and components for or between single symmetrical systems. Further details about the data format are not essential for the research work, so they are not presented here.

\(^1\)See also http://www.ee.washington.edu/research/pstca/
4.1 Modelling Assumptions

As it was mentioned above, most of components or models can be used in a single system (positive, negative, zero or HG sequence system) arrangement, in a classical three phases arrangement (all three classical symmetrical systems involved) or in a four-wire arrangement (three classical symmetrical systems plus a highground wire involved). As a consequence, the actual component model used in the simulation varies dependent on the specific circuit configuration. All models are described below.

To provide a kind of high-level component hierarchy, it will be distinguished between one-sided and two-sided components, based on the representation of components in a single-line diagram. For instance, generators and loads have only one connection point on the single-line diagram, so they belong to the one-sided component class. In opposite, transmission lines and switches have two connection points on a single-line diagram, so they belong to the two-sided component class. The classification is useful to distinguish which part, bus or branch, of the network list the component can be assigned to. One- or two-sided components have not necessarily only one or two ports, according to ports specification in [20]. Both one- and two-sided components can have a multiple of one or two ports, if they are defined as three- or four-wire elements.

The simulation program is built in such a way, that most of components should be described in terms of $M_I$ and $M_U$ matrices [20]:

$$M_U \cdot U + M_I \cdot I = b$$

(4.1)

where $U$ is voltage vector at a node and $I$ is current vector, which flows into the same node. It is a classical component description, which allows easy handling of component models in a frame of system modelling.

If a component, i.e. generator, can not be described linearly with aid of the $M$-matrices, it is described by special equations. These equations are needed to be re-calculated at every step of solution iterations in Newton-Raphsons method.

Three complex components: four-wire transmission line, transformer and composite series-shunt compensator - will be discussed in detail below in this section. There are some specialities in modelling these components, which cannot be found in the classical literature. All other components seem to be simple and their description is placed
General denotations and assumptions which will be used in the further models description and in Appendix B:

Vector $b$ at the right side of (4.1) is zero vector for passive components. If vector $b$ will not be explicitly specified, it means, that it is zero vector.

Calculations are conducted in real numeric, all complex values are represented by two real numbers.

Index "r" stands for the real part of a complex number;

Index "im" stands for the imaginary part of a complex number;

4.1.1 Calculated Transmission Line

The calculated model of the transmission line has been developed to enable a more precise modelling of a transmission line, including earth currents and inductive interference with the highground wire. All electrical properties of the line are derived from assumptions for the wire material properties and for the space arrangement of the conductors. The calculation way multi-conductor arrangements is well documented in literature, i.e. in [14].

In the line model a predefined space layout of the HV tower is used as basis for the calculation of the transmission line properties. The conductor space positions ($x$, $y$) in meters are as follows: (6.5, 25), (11.5, 25), (16.6, 25) for the phase wires and (0, 25) for the highground wire. This pattern is taken from [14], picture 9.3, 220 kV circuit. The layout can be proportionally scaled to represent different tower sizes. The calculated transmission line can only be used as a four-system component. The modelling of the normal three-phase transmission lines is covered by classical Π-model, see Appendix B.

For phase conductors the wire type 240/40 Al/St has been chosen, as it is typical for 220kV lines [21]. For the HG-wire has been chosen a lighter wire 150/25 Al/St. Physical parameters of these wire types are as follows:

240/40 Al/St: $r = 10.85 \, mm$, $\rho = 0.121 \, \Omega/km$;
150/25 Al/St: $r = 8.65 \, mm$, $\rho = 0.194 \, \Omega/km$.

For the calculation of earth currents parameter $d$ (depth of the earth current, [14]) is taken to be equal $2500 \, m$.

The HG-wire is supposed to be grounded at the middle of the line. The phase wires are supposed to be fully transposed, that is three times before the grounding and three times after the grounding, figure 4.1.

The line parameters are calculated for the working frequency of $50\,Hz$ and are normalized to the specified per-unit base voltage (default: $220 \, kV$) and per-unit base power (default: $100\,MVA$). The calculated matrices $M_U$ and $M_I$ for the representation (4.1) are full and reflect all interactions between the conductors. See impedance matrix (3.11) to get an idea of
number values for the calculated line with scaling factor of unity and length of 100km.

4.1.2 Transformers

A single-system transformer is modelled in the classical way [20], figure 4.2:

\[
\begin{align*}
M_U &= - \begin{bmatrix}
\frac{1}{|t|^2} t^*(R+jX) & j \frac{B}{2} \\
-\frac{1}{i(R+jX)} & \frac{1}{R+jX} + j \frac{B}{2}
\end{bmatrix} \\
M_I &= - \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\end{align*}
\]

Parameters \( t, R, X, G, B \) are given in standard IEEE network list.

In a multiple-sequence model the positive sequence system of a transformer is modelled in the same way, according to equations (4.2).

The negative sequence system is modelled similarly to the positive sequence system. The only difference is the different transformer ratio, which is complex conjugate of the positive sequence one: \( t_{Neg} = t_{Pos}^* \). This follows from the cyclic symmetrical structure of the transformer and from the essentially real coefficients in the voltage transformation matrix. In this case the eigenvalues of the positive and negative sequences will be mutually complex conjugate.

The modeling of the zero sequence is more complicated and knowledge of the transformer internal interconnection structure is needed. The derivation of transformer models below is based on models from [13]. For a three-windings transformer, as the most general case, we use a star-model (figure 4.3):
A tertiary winding is optional, that is why the corresponding impedance is shown in a different way from other impedances in the picture. The shown scheme is only used for the determination of transformer parameters, the actual interconnection of the impedances depends on the winding interconnection, as will be shown below.

The transformer ratio in this model is supposed to be equal to the absolute value of the positive sequence transformer ratio: \( t_0 = |t_{pos}| \). This assumption, which is valid in most cases, has been made by consideration of two facts. At first, the zero sequence transformer ratio is a real number, if we speak about a cyclic symmetrical built transformer. Secondly, for transformers in practical use the zero system transformer ration is non-negative.

Impedances \( Z_{op}, Z_{os} \) and \( Z_{ot} \) are determined on the basis of short circuit measurements on the transformer [13]:

\[
Z_{op} = \frac{1}{2} (Z_{ops} + Z_{opt} - Z_{ost}) \\
Z_{os} = \frac{1}{2} (Z_{ops} - Z_{opt} + Z_{ost}) \\
Z_{ot} = \frac{1}{2} (-Z_{ops} + Z_{opt} + Z_{ost})
\] (4.3)

Where \( Z_{ops}, Z_{opt} \) and \( Z_{ost} \) are the zero sequence short circuit impedances, measured between corresponding transformer terminals. These impedances are usually measured in per unit and should be represented in Ohms at first. These impedances are not directly known from the IEEE network list and it is necessary to meet some realistic
assumptions. These assumptions are as follows:

\[ Z_{0ps} := z_{ps} \]
\[ Z_{0pt} := 0.9 \cdot z_{ps} \quad \text{in per unit} \] (4.4)
\[ Z_{0st} := 0.5 \cdot z_{ps} \]

Where \( z_{ps} = R_{short} + jX_{short} \) is a parameter, which is given in the IEEE network list. It is to note, that these assumptions are made for the case, where the primary winding has the higher voltage and the secondary winding has the lower voltage. The transformer is not completely symmetrical in this case.

Concerning the nominal power of the windings the following is assumed:

\[ S_{pt} = S_{st} = \frac{1}{3} S_{ps} \] (4.5)

In Ohm units it will look as follows:

\[ Z_{ps} = z_{ps} \cdot \frac{U_{ref}^2}{S_{ps}} \]
\[ Z_{pt} = z_{pt} \cdot \frac{U_{ref}^2}{S_{pt}} = 2.7 \cdot Z_{ps} \quad \text{in Ohms} \] (4.6)
\[ Z_{st} = z_{st} \cdot \frac{U_{ref}^2}{S_{st}} = 1.5 \cdot Z_{ps} \]

From equations (4.3), which are valid both in Ohms or in per unit in primary circuit units, we get:

\[ Z_{0p} = 1.1 \cdot Z_{ps} \]
\[ Z_{0s} = -0.1 \cdot Z_{ps} \] (4.7)
\[ Z_{0t} = 1.6 \cdot Z_{ps} \]

The last unknown parameter in figure 4.3 is \( Z_{0m} \). This parameter depends on the particular transformer design and we make the following assumptions:
\[ Z_{0m} = 4.5 \cdot Z_{ps} \] - for a 3-limbed transformer design;
\[ Z_{0s} = -0.1 \cdot Z_{ps} \] - for a 5-limbed transformer design or if the transformer is built from three independent single-phase units.

Then the assumptions about all zero-sequence transformer impedances are done. Now it is important to consider possible windings interconnections and their modelling. Referring to [13], a general scheme can be represented, figure 4.4.

\[ Z_{0m} \]

\[ Z_{dp} \]

\[ Z_{ds} \]

\[ Z_{dt} \]

**Primary**

**Secondary**

**Tertiary**

**Optional**

*Figure 4.4: Zero sequence of transformer*

Where (figure 4.4):

Switch \( S_1 \) is open, if the corresponding winding is star-connected without earthing.

Switch \( S_2 \) is in the upper position, if the corresponding winding is star-connected, and is in the lower position, if the winding has delta-connection.

If a star-connected winding \( x \) is not directly grounded, but through an impedance \( Z_{gx} \), then this impedance, multiplied by 3, should be added to the corresponding \( Z_{0x} \).
So far the model of the transformer zero-sequence system is complete. Now we need to integrate also a HG-wire into this model, because the zero sequence current can be directed into the HG-wire.

The HG-wire can be connected to the star point of a star-connected winding of a transformer. In this case the transformer model can be extended as in figure 4.5.

![Diagram of transformer with HG-wire](image)

*Figure 4.5: Zero & HG sequence of transformer*

\[ Z_{gx} = \infty, \] if the corresponding star-connected winding is not grounded in the star point, or in the case of the delta-connected winding. The HG currents are 3 times larger than the corresponding zero sequence currents, that is why there is the factor 3.

For the sake of simplicity, the transformer configuration shown in figure 4.6 has been chosen as standard and is assumed by default at reading from the network list.

It is supposed that star points of the main (primary or secondary) transformer windings are directly grounded unless no HG wire is connected to the corresponding winding. The tertiary winding is the compensating winding for the zero-sequence system.
4.1.3 Composite Series-Shunt Compensator

This is a component, which can simulate both negative- and zero-sequence compensation, as well as an open phase, figure 4.7.

Zero sequence compensation is equivalent to the model of the one-sided shunt compensator, section B.1.5: the same currents are taken from all three phase wires and directed into the highground wire to achieve the condition that the zero sequence voltage is zero.

Like a single-phase switch, section B.2.3, the composite compensator cannot be used as a single-system element, because a current in a single phase being transformed into symmetrical systems will cause currents in all three symmetrical systems. The HG sequence system may be present or not, it must only be present if the zero sequence compensation is activated.

Negative sequence compensation is achieved by series capacitors. $X_R$, $X_S$ and $X_T$ are supposed to be adjustable reactances, their inductive or
capacitive behavior is determined by the sign of simulation results. If the negative sequence compensation is not activated, these reactances are set to zero. The activated negative sequence compensation means a condition, when no negative sequence current flows through the phases. If one phase is open, the corresponding reactance is set to zero, otherwise the sum of all three reactances is set to zero.

Other models used in the simulator are presented in Appendix B. All these models allow quite flexible network configurations and have been successfully used for the simulations in the present work.

4.2 Study of Sensitivity to Compensation

In section 3.9 it has been discussed, that for the planning purposes it is important to know the sensitivity of the system to controlled parameters of compensators. In particular, the dependence of the negative system voltages and currents from the controlled parameters are of interest. There are two general types of the compensation equipment: the series and shunt devices. From the network topology view, the shunt devices are assigned to nodes and the series devices are assigned to branches. This difference makes the study of system sensitivity for each type specific. The simulator can supply the sensitivity quantities for both types.

4.2.1 Controlled Shunt Elements

The general idea how to find a sensitivity of a given system to a controlled parameter $\Delta p \approx 0$ is to consider a linear approximation of the whole system near the initial working point. The initial working point of the system is the state of the system with constant controlled parameter: $p = p_0 = \text{const}$. This working point is denoted further as $x_0$. A linear model of the system near the working point is then analyzed with respect to the influence of small changes of the control parameter $p$.

There is a straightforward way of analyzing such linear sensitivity, if the system is solved by the Newton-Raphson iteration method. A set of non-linear equations $f(x, p_0) = b$ is used for solving the system at the initial working point $x_0$. Vector $x$ is the vector of all system variables, like node voltages and port currents of the system. The changes of the
system variables can be analyzed, if the system equations, which contain a dependency on the controlled parameter $p$, can be represented by a linear approximation like:

$$f(x, p) \approx f(x, p_0) - h(x) \cdot \Delta p = b$$
$$f(x, p_0) \approx b + h(x) \cdot \Delta p,$$

where $\Delta p = p - p_0 \approx 0$

A finite vector $h(x)$ should exist in the initial working point of the system $(x = x_0, \ p = p_0)$. The Jacobian of the system is calculated at every step of the Newton-Raphson solution method. The Jacobian matrix of the equation set $f(x)$ is denoted as $J(x)$. Near the initial working point the following linear equations are valid:

$$J(x_0) \cdot \Delta x = h(x_0) \cdot \Delta p$$
$$\Delta x = (J(x_0))^{-1} \cdot h(x_0) \cdot \Delta p$$

The vector of the sought sensitivities can be expressed as follows:

$$\frac{\partial x}{\partial p} = (J(x_0))^{-1} \cdot h(x_0)$$

This is the main equation, which is used in the simulator for calculating the sensitivity of the system on the controlled parameters of compensators. In case of the shunt compensators, as in figure 3.14, the following variables represent the main interest:

$$\frac{\partial U_{neg}}{\partial I_{neg}} \text{ and } \frac{\partial U_{zero}}{\partial I_{zero}}$$

- the dependencies of node voltages in the negative and zero sequence systems from the corresponding node currents, which are supplied to the node by shunt symmetrization compensators. The sensitivities can be derived in a natural way from the standard power flow solution. The set of equations for the power flow calculation contains Kirchhoff’s equations for the nodes’ currents as follows:

$$\Sigma I_i = 0, \text{ for each node } i$$

For nodes in the negative and zero sequence systems it is only necessary to add the compensation currents $p_i$ to that sums, so the corresponding
member of the $h$-vector from (4.9) becomes $-1$:
\[ \sum I_i + p_i = 0 \quad \Rightarrow \quad h_i = -1 \]  

(4.12)

Equation (4.10) gives then sensitivities to the compensation currents or to the additional node currents in the negative and zero sequence systems. The nodes with the highest values of the partial derivatives (4.11) are the best candidates for the shunt compensation method, see figure 3.14. The non-symmetrical voltages at those nodes can be most effectively influenced.

### 4.2.2 Controlled Series Elements

To find the influence of the series compensators on the currents in the branch, where the compensator is inserted, it is needed to consider in detail the representation of the two-sided elements in the simulation program. The sensitivities of the currents to a parameter have to be considered in a particular operational point of the system, because the sensitivities are dependent on the concrete state of the system.

The general approach will be as follows. A passive branch is given, it can be a transmission line, a transformer or any other passive two-sided element. This branch is described by two matrices $M_U$ and $M_I$, like in equation 4.1. In series with the branch another element is connected, described by matrices $m_U$ and $m_I$. Matrices $M_U$ and $M_I$ have some parameters, which can be varied or controlled, i.e. capacitance of the serial capacitor in case of a single-phase controlled capacitor. The scheme of the serial connection is presented in figure 4.8. Terminal nodes have numbers 1 and 2, an additional intermediate node is number 3. All voltages and currents needed for the calculations are given in the picture.

![Figure 4.8: Series connection](image)

Being expressed in denotations from figure 4.8, the description of the
line and of the series compensator look as follows:

\[
\begin{vmatrix}
I_1 \\
-I_3
\end{vmatrix}
+ \begin{vmatrix}
U_1 \\
U_3
\end{vmatrix}
= 0
\]

\[
\begin{vmatrix}
I_3 \\
I_2
\end{vmatrix}
+ \begin{vmatrix}
U_3 \\
U_2
\end{vmatrix}
= 0
\]

(4.13)

The vectors of currents and voltages are explicitly described as consisting of two parts, the parts for input and output of the corresponding element. Every partial vector like \( I_x \) or \( U_x \) has as many elements as the number of inputs for the particular branch element. It can be one, three or four elements, depending on whether a single-phase, three-phase or three-wire with HG-wire element is modelled. The derivations are very general and can be applied to systems with any number of wires. Furthermore, the derived formulas can be applied in any linear system of coordinates. They can be used both in the natural coordinates with phase voltages and currents or in the classical or extended symmetrical sequence system with sequence voltages and currents.

At the next step it is needed to split \( M \)-matrices into left and right parts,

\[
m_I = \begin{bmatrix}
m_I^L & m_I^R \\
M_I^L & M_I^R
\end{bmatrix}
\]

\[
m_U = \begin{bmatrix}
m_U^L & m_U^R \\
M_U^L & M_U^R
\end{bmatrix}
\]

(4.14)

where the left part is those part, which is multiplied with the input or left-handed quantities, and the right part is that part, which is multiplied with the output or right-handed quantities.

Taking (4.14) into account, the following derivation from equations (4.13) can be done:

\[
\begin{vmatrix}
m_I^L \cdot I_1 - m_I^R \cdot I_3 + m_U^L \cdot U_1 + m_U^R \cdot U_3 \\
M_I^L \cdot I_3 + M_I^R \cdot I_2 + M_U^L \cdot U_3 + M_U^R \cdot U_2
\end{vmatrix}
= 0
\]

(4.15)

\[
\begin{vmatrix}
-I^R_I \\
m_U^R
\end{vmatrix}
\begin{bmatrix}
I_3 \\
U_3
\end{bmatrix}
+ \begin{vmatrix}
m_I^L \\
m_U^L
\end{vmatrix}
\begin{bmatrix}
I_1 \\
U_1
\end{bmatrix}
= 0
\]

(4.16)
\[
\begin{bmatrix}
I_3 \\
U_3
\end{bmatrix} = C \begin{bmatrix}
I_1 \\
U_1
\end{bmatrix}
\]

\[\text{where } C := \begin{bmatrix}
m_f^R & -m_u^R \\
m_f^I & m_u^I
\end{bmatrix}^{-1} \begin{bmatrix}
m_f^I & m_u^I \\
m_f^R & -m_u^R
\end{bmatrix} \]

Important: Matrix \( C \) is dependent only on parameters of the controlled series element.

\[
\begin{bmatrix}
M_f^I & M_u^I \\
M_f^U & M_u^U
\end{bmatrix} \begin{bmatrix}
I_1 \\
U_1
\end{bmatrix} + \begin{bmatrix}
M_f^R & M_u^R \\
M_f^I & M_u^I
\end{bmatrix} \begin{bmatrix}
I_2 \\
U_2
\end{bmatrix} = 0
\]

\[
\begin{bmatrix}
M_f^I & M_u^I \\
M_f^U & M_u^U
\end{bmatrix} \begin{bmatrix}
I_1 \\
U_1
\end{bmatrix} + \begin{bmatrix}
M_f^R & M_u^R \\
M_f^I & M_u^I
\end{bmatrix} \begin{bmatrix}
I_2 \\
U_2
\end{bmatrix} =
\]

\[
= \begin{bmatrix}
M_f^I & M_u^I \\
M_f^U & M_u^U
\end{bmatrix} (E - C) \begin{bmatrix}
I_1 \\
U_1
\end{bmatrix}
\]

\[
\text{where } E \text{ is a unity diagonal matrix.}
\]

\[
M_f \begin{bmatrix}
I_1 \\
I_2
\end{bmatrix} + M_u \begin{bmatrix}
U_1 \\
U_2
\end{bmatrix} = d
\]

\[\text{where } d := \begin{bmatrix}
M_f^I & M_u^I \\
M_f^U & M_u^U
\end{bmatrix} (E - C) \begin{bmatrix}
I_1 \\
U_1
\end{bmatrix} \]

If the right part of equation (4.18) is zero, it is identical to the equation of the transmission line connected between nodes 1 and 2. It can easily be checked that for a series passing-through element, which simply connects every input with the corresponding output, matrix \( C \) is unity matrix and vector \( d \) is zero vector. A series passing-through element does not change the electrical properties of the branch, which it is connected to.

For a series element with controlled scalar parameter \( p \), vector \( d \) can have a form, which is linear dependent from the controlled parameter \( x \), in the vicinity of the working point \( p_0 \):

\[d = b \cdot p, \quad p \approx p_0 \] (4.19)

if the linear controlled element has the property of a passing-through element at \( p = 0 \).

If the controlled series element allows the representation (4.19), the procedure of deriving the sensitivities of currents from the controlled parameter \( p \) is straightforward, if the whole network power flow solution
is sought by the Newton iteration method. Let us denote the Jacobian matrix of the original system without the controlled element as $J$. The original system solution for the system without the controlled series element is point $x_0$, where vector $x$ composes all sought system variables.

To simplify the explanation, let us suppose, that the equations of the considered line are placed at the first positions of the system equations. The linear approximation of the considered line lies in the first rows of the Jacobian $J$. Similar to (4.9), a small variation of the system solution $\Delta x$ near the point $x_0$, caused by small values of parameter $p$, $\Delta p = p - p_0 \approx 0$, fulfills the following linear approximation:

$$J(x_0) \cdot \Delta x = \begin{bmatrix} b(x_0) \\ 0 \\ \vdots \\ 0 \end{bmatrix} \cdot \Delta p$$

(4.20)

$$\Delta x = (J(x_0))^{-1} \begin{bmatrix} b(x_0) \\ 0 \\ \vdots \\ 0 \end{bmatrix} \cdot \Delta p$$

both the Jacobian $J$ and the vector $b$ are calculated at $x = x_0$.

Equation (4.20) gives the key to the sought sensitivities of the system variables to small variations of the controlled parameter $p$:

$$\begin{bmatrix} \frac{\partial x_1}{\partial p} \\ \vdots \\ \frac{\partial x_N}{\partial p} \end{bmatrix} \bigg|_{x=x_0} = (J(x_0))^{-1} \begin{bmatrix} b(x_0) \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

(4.21)

Vector $b$ should be calculated for the particular working point of the system. To illustrate how to determine this vector for a particular series device, let us consider an example of a controlled single-phase capacitor.

**Example**

Let us consider a controlled single-phase capacitor with reactive impedance $z = jX_{C1} = jp$ in phase $R$, figure 4.9. It is a three-phase
element, but with impedance only in the single phase. If the controlled parameter $p$ is zero, the element represents a passing-through element, vector $d$ in equation (4.18) is zero vector. $m$-matrices of the single-phase capacitor are linear dependent from the parameter $p$, see (4.22), that is why the theory discussed above can be applied.

\begin{equation}
\begin{bmatrix}
I_{R1} \\
I_{S1} \\
I_{T1}
\end{bmatrix} +
\begin{bmatrix}
I_{R2} \\
I_{S2} \\
I_{T2}
\end{bmatrix} =
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\end{equation}

\begin{equation}
\begin{bmatrix}
U_{R1} \\
U_{S1} \\
U_{T1}
\end{bmatrix} -
\begin{bmatrix}
U_{R2} \\
U_{S2} \\
U_{T2}
\end{bmatrix} =
\begin{bmatrix}
jp \\ 0 \\
0
\end{bmatrix}
\end{equation}

These equations can be presented by following $m$-matrices, according to representation (4.1):

\begin{equation}
m_I =
\begin{bmatrix}
1 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 0 & 1 \\
0 & 0 & 0 & jp & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\end{equation}

\begin{equation}
m_U =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & -1 & 0 & 0 \\
0 & 1 & 0 & 0 & -1 & 0 \\
0 & 0 & 1 & 0 & 0 & -1
\end{bmatrix}
\end{equation}
Vector $b$, according to (4.1), is zero vector. Matrix $C$, according to (4.17) looks like:

$$
C = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
-jp & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

(4.24)

According to 4.18, vector $d$ looks like:

$$
d = \begin{bmatrix}
I_{R1} \\
I_{S1} \\
I_{T1} \\
U_{R1} \\
U_{S1} \\
U_{T1}
\end{bmatrix} (E - C) = \begin{bmatrix}
M_f^L \\
M_f^L \\
M_f^L \\
M_f^L \\
M_f^L \\
M_f^L
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
$$

(4.25)

Vector $b$, according to 4.19, looks like:

$$
d = b \cdot p \quad \Rightarrow \quad b = \begin{bmatrix}
M_f^L \\
M_f^L \\
M_f^L \\
M_f^L \\
M_f^L \\
M_f^L \\
M_f^L
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
$$

(4.26)

The vector $b$ can be calculated in this way at any working point of the system and with any branch, described by $M$-matrices. With aid of equation 4.21 it is now possible to calculate the sensitivities of the negative and zero sequence currents in the branch from the series capacitive reactance in one phase ($p = X_{C1}$):

$$\frac{\partial I_{neg}}{\partial X_{C1}} \quad \text{and} \quad \frac{\partial I_{zero}}{\partial X_{C1}}$$

(4.27)

The described methods for the analysis of the sensitivities of the system to specific control parameters can be used as background principle for the determination of sensitivities in other compensation schemes and of other controlled parameters.
Chapter 5

Local Symmetrical Compensation

With term *local compensation* we will understand entire symmetrization methods and techniques, where unsymmetrical conditions are isolated by the region of the faulted transmission line. The surrounding network does not experience any non-symmetrical voltages or currents, at least not those, of which the reason lies in the compensated faulted transmission line. This symmetrization case is illustrated by figure 5.1. Line between substations 1 and 2 is damaged, but is compensated in such a way, that no neighbour substation or line experiences non-symmetrical influence from it.

![Figure 5.1: Local symmetrical compensation](image)

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In general the compensated line changes its impedance, so the surrounding network is still influenced by the changes on the line. The power flow through the damaged line is also different, compared with normal, or healthy, conditions. The line transmission capacity, or its thermal limit, changes remarkably, because only two of three phase conductors participate in the power transport. The extent of the system changes will be shown further in this chapter.

Although line and system parameters change during the active compensation mode, it is still important, that the system can operate, there are no hazards for the equipment from non-symmetrical voltages. The grid has to cope with the stress of the changed line impedance and of restrictive load ability of the damaged line. As a prize for this the transfer capacity of the damaged line can be used. The system indicates robustness and reliability.

Local compensation is the most obvious idea of compensation. The extent of non-symmetrical influence is kept as small as possible. An earlier analysis of one compensation possibility has been represented in [11] in an easily understandable way.

5.1 Modelling Configurations and Result Tables

For the illustration of different compensation techniques, two meshed topologies have been taken: IEEE power systems test cases with 14 and 30 buses (figures 3.26 and 3.27). The networks will be later referred to as IEEE14 and IEEE30 network correspondingly. At IEEE14 network the line between nodes 4 and 5 has been arbitrarily chosen as the faulted line. At IEEE30 the same function has been granted to the line between nodes 6 and 28.

To incorporate the highground wire into the test networks, the lines with an installed HG-wire have been modelled by a more advanced model described in section 4.1.1. The model is based on a certain assumption about physical dimensions and properties of the towers and conductors. It calculates in a detailed way the inductive interference between all four wires. The calculated line model takes into account distributed mutual inductances and the capacity of the conductors. That is why it is impossible to get exactly the same line parameters as in the original IEEE
network lists, which suppose the modelling of the line by concentrated elements, like in section B.2.1. By adjusting the scaling factor, the line length and the base voltage, one has managed to get line quantities, which are very close to those from the network list. These parameters are as follows:

- Test case IEEE14, line 4-5: Scale = 1, Length = 48 km, $U_{\text{base}} = 220 \text{ kV}$
- Test case IEEE30, line 6-28: Scale = 1, Length = 25 km, $U_{\text{base}} = 132 \text{ kV}$

For the simulation of different cases all network parameters are kept constant. Only compensator configurations and parameters are different, the considered transmission line has only two phases of three in operation during the faulty operation. The active power balance of the network is provided by a slack generator at node 1, in both test networks. In such a framework the influence of the compensated two-phase line operation has been studied.

Simulation results for the local compensation methods are presented in tables 5.1 and 5.2. The tables give a picture of the extent of advantages of different methods. The quantities used in the tables are explained here:

1. Transferred power shows, how much energy is transported through the line in the positive sequence system. Power is measured at the first line node, that means at node 4 in IEEE14 and at node 6 in IEEE30. As positive direction for the power flow the flow from the node is taken into the line.

2. Currents in the different symmetrical systems of the considered transmission line. Numbers in the parentheses show corresponding values from the side of the surrounding network, outside of the compensated line.

3. $I_{\text{phase max}}$, the maximal phase current in the line, gives an idea of thermal limit of the line.

4. Quantity $I_{\text{compensator phase max}}$ shows the maximal phase current in the shunt compensator, what is essential for the dimensioning of the compensator.
5. $I_{HG}$ is the current through the highground wire.

6. Quantity $I_{\text{phase max}}/S_+$ shows the effectiveness of the line regarding its thermal limit. It shows how much the line conductors are loaded to transfer a unit of energy in the positive sequence system.

7. $Z_{+ \text{effective}}$ is the effective line impedance in the positive sequence system, as seen from the first node of the line.

8. $U_{HG}$ is voltage at HG-wire at the end of the line. The HG-wire is grounded in the middle of the line.

9. Series capacitors show reactances of the phase series capacitors for the symmetrization by line impedance compensation (section 5.3).

Column 4 of the result tables 5.1 and 5.2 represents the reference case of normal operation. Results of different compensation techniques can be compared with that data of the sound symmetrical operation to see advantages of the chosen symmetrical compensation technique.

Column 5 shows a hypothetical case of system operation with an open phase at the discussed line, but without any measures against the non-symmetrical conditions. This case should give a picture of the extent of the non-symmetrical conditions on the network in case of fault. The simulation results for this operation mode should be understood as only indicative, because earth currents cannot be modelled precisely without field measurements, as it was explained in Chapter 4. This mode of operation is normally not allowed at a high voltage grid and serves here only as another reference case.

5.2 Short Circuiting of Zero and Negative Sequence Systems

The basic idea of symmetrical compensation by short circuiting of zero and negative sequence systems has already been explained in chapter 3, figure 3.15. A new moment to that explanation is the interference between phase conductors and the highground wire, which is integrated into the model of the compensated line.

Compensators, which fulfill the symmetrization, are modelled according to section B.1.5. Compensators are shunt devices and should be
dimensioned for the whole system voltage and be able to withstand $I_{\text{compensator phase max}}$ current (quantity No.4 in the result tables) per phase. More details about a possible physical implementation of such a kind of compensators and about their electrical dimensioning can be found in [15].

Results for this section, for the method of the short circuiting of the zero and negative sequence systems, are presented in column 6 of tables 5.1 and 5.2.

The simulation results for the both networks are very close to each other, so some conclusions can be withdrawn from them. For both cases of symmetrization it can be observed, that:

- The effective line reactance increases by about 55%
- The phase conductor thermal loading, the maximum phase current $I_{\text{phase max}}$, increases by about 38%
- The power transmission effectiveness, the quantity $I_{\text{phase max}}/S_{\text{useful}}$, increases by less than 55%
- The transmitted real power sinks only by something more than 10%.

This compensation method is very effective as it concerns the phase conductor loading of the damaged line. During the fault compensation, the energy is transferred through 2 of 3 conductors and the quantity $I_{\text{phase max}}/S_{\text{useful}}$ changes by factor less than 1.55, where factor 1.5 would be an ideal case. This fact lies in the nature of the shunt compensation, because both sound conductors, which transmit energy are directly connected to the AC phase voltages of the surrounding network. No big distortion of currents can happen in this case, because voltages at the ends of line have to be symmetrical, no voltage in negative or zero sequence systems.
<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Unit</th>
<th>Normal Operation</th>
<th>Open Phase without compensation (not allowed mode)</th>
<th>Open Phase compensated by short circuiting</th>
<th>Open Phase compensated by impedance compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transferred power (useful, pos.sequence)</td>
<td>P, x10⁻² pu</td>
<td>-61.79</td>
<td>-38.50</td>
<td>-55.36</td>
<td>-72.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q, x10⁻² pu</td>
<td>12.68</td>
<td>7.72</td>
<td>11.73</td>
<td>28.98</td>
</tr>
<tr>
<td>2</td>
<td>$I_+$, $I_-$</td>
<td>pu</td>
<td>0.62</td>
<td>0.38</td>
<td>0.56 (0.55)</td>
<td>0.77 (0.77)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pu</td>
<td>0</td>
<td>0.29</td>
<td>0.31 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pu</td>
<td>0</td>
<td>0.10</td>
<td>0.25 (0)</td>
<td>0.77 (0)</td>
</tr>
<tr>
<td>3</td>
<td>$I_{\text{phase max}}$</td>
<td>pu</td>
<td>0.62</td>
<td>0.60</td>
<td>0.85</td>
<td>1.33</td>
</tr>
<tr>
<td>4</td>
<td>$I_{\text{compensator phase max}}$</td>
<td>pu</td>
<td>–</td>
<td>–</td>
<td>0.57</td>
<td>0.81²</td>
</tr>
<tr>
<td>5</td>
<td>$I_{HG}$</td>
<td>pu</td>
<td>–</td>
<td>–</td>
<td>0.76</td>
<td>2.30</td>
</tr>
<tr>
<td>6</td>
<td>$I_{\text{phase max}}/S_+$</td>
<td>pu/pu</td>
<td>0.98</td>
<td>1.54</td>
<td>1.51</td>
<td>1.71</td>
</tr>
<tr>
<td>7</td>
<td>$Z_{\text{effective}}$</td>
<td>x10⁻² pu</td>
<td>$1.07 + 4.22i$</td>
<td>$4.36 + 17.42i$</td>
<td>$1.58 + 6.56i$</td>
<td>$2.25 - 0.89i$</td>
</tr>
<tr>
<td>8</td>
<td>$U_{HG}$</td>
<td>x10⁻² pu</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.88</td>
</tr>
<tr>
<td>9</td>
<td>Series capacitors</td>
<td>x10⁻² pu</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>$X_S = 4.43$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$X_T = 5.82$</td>
</tr>
</tbody>
</table>

1 - Numbers in the parentheses show the value from the side of the surrounding network
2 - For the shunt part of the composite compensator

Table 5.1: IEEE 14 test case, fault at line 4-5, different methods of local compensation
<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Unit</th>
<th>Normal Operation</th>
<th>Open Phase without compensation (not allowed mode)</th>
<th>Open Phase compensated by short circuiting</th>
<th>Open Phase compensated by impedance compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transferred power (useful, pos. sequence)</td>
<td>P, x10^-2 pu</td>
<td>18.64</td>
<td>10.78</td>
<td>16.69</td>
<td>24.67</td>
</tr>
<tr>
<td></td>
<td>Q, x10^-2 pu</td>
<td></td>
<td>0.95</td>
<td>0.47</td>
<td>0.91</td>
<td>3.58</td>
</tr>
<tr>
<td>2</td>
<td>I_+</td>
<td>pu</td>
<td>0.18</td>
<td>0.11</td>
<td>0.16 (0.16)^1</td>
<td>0.25 (0.25)^1</td>
</tr>
<tr>
<td></td>
<td>I_-</td>
<td>pu</td>
<td>0</td>
<td>0.08</td>
<td>0.09 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>I_0</td>
<td>pu</td>
<td>0</td>
<td>0.02</td>
<td>0.07 (0)</td>
<td>0.25 (0)</td>
</tr>
<tr>
<td>3</td>
<td>I_{phase max}</td>
<td>pu</td>
<td>0.18</td>
<td>0.17</td>
<td>0.25</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>I_{compensator phase max}</td>
<td>pu</td>
<td>–</td>
<td>–</td>
<td>0.16</td>
<td>0.25^2</td>
</tr>
<tr>
<td>5</td>
<td>I_{HG}</td>
<td>pu</td>
<td>–</td>
<td>–</td>
<td>0.22</td>
<td>0.74</td>
</tr>
<tr>
<td>6</td>
<td>I_{phase max/S_+}</td>
<td>pu/pu</td>
<td>0.99</td>
<td>1.55</td>
<td>1.50</td>
<td>1.71</td>
</tr>
<tr>
<td>7</td>
<td>Z_{+ effective}</td>
<td>x10^-2 pu</td>
<td>1.94 + 5.92i</td>
<td>8.42 + 24.93i</td>
<td>2.81 + 9.17i</td>
<td>3.62 - 1.49i</td>
</tr>
<tr>
<td>8</td>
<td>U_{HG}</td>
<td>x10^-2 pu</td>
<td>–</td>
<td>–</td>
<td>0.80</td>
<td>2.66</td>
</tr>
<tr>
<td>9</td>
<td>Series capacitors</td>
<td>x10^-2 pu</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>X_S = 6.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X_T = 8.41</td>
</tr>
</tbody>
</table>

1 - Numbers in the parentheses show the value from the side of the surrounding network
2 - For the shunt part of the composite compensator

Table 5.2: IEEE 30 test case, fault at line 6-28, different methods of local compensation
5.3 Symmetrization by Line Impedance Compensation

The idea of the symmetrization by line impedance compensation is to force the zero sequence impedance of the line to zero and to bypass the zero sequence current by shunt compensators through the highground wire. This method has been explained in chapter 3, figure 3.17.

This method of symmetrization by line impedance compensation, as it is simply described in chapter 3, obviously works at purely inductive lines without any losses. It has turned out that the method works also under realistic circumstances, with lines with some reactive losses as well. In case of compensating the purely reactive lines, the simulation results in equal values for the series capacitors in both phases, what is completely according to the theory. In case of resistive line losses, the compensating capacitors are not equal anymore, see equations 3.15. This is also visible from the results presented later in this section.

From the mathematical point of view, the condition to force one complex value to zero, in this case it is the line impedance in the zero sequence system, means an additional complex equation in the set of equations describing the system. To ensure that the system of equations can be solved, it is necessary to provide an additional complex parameter, which can be adjusted at the solution search. Instead of one complex parameter we introduce two real parameters, the capacitances of series capacitors, which are inserted into two sound phases. The simulation has shown, that a solution can be found and that this type of symmetrization can be really implemented.

For this compensation a composite compensator, as in section 4.1.3, has been inserted at the first node of the line and a shunt compensator has been put at the end of the line. The shunt part of the composite compensator and the shunt compensator at line end work as zero system compensators only. Adjusting of the series part of the composite compensator guarantees, that no currents flow in the negative sequence system. Shunt compensation of the zero sequence system can be implemented by only one current source and three-limbed transformer with a delta-connection, figure 3.2.

The simulation results for both test networks are listed in tables 5.1 and 5.2 in column 7.
This compensation method also indicates similar results on the both test networks. As general characteristics of the method the following items can be derived:

- The effective line impedance remarkably changes during the compensated operation. Line impedance becomes capacitive instead of reactive.

- The phase conductor thermal loading, the maximum phase current $I_{phase \ max}$, increases by about 70%.

- The current loading of the HG-wire is about 70% over the maximal loading of phase wires.

- Shunt zero sequence compensators have to cope with the zero sequence system, which is equal to the useful positive sequence system and with a small current in the positive sequence system for covering of losses in the HG-wire.

This compensation method seems not to be very effective, though under circumstances it could be worth to implement such a compensation, for instance, if some already installed equipment can be used as a part of the compensation scheme. For example, if the line is connected to star-connected windings of a transformer, which has a delta-connected windings, this transformer can be used as zero system shunt compensator, see section 3.2. In the present modelling it was assumed, that the HG-wire is grounded at the middle of the line distance, but it can be directly grounded at one shunt compensator. In that case, only one current source is needed for the zero sequence compensation, see also section 3.10.1. The series part of the compensator does not need any control, the capacitors have the same capacitance for any line loading, see section 3.10.2.

### 5.4 Advantages of Local Compensation

In this chapter two compensation methods in the local topology have been discussed, when the non-symmetrical conditions does not propagate over the line limits. The rest of the network still operates with only positive sequence system. The presented results show, that a successful symmetrical compensation of an one-phase fault is possible by the
presented methods and that the damaged line still can be employed for power transfer. The extent, how much energy can be transmitted over the damaged section, depends on the method selected for this task. It varies between 58% and 65%, if only thermal limits of the phase conductors are considered as limiting factor.

In the following chapter the idea of symmetrization will be extended by a distributed approach, when some parts of the network can tolerate negative sequence currents.
Chapter 6

Distributed Compensation

In this chapter the compensation of a damaged transmission line by distributed compensation will be considered. As "damaged line" will again be understood a transmission line with one phase open and with only two sound phases, which stay in operation. The damaged line is supposed to be equipped with a HG-wire to bypass or to loop the arising zero sequence currents.

The main idea of distributed compensation is the space separation of the zero and negative sequence compensation (see also figure 3.20). Zero sequence currents have to be locally compensated to prevent their propagation through the earth. On the contrary, the negative sequence system can be tolerated to some extent on the high voltage grid, especially if no big synchronous machines are influenced by it.

Synchronous machines like generators should be very carefully handled, because currents in the negative sequence system cause heating, which is a hazard for the machines. The cooling system of generators can cope with small currents in the negative sequence system. Those currents are difficult to avoid in a real system, because any three-phase equipment is not completely identical in all three phases. Any non-identical equipment causes currents and voltages, which are not completely symmetrical, but contain some components in the negative and zero sequence systems as well. Of course, in normal operation the part of those non-symmetrical components is kept as low as possible. As a guideline for the generator
tolerance against the negative sequence current in the present investigation was assumed 5% of the generator nominal current [2].

## 6.1 Assumptions and Analysis Strategy

If no sensitive synchronous machines are directly connected to substations at the ends of a considered line, the idea of space separation of zero and negative sequence compensation can be implemented. For the sake of simplicity it was supposed that the only equipment type sensitive to negative sequence currents is the generator. Loads are supposed to be resistant to the negative sequence system and no special measures are needed to protect them. As it will be seen later, negative sequence voltage at line terminals will be rather low, even if the negative sequence is not directly compensated on those nodes. The reason for it lies in low impedance of lines in the negative system. No remarkable negative sequence voltage can arise at a node, if at a neighbour node that voltage is forced to zero. So the concentration on the generator protection only seems to be a quite acceptable assumption. If some nodes contain equipment sensitive to negative sequence component, the protection of this equipment can be treated similarly to generator protection. More detailed models and more detailed tolerance specifications for such equipment are needed in that case. Then analysis of the protection scheme can be also done easily. At this point it is supposed, that only protection of generator against negative sequence system should be taken into account.

With the assumptions mentioned above, the networks and the damage cases, which have been considered in chapter 5 for local compensation, fulfill all conditions for the application of the distributed compensation. So the same networks with the same damaged line will be considered in this chapter. This approach enables a direct comparison with local compensation techniques from the previous chapter. At IEEE14 (fig. 3.26) network the compensation of the line between nodes 4 and 5 has been considered. At IEEE30 network (fig. 3.27) it is the line between nodes 6 and 28. Selective parts of the considered networks are shown in figures 6.1 and 6.2.

In principle, the distributed compensation assumes local compensation of the zero sequence system at the terminals of the damaged line and compensation of the negative sequence at neighbour nodes surrounding
the damaged line terminals. The number of nodes, where the negative system compensation should be undertaken, can be reduced, if some non-critical nodes are not compensated, but a small negative sequence voltage is tolerated. Those nodes, which contain generators (or, in general, any sensible equipment), should be compensated in any case. At all other nodes it should be carefully checked, whether the remaining negative sequence voltage can be tolerated. By selective exclusion of some non-critical nodes it is possible to reduce both the total rating power of the installed equipment and the number of nodes, where the negative system compensators should be installed.

The same procedure has been chosen to investigate the test cases. The compensation of the zero sequence system has been local. The arising zero sequence currents are looped through an additional HG-wire by two shunt zero sequence compensators, which sit at both ends of the damaged line. For the compensation of the negative sequence system two cases will be considered:

Firstly, a complete surrounding negative sequence system (NSS) compensation is simulated, i.e. NSS compensators are placed at all nodes, which have a direct link to the terminal nodes of the damaged line. In particular, for the considered damage on the IEEE14 network (pic. 6.1), zero system compensators are placed at nodes 4 and 5, whereas negative sequence system compensators are located at nodes 1, 2, 3, 6, 7 and 9. This is the most secure case of the distributed compensation. The ZSS is only localized at terminal nodes of the damaged line. At all other nodes the NSS voltage is not present, it is either compensated at the node (neighbour to the terminal node of the damaged line) or it does not propagate over the border of compensators.

Secondly a more economical solution will be found. That means that as much as possible non-critical NSS compensators will by excluded from the complete topology. The NSS presence in small extent is tolerated. To find this solution, the NSS is left without any compensation. NSS voltages and currents around the damaged line are analyzed, checked, either they can be tolerated. If in some nodes the negative sequence system exceeds tolerance limits, additional compensators are added until all limits are respected. 5% of nominal current is considered in the following simulations as the tolerance limit for NSS current in generators. NSS node voltages always were in a very low range, under 1.5% even at the terminal nodes of the damaged line. Such voltages have been
supposed to be accepted and tolerated by grid equipment.

The rating power of generators of the considered IEEE test cases was unknown. 5% of a generator operating positive sequence current has been taken as a limit for the negative sequence current of this generator. The operating current is not larger than the nominal current, so the new restriction criteria is more restrictive than the initial one. NSS impedance of generators is completely neglected in the generator modelling. This makes consideration of the current limits in the NSS even more restrictive.

The economical compensation topology brings significant equipment savings compared with the complete surrounding topology, as will be shown in the result analysis.

### 6.2 IEEE14 Network

A part of the IEEE14 test case network is repeated in figure 6.1. This is the part, which is of most interest as it concerns non-symmetrical conditions caused by a single-phase fault on line 4-5.

*Figure 6.1: Part of IEEE14 network around the damaged line 4-5*
At first, the complete surrounding compensation topology has been tried out. Zero sequence compensators are located at nodes 4 and 5, negative sequence compensators are located at all nodes, neighbour to 4 and 5. Compensator currents in this compensation topology are presented in table 6.1. Two zero sequence and six negative sequence shunt compensators are involved in this scheme. The total current of NSS compensators is calculated at the bottom of the table.

<table>
<thead>
<tr>
<th>Node No.</th>
<th>$I_0$ (p.u.)</th>
<th>$U_-$ (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.4024</td>
<td>0.0071</td>
</tr>
<tr>
<td>5</td>
<td>0.4028</td>
<td>0.0088</td>
</tr>
</tbody>
</table>

Table 6.1: IEEE14: Results for complete surrounding compensation topology (damaged line 4-5)

As a next step, all negative sequence compensators are switched off and currents and voltages in the negative sequence at nodes surrounding the damaged line are analyzed. Results for this configuration are shown in table 6.2. Generators are assumed to have zero impedance in the negative system. That is why the nodes with generators indicate no NSS voltage, but some currents in the negative system. The comparison of currents in the negative and positive sequences for generators (see column $I_{Neg}/I_{Pos}$) indicate that generators at nodes 3, 6 and 8 have unacceptably high values of the NSS currents. These selected generators have to be protected by NSS compensators.

The compensation on the selected generators leads to a compensation configuration with only three NSS compensators at nodes 3, 6 and 7.
Without NSS compensation

<table>
<thead>
<tr>
<th>Node No.</th>
<th>$I_0$ (p.u.)</th>
<th>$U_-$ (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.4073</td>
<td>0.0080</td>
</tr>
<tr>
<td>5</td>
<td>0.4077</td>
<td>0.0084</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node No.</th>
<th>$U_-$ (p.u.)</th>
<th>$I_-$</th>
<th>$I_+$</th>
<th>$I_-/I_+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0036</td>
<td>0.0364</td>
<td>2.2318</td>
<td>1.63%</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.0053</td>
<td>0.5596</td>
<td>0.95%</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.0437</td>
<td>0.2256</td>
<td>19.37%</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.0243</td>
<td>0.1041</td>
<td>23.34%</td>
</tr>
<tr>
<td>7</td>
<td>0.0037</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.0036</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.0208</td>
<td>0.1592</td>
<td>13.07%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Generators</th>
<th>$I_-$</th>
<th>$I_+$</th>
<th>$I_-/I_+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0364</td>
<td>2.2318</td>
<td>1.63%</td>
</tr>
<tr>
<td>2</td>
<td>0.0053</td>
<td>0.5596</td>
<td>0.95%</td>
</tr>
<tr>
<td>3</td>
<td>0.0437</td>
<td>0.2256</td>
<td>19.37%</td>
</tr>
<tr>
<td>6</td>
<td>0.0243</td>
<td>0.1041</td>
<td>23.34%</td>
</tr>
</tbody>
</table>

Table 6.2: IEEE14: Negative sequence compensation switched off (damaged line 4-5)

Node currents and voltages with this economical compensation topology are presented in table 6.3. The relation $I_{neg}/I_{pos}$ for generators lies clearly under 5%. Such low NSS currents do not hazard generators and are also acceptable for continuous operation.

The selective compensation of the negative sequence system has brought the number of NSS compensators to 3 compared with 6 compensators in the complete compensation topology. The total current of the NSS compensators sank from 0.17p.u. to 0.12p.u.. That means considerable savings in equipment. The efforts to force the system to a symmetrical mode were devoted to get some transmission capacity from the damaged line. Electrical parameters of the compensated line in this case are presented in table 6.4, in column 5. Similar to table 5.1, the parameters of normal operation are repeated there to enable direct comparison (column 4).

The acquired data will be discussed later in section 6.4, together with the results from the IEEE30 network.
### Nodes with Zero Sequence Compensators

<table>
<thead>
<tr>
<th>Node No.</th>
<th>$I_0$ (p.u.)</th>
<th>$U_-$ (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.4028</td>
<td>0.0071</td>
</tr>
<tr>
<td>5</td>
<td>0.4031</td>
<td>0.0087</td>
</tr>
</tbody>
</table>

| Surrounding Nodes

<table>
<thead>
<tr>
<th>Node No.</th>
<th>$I_-$ (p.u.)</th>
<th>$U_-$ (p.u.)</th>
<th>$I_-$</th>
<th>$I_+$</th>
<th>$I_-/I_+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.0381</td>
<td>2.2310</td>
<td>1.71%</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0.0095</td>
<td>0.5594</td>
<td>1.70%</td>
</tr>
<tr>
<td>3</td>
<td>0.0389</td>
<td>0</td>
<td>0</td>
<td>0.2252</td>
<td>0.00%</td>
</tr>
<tr>
<td>6</td>
<td>0.0342</td>
<td>0</td>
<td>0</td>
<td>0.1042</td>
<td>0.00%</td>
</tr>
<tr>
<td>7</td>
<td>0.0438</td>
<td>0</td>
<td>0</td>
<td>0.1590</td>
<td>0.00%</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0.0010</td>
<td>0</td>
<td>0.1590</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

\[0.1169\]

**Table 6.3**: IEEE14: Selective distributed compensation (damaged line 4-5)

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Unit</th>
<th>Normal Operation</th>
<th>Compensated Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transferred power (positive sequence)</td>
<td>P, $x10^{-2}$ pu</td>
<td>-61.79</td>
<td>-52.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q, $x10^{-2}$ pu</td>
<td>12.68</td>
<td>10.91</td>
</tr>
<tr>
<td>2</td>
<td>$I_+$</td>
<td>pu</td>
<td>0.62</td>
<td>0.53 (0.51)(^1)</td>
</tr>
<tr>
<td></td>
<td>$I_-$</td>
<td>pu</td>
<td>0</td>
<td>0.12 (0.12)</td>
</tr>
<tr>
<td></td>
<td>$I_0$</td>
<td>pu</td>
<td>0</td>
<td>0.40 (0)</td>
</tr>
<tr>
<td>3</td>
<td>$I_{phase \max}$</td>
<td>pu</td>
<td>0.62</td>
<td>0.83</td>
</tr>
<tr>
<td>4</td>
<td>$I_{HG}$</td>
<td>pu</td>
<td>–</td>
<td>1.21</td>
</tr>
<tr>
<td>5</td>
<td>$I_{phase \max}/S_+$</td>
<td>pu/pu</td>
<td>0.98</td>
<td>1.54</td>
</tr>
<tr>
<td>6</td>
<td>$Z_{\text{effective}}$</td>
<td>$x10^{-2}$ pu</td>
<td>1.07 + 4.22i</td>
<td>1.90 + 8.37i</td>
</tr>
<tr>
<td>7</td>
<td>$U_{HG}$</td>
<td>$x10^{-2}$ pu</td>
<td>–</td>
<td>3.01</td>
</tr>
<tr>
<td>8</td>
<td>NSS Compensators</td>
<td>pieces</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Total current of</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NSS compensators</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) - Numbers in the parentheses show the value from the side of the surrounding network

**Table 6.4**: IEEE 14: Electrical parameters at selective compensation, fault at line 4-5
6.3 IEEE30 Network

In figure 6.2 a part of the IEEE30 test case network is repeated, the part which is of most interest for the present investigation. The complete test network is shown in figure 3.27. The considered line damage is a single-phase fault on line 6-28, when a single phase is taken out of operation. The investigation approach is completely identical to that for IEEE14 test case in section 6.2.

At first a complete surrounding compensation topology has been tried out. Zero sequence compensators are located at nodes 6 and 28, negative sequence compensators are located at all nodes, neighbour to 6 and 28 that means at nodes 2, 4, 7, 8, 9, 10 and 27. Compensator currents in this compensation topology are presented in table 6.5. Altogether two zero sequence and seven negative sequence shunt compensators are involved in this scheme. The total current of the NSS compensators is calculated at the bottom of the table.

In the next investigation step all negative sequence compensators are switched off. All currents and voltages in the negative sequence system at nodes surrounding the damaged line are analyzed. Results for this configuration are shown in table 6.6. Nodes with generators indi-
cate no NSS voltage because of the zero impedance of generators in the NSS. The comparison of currents in the negative and positive sequences for generators indicate that the critical quantity \( I_{Neg}/I_{Pos} \) lies in the acceptable range for all generators. All generators indicate \( I_{Neg}/I_{Pos} \) under 5\%, the generators can withstand such a portion of the negative sequence currents. No additional negative sequence compensation has to be undertaken!

The permissible values of the negative sequence currents at all generators allow to manage the symmetrization without any special negative sequence compensation. This is a very significant fact and considerable savings in equipment are achieved in this way.

Electrical parameters of the compensated line in this case are presented in table 6.7, in column 5. Similar to table 5.2, parameters of normal operation are repeated there to enable direct comparison (column 4).

---

**Table 6.5: IEEE30: Results for complete surrounding compensation topology (damaged line 6-28)**

<table>
<thead>
<tr>
<th>Node No.</th>
<th>( I_0 ) (p.u.)</th>
<th>( U_- ) (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.1138</td>
<td>0.0006</td>
</tr>
<tr>
<td>28</td>
<td>0.1138</td>
<td>0.0056</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node No.</th>
<th>( I_- ) (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0031</td>
</tr>
<tr>
<td>4</td>
<td>0.0134</td>
</tr>
<tr>
<td>7</td>
<td>0.0067</td>
</tr>
<tr>
<td>8</td>
<td>0.0135</td>
</tr>
<tr>
<td>9</td>
<td>0.0028</td>
</tr>
<tr>
<td>10</td>
<td>0.0010</td>
</tr>
<tr>
<td>27</td>
<td>0.0141</td>
</tr>
<tr>
<td>11</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td><strong>0.0546</strong></td>
</tr>
</tbody>
</table>
### Without NSS compensation

<table>
<thead>
<tr>
<th>Node No.</th>
<th>$I_0$ (p.u.)</th>
<th>$U_-$ (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.1184</td>
<td>0.0007</td>
</tr>
<tr>
<td>28</td>
<td>0.1184</td>
<td>0.0061</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node No.</th>
<th>$U_-$ (p.u.)</th>
<th>$I_-$</th>
<th>$I_+$</th>
<th>$I_-/I_+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>0.0064</td>
<td>0.6079</td>
<td>1.05%</td>
</tr>
<tr>
<td>4</td>
<td>0.0005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.0004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.0127</td>
<td>0.2626</td>
<td>4.84%</td>
</tr>
<tr>
<td>9</td>
<td>0.0001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.0001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>0.0043</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0.0007</td>
<td>0.2178</td>
<td>0.32%</td>
</tr>
</tbody>
</table>

*Table 6.6: IEEE30: Negative sequence compensation switched off (damaged line 6-28)*
Table 6.7: IEEE 30: Electrical parameters at selective compensation, fault at line 6-28

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Unit</th>
<th>Normal Operation</th>
<th>Compensated Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transferred power</td>
<td>P, x10^{-2} pu</td>
<td>18.64</td>
<td>15.63</td>
</tr>
<tr>
<td></td>
<td>(positive sequence)</td>
<td>Q, x10^{-2} pu</td>
<td>0.95</td>
<td>0.91</td>
</tr>
<tr>
<td>2</td>
<td>$I_+$</td>
<td>pu</td>
<td>0.18</td>
<td>0.15 (0.15)(^1)</td>
</tr>
<tr>
<td></td>
<td>$I_-$</td>
<td>pu</td>
<td>0</td>
<td>0.03 (0.03)</td>
</tr>
<tr>
<td></td>
<td>$I_0$</td>
<td>pu</td>
<td>0</td>
<td>0.12 (0)</td>
</tr>
<tr>
<td>3</td>
<td>$I_{phase\ max}$</td>
<td>pu</td>
<td>0.18</td>
<td>0.24</td>
</tr>
<tr>
<td>4</td>
<td>$I_{HG}$</td>
<td>pu</td>
<td>–</td>
<td>0.36</td>
</tr>
<tr>
<td>5</td>
<td>$I_{phase\ max}/S_+$</td>
<td>pu/pu</td>
<td>0.99</td>
<td>1.56</td>
</tr>
<tr>
<td>6</td>
<td>$Z_{\ eff\ effective}$</td>
<td>x10^{-2} pu</td>
<td>1.94 + 5.92i</td>
<td>3.39 + 11.51i</td>
</tr>
<tr>
<td>7</td>
<td>$U_{HG}$</td>
<td>x10^{-2} pu</td>
<td>–</td>
<td>1.28</td>
</tr>
<tr>
<td>8</td>
<td>NSS Compensators</td>
<td>pieces</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>Total current of NSS compensators</td>
<td>pu</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

\(^1\) - Numbers in the parentheses show the value from the side of the surrounding network
6.4 Comparison of Results

The two previous sections present in principle similar results for two different test networks. Some general conclusions can be drawn from these results.

The distributed compensation seems to be a very effective compensation solution. Under circumstances it allows savings in the total power of the installed power electronics equipment. If the zero sequence system compensation is done according to scheme 3.2 with current sources of low power, the overwhelming part of the power electronics is requested for NSS compensators. Power electronics of the zero sequence system compensators work with the same power as power through the HG-wire, which is low, because of very low voltage on the HG-wire. Depending on the transformer ratio of the windings in the zero sequence transformer, the distribution between voltage and current in the ZSS current source can be arbitrary. The product of the voltage and current gives the needed HG-wire power.

A comparison of the compensator currents at the local compensation by shunt compensators with distributed compensation with the economical topology leads to a saving of factor 2.6 for the IEEE14 network. For the IEEE30 case the economical topology means the complete absence of the NSS compensators, the existing network element overtake their function.

The saving is also significant, if at the local compensation only the negative sequence compensation is done by the power electronics devices, whereas the zero sequence system is compensated by the zero sequence transformers, as shown in section 3.2, at the same nodes. Even in this case the total power of NSS compensators sinks by a factor 1.5 for IEEE14 network.

The savings could be even more significant, if some residual NSS currents would be allowed in generators at nodes, where NSS compensators were placed. This possibility is not directly shown, but it should be kept in mind that directly protected generators can contribute to the NSS compensation by up to 5% of their nominal current without any overheating.

Such a big difference in the NSS compensation currents is caused by the stabilizing function of the network. Generators and loads contribute remarkably to the reduction of currents, which should be compensated
by NSS compensators. Equipment tolerance to small NSS currents and voltages is employed for the purpose of symmetrization. Additionally, if the NSS compensators are placed at some distance to the terminal nodes of the damaged line, the impedance for the NSS currents goes up. This leads to re-distribution of non-symmetrical currents between zero and negative sequences and to additional sinking of the NSS currents. It can be seen by comparison of non-symmetrical currents at the damaged segment at local and distributed compensation topologies.

The example with IEEE30 network is very representative for the stabilizing function of the grid equipment. The transferred power through the line 6-28 in IEEE30 case was relatively low, so that during the two-phase operation all the NSS currents could be compensated by the existing grid equipment. This case also makes it obvious that the number of substations, where the NSS compensation should be undertaken, can even be zero. So the term distributed concerning the compensation does not necessarily mean that the compensators should be installed at many nodes of the network. Concrete parameters of the surrounding network and equipment tolerance to the negative sequence play the crucial part in the needed compensation and should be carefully studied from case to case.

As the power efficiency of the damaged line is concerned, the factor \( \frac{I_{\text{phase max}}}{S_+} \), the considered cases of the distributed compensation indicate a very high efficiency, close to those at local compensation by the short circuiting method. The transferred power is somehow lower in case of the distributed compensation, about 6% difference, and the effective line impedance is about 25% higher, compared with the case of the local compensation by the short circuiting method. The resulting re-distribution of the network power flow leads to advantageous conditions for the phase conductors of the damaged line section. The maximal phase current rises less significantly. This enlarges the scope of lines, which can be compensated, because also relatively heavy loaded lines, considered by thermal limits, can be compensated by the proposed method.
Conclusions

This thesis focused on the possibilities for enhancing the reliability of the existing transmission lines by the application of symmetrical compensation. Different schemes of the symmetrization have been considered. Both local and distributed methods of compensation have been studied. Two selected schemes of local compensation and one scheme of distributed compensation have been examined in detail. The methods have been modelled for lines in meshed networks. The results seem to be promising.

During the simulation it has been shown that symmetrical compensation is technically possible. With the aid of additional equipment at the substations a transmission line can safely operate during fault conditions, such as single-phase line faults. It opens a wide range of new possibilities in the grid operation. This includes a better overall system reliability, because up to approximately 2/3 of the original transmission capacity of the line can be used even during fault conditions.

An important issue of the application of the proposed methods is that the repairs of the damaged lines can be carefully planned and scheduled at convenient times. It is particularly important for difficult reachable regions like high mountains.

In contrast to the construction of the new lines, the symmetrization schemes can be much faster implemented and need less approval procedures. The efficiency of the proposed methods depends on the system
structure, but the results in this work indicate that competitive solutions can be provided. Compensators, installed over the network, can serve for other purposes of the network control during the normal operation, for instance for the power flow control, reactive power control, voltage quality and others. The technology uncloses flexible possibilities for the operation of the electrical power grids. The presented possibilities for the symmetrization of line sections with a single damaged phase can also be used if a higher reliability is required and an usual grid extension is not desired or difficult to force through. The solutions provide an ecologically beneficial (no new transmission corridors), faster and, probably, cheaper way in comparison with the construction of new transmission lines.

Suggestions for future work

The proposed methods at the current stage are far away from the practical implementation in a real grid. Though the symmetrization is technically possible with the aid of modern power electronics technology, it is quite a new concept for high voltage networks. It is necessary to carefully evaluate the economic aspects connected with a real implementation. It seems to be meaningful to conduct such a project in close cooperation with equipment producers. The prices and other practical numbers for the equipment are mostly not available in public. Only the careful and persuasive financial evaluation can provide a firm basis for the practical implementation of the proposed schemes.

It is important to evaluate the most attractive scope of applications of the proposed technology too. What kind of networks and what kind of transmission conditions are the best candidates for such a security update? It seems that long distance transmission lines without a possibility of swerving to another transmission route in case of a fault could be the best candidates for the symmetrical compensation. Another attractive possibility could also be the important mainstream routes in meshed networks. Under certain circumstances the symmetrical compensation can be an economic solution as an alternative to spinning security reserves at the import side of the mainstream transmission line.

The power electronics compensators can be used for a number of active control functions during the normal grid operation. The achieved power quality and additional grid flexibility contribute to the positive arguments for the proposed techniques. In every concrete case the eco-
nomical benefit of the additional control possibilities has to be studied. Another important aspect is of technical character. The dynamic behaviour of the compensated line should be studied. The hardware for the compensators have been considered in [15], the work can be extended for a particular compensation scheme.

If all the proposed studies provide positive confirmations for the possibility of the real implementation, the symmetrization methods can become a useful technology for the enhancing of the HV grid reliability in future.
Appendix A

Phase Interruption Modeling

The representation of single and double phase interruptions in the symmetrical components is important for the analysis of the symmetrization methods. Such a representation facilitates the understanding of the non-symmetrical phenomena. The following sections document in detail the derivation of the corresponding models.

A.1 Modeling of Single Phase Interruption

This section represents a derivation of a model for an interrupted phase, phase R, in symmetrical components. Another less clear approach can be found in [13]. A three phase system is assumed. The initial definition of the task is shown in figure A.1, together with the corresponding set of equations A.1 and A.2.

Being re-written in the symmetrical components representation, equations A.1 look as follows:

\[
\begin{align*}
I_{+1} + I_{-1} + I_{01} &= I_{+2} + I_{-2} + I_{02} = 0 \\
\alpha^2 I_{+1} + \alpha I_{-1} + I_{02} &= \alpha^2 I_{+2} + \alpha I_{-2} + I_{02} \\
\alpha I_{+1} + \alpha^2 I_{-1} + I_{01} &= \alpha I_{+2} + \alpha^2 I_{-2} + I_{02}
\end{align*}
\]

where indexes +, − and 0 stand for the positive, negative and zero sequences correspondingly. These four equations can be easily transformed
into a convenient form:

\[
\begin{align*}
I_{+1} = I_{+2} & \quad I_{-1} = I_{-2} & \quad I_{01} = I_{02} \\
I_{+1} + I_{-1} + I_{01} = 0 & \quad \text{(or: } I_{+2} + I_{-2} + I_{02} = 0) \quad (A.4)
\end{align*}
\]

Equations A.2, being transformed into the symmetrical components, look as follows:

\[
\begin{align*}
U_{+1} + U_{-1} + U_{01} = U_{+2} + U_{-2} + U_{02} + \Delta U_R \\
a^2U_{+1} + aU_{-1} + U_{01} = a^2U_{+2} + aU_{-2} + U_{02} \\
aU_{+1} + a^2U_{-1} + U_{01} = aU_{+2} + a^2U_{-2} + U_{02}
\end{align*}
\]

(A.5)

These equations can also be transferred into a convenient form:

\[
U_{+1} - U_{+2} = U_{-1} - U_{-2} = U_{01} - U_{02} = \Delta U_R/3 \quad (A.6)
\]

For the derived current and voltage equations (A.4) and (A.6) an equivalent electrical scheme can be proposed, see figure A.2. The scheme employs three equal ideal transformers. The transformers guarantee the equal voltage jumps from input 1 to output 2 at all three sequence systems according to the voltage equations. They also guarantee that the sum of the three symmetrical currents leads to zero, according to the current equations. Input and output currents are equal in each sequence system.

This scheme can always be used, no assumptions concerning the surrounding network have been done for its derivation. The scheme can be further simplified, if networks on both sides of the open switch have no interaction between symmetrical systems. In this case three ideal transformers can be replaced by scheme, represented on figure A.3
The source and passive impedances shown in dotted lines symbolize networks, which have no interactions between the symmetrical sequence systems. In this case input 1 and output 2 currents in each symmetrical system are equal, at points C and D the currents sum up to zero. This corresponds to the current equations (A.4). Voltage equations (A.6) are also satisfied, because the voltage jumps in all three systems correspond to the voltage difference between points C and D.

The usage of the simplified scheme from figure A.3 facilitates the analysis of small networks, in which inter-system interaction can be neglected [11]. In more complicated cases the complete scheme from figure A.2 must be used.
A.2 Modeling of Double Phase Interruption

To complete the consideration of different phase interruptions, an interruption of two phase conductors is considered here. Phases S and T are opened, while phase R stays in operation. All derivations and denotations are analogous to those in the previous section. Figure A.4 and the corresponding set of equations A.7 and A.8 represent the definition of the problem.

\[
\begin{align*}
I_{R1} &= I_{R2} \\
I_{S1} &= I_{S2} = 0 \\
I_{T1} &= I_{T2} = 0 \\
U_{R1} &= U_{R2}
\end{align*}
\] (A.7) (A.8)

Figure A.4: Double phase interruption with describing equations in natural system

Being transformed into the symmetrical components representation, the equations A.7 and A.8 look as follows:

\[
\begin{align*}
I_{+1} + I_{-1} + I_{01} &= I_{+2} + I_{-2} + I_{02} \\
\alpha^2 I_{+1} + aI_{-1} + I_{01} &= \alpha^2 I_{+2} + aI_{-2} + I_{02} = 0 \\
\alpha I_{+1} + a^2 I_{-1} + I_{01} &= \alpha I_{+2} + a^2 I_{-2} + I_{02} = 0 \\
U_{+1} + U_{-1} + U_{01} &= U_{+2} + U_{-2} + U_{02}
\end{align*}
\] (A.9) (A.10)

Equations A.9 can be easily transformed into a convenient form:

\[
I_{+1} = I_{+2} = I_{-1} = I_{-2} = I_{01} = I_{02}
\] (A.11)

For the derived current and voltage equations (A.11) and (A.10) an equivalent electrical scheme can be proposed, see figure A.5. The scheme employs three equal ideal transformers.

An interesting observation: The parallel connections of schemes A.2 and A.5 give an element, in which all inputs are directly short-circuited to the corresponding outputs, as it should be expected in case of the parallel connection of an element "interrupted phase R" with an element "interrupted phases S and T".
Figure A.5: Open phases S and T in symmetrical components
Simulator Basic Models

In this Appendix most of the basic mathematical models, which are implemented in the simulator, are described. The models, presented here, are simple and partially well-known in application of the power flow calculations. They are introduced here to show the background assumptions in the modelling and to show the scope limits of the received results. Several components, which are special for this work, are directly described in the section 4.1.

The components will be distinguished by the interconnection way with other components. Two simple categories will be defined: one- and two-sided components. From one side it creates a rough hierarchy and systematization between components, from the other side it shows, to which part of the network list, bus or brunch, the component belongs to.

The components are described in terms of $M_I$ and $M_U$ matrices:

$$M_U \cdot U + M_I \cdot I = b$$

(B.1)

See also explanation to equation 4.1.

Vector $b$ at the right side of (B.1) is a zero vector for passive components. Later, if vector $b$ is not explicitly specified, that means it is zero.

The calculations are conducted in real numeric, all complex values are represented by two real numbers.
Index "r" stands for the real part of a complex number;
Index "im" stands for the imaginary part of a complex number;

**B.1 One-Sided Components**

The class of one-sided components comprises those components, which in the single line diagram have only one connection point. They are specified in the nodes part of the network list. The term *one-sided component* hides the fact that these components are not necessarily one-port components. Being considered as multiple-system components, they can have up to four ports.

**B.1.1 P-U Generator**

Generators can be used either in a single sequence, positive, negative, zero or highground system (PSS, NSS, ZSS or HGS) or in a three or four wire system. If used in a multiple wire system, the generator model contains a voltage source model only in the positive sequence system, while the negative sequence system is short-circuited to the ground, the zero and HG sequence system are open-ended. In case of using a generator in a single system, only the voltage source model is used.

As voltage source model the following P-U model is understood, which has no M-matrices, but supplies nonlinear equations:

1. Statement about constant voltage magnitude:
   \[ U_r^2 + U_{im}^2 = U_0^2 \], where \( U_0 \) is the given generator voltage;

2. Statement about constant generated active power:
   \[ U_r I_r + U_{im} I_{im} = P_0 \], where \( P_0 \) is the given active power of the generator.

The first voltage source model met in the network list is considered as slack generator, for which a condition for voltage angle is used instead of the condition for real power.
B.1.2 P-Q Load

P-Q load can be used either in a single or multiple system. Been used in a single system, the load model provides specified active and reactive power consumption at the specified node.

In a multiple wire system, the positive sequence system model provides that the total consumption of active and reactive powers in all symmetrical systems corresponds to the specified value. In the negative and zero sequence systems P-Q load is treated as a passive load, which impedance is assumed to be equal to the value derived from the initial node voltage and node consumed power: \( Z = (|U|^2/S)^* \). The HG wire is assumed to be open. It is a simple assumption, which has been necessary to declare for the modeling P-Q loads in multiple phase systems. The fact that the HG wire is open allows the addition of shunt compensators to a node, which already has loads and generators.

The declaration of the constant reactive and active power consumption is defined in the non-linear way:

1. \( U_r I_r + U_{im} I_{im} = P_0 \), where \( P_0 \) is the given active power of the load;

2. \( U_{im} I_r - U_r I_{im} = Q_0 \), where \( Q_0 \) is the given reactive power of the load;

In a multiple system configuration these equations are modified to:

1. \( \sum(U_r I_r + U_{im} I_{im}) = P_0 \)

2. \( \sum(U_{im} I_r - U_r I_{im}) = Q_0 \)

The first voltage source model seen in the network list is considered as slack generator, for which the condition for voltage angle is used instead of a condition for real power.
B.1.3 Shunt

Shunt is a simple passive load with constant impedance, specified by its conductance $G$ and susceptance $B$. $M$-Matrices in real number presentation (split presentation of the complex numbers) are as follows:

\[
M_U = \begin{bmatrix}
U_r & U_{im} \\
-G & B \\
-B & -G
\end{bmatrix} \quad M_I = \begin{bmatrix}
I_r & I_{im} \\
1 & 0 \\
0 & 1
\end{bmatrix}
\]

Been used as a multiple system component, the shunt has identical impedances in all systems. The symmetrical sequence systems are independent.

B.1.4 Short-Circuit

Short-circuit can be considered as a shunt with zero impedance and is modelled by equations $U = 0$ for all systems. All symmetrical sequence systems are independent.

B.1.5 Shunt Compensator

The shunt compensator is thought as a shunt connected power electronics device, which is able to compensate the negative and/or zero sequence system. The compensator can be only simulated as a three or four-wire component.
A four-system shunt compensator can compensate both NSS and ZSS, while a three-system compensator can only compensate NSS, because the ZSS compensation requires a sink path for the compensated ZSS current, which is the high ground wire in case of the four wire system.

The model of the multiple system compensator has 8 or 6 equations in terms of the expanded real representation of complex values, which practically corresponds to 4 or 3 complex equations. Here are those equations:

1. $\sum P = 0$, where the sum is done over all symmetrical systems involved - that is the conservation law of the active power;

2. $Q_{PSS} = 0$ that is the condition of no-consumption of reactive power in PSS (this condition could be modified in future);

3,4 If NSS is not compensated: If NSS is compensated:
    $I_{NSS} = 0$  
    $U_{NSS} = 0$
These are 2 equations in the expanded representation of the complex values.

5,6 If ZSS is not compensated: If ZSS is compensated:
    $I_{ZSS} = 0$  
    $U_{ZSS} = 0$

7,8 If ZSS is not compensated: If ZSS is compensated:
    $I_{HG} = 0$  
    $3 \cdot I_{ZSS} + I_{HG} = 0$

Equations 7,8 and right part of 5,6 are only relevant in connection with a 4-system compensator, when HG wire is available.

If a shunt compensator compensates the negative sequence system and is defined at a node with a generator (section B.1.1), then the generator looses its short-circuiting of the negative sequence and all the current in the negative sequence flows through the compensator only. This assumption is needed to avoid uncertainties in current distribution between the
two short-circuiting links, one of the generator and one of the compensator.

B.2 Two-Sided Components

The class of two-sided components comprises those components, which on the single line diagram have two connection points. These components are listed in the branch part of the network list. The elements can have two, six or eight ports, dependent on, in which systems they are defined.

B.2.1 Simple Transmission Line

The simple transmission line is the standard model of a transmission line, as it is usually used for the power flow calculation purposes [20]. The model has been extended for the modelling of the zero and negative sequences as well.

In a single-system usage a line is modelled in the classical way (see figure B.1). Complex M-matrices look as follows:

\[
\begin{align*}
M_U &= -\begin{bmatrix}
\frac{1}{R+jX} + \frac{jB}{2} & -\frac{1}{R+jX} \\
-\frac{1}{R+jX} & \frac{1}{R+jX} + \frac{jB}{2}
\end{bmatrix} \\
M_I &= \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\end{align*}
\]

The following assumptions have been made for modelling of the line as a multiple system component:

- All symmetrical and HG systems are independent, each system is modelled like a single-system model shown above.\(^1\)

\(^1\)Important: The simple transmission line model does not reflect the interdepen-
• Positive, negative and HG sequence systems are identical and have parameters R, X, B as they are specified in the net list.

• Zero sequence system has parameters, being different from other systems: $R_{ZSS} = 3R_{PSS}$, $X_{ZSS} = 3X_{PSS}$, $B_{ZSS} = B_{PSS}$.

B.2.2 All-Phase Switch

The all-phase switch is the simplest two-sided component. It can be implemented either as a single-system element or as a multiple-system element. In "closed" position the input and output voltages are equal, in "open" position input and output currents are zero.

B.2.3 Single-Phase Switch

The idea of this component is to simulate faults on a single phase wire. The single-phase switch allows to break or to close a specified single phase. This element cannot be used as a single-system element, because any single phase in the natural system is present in transformed form in all three symmetrical systems.

The models presented in this Appendix together with the models from the section 4.1 represent all models used in the simulator. The models allow quite flexible configurations and have been successfully used for simulations in the scope of the present work.
Appendix C

Abbreviations

The following abbreviations have been used in the dissertation text. The number in parentheses represents the page, where the abbreviation has been introduced.

AC - Alternating Current (2)
DC - Direct Current (16)
EF - Earth Fault (10)
FACTS - Flexible AC Transmission System (4)
HG - **Highground**, about wire or system. Highground wire is an additional conductor to three phase conductors, which serves as return path for the zero sequence system currents. (16)
HGS - **Highground System** (124).
HV - High Voltage (21)
NSS - Negative Sequence System (3)
PSS - Positive Sequence System
SVC - Static Var Compensator (51)
VDEW - germ.: Vereinigung Deutscher Elektrizitätswerke, Association of German Power Utilities (9)

VSE - germ.: Verband Schweizerischer Elektrizitätswerke, Association of Swiss Electrical Utilities (9)

ZSS - Zero Sequence System (3)
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Andrei Karpatchev
Андрей Анатольевич Карпачёв


Education

1998-2003 ETH Zürich (Swiss Federal Institute of Technology)  
Ph.D. study in El. Engineering, Power Transmission  
Thesis: ”Increased Transmission Capacity by  
Forced Symmetrization”

1996-1998 ETH Zürich (Swiss Federal Institute of Technology)  
Post-diploma study in Information Technology  
Diploma Thesis: ”Synthesis of code sequences with advan-  
tageous correlation properties for CDMA-Systems”

1990-1995 Moscow Institute of Physics and Technology, Russia  
Department of Radio Technology and Cybernetics  
Master of Science in Electronics, with honours  
Diploma Thesis: ”Development of a register file control  
block for Processor with Very Large Instruction Word  
Architecture”

1980-1990 Secondary school, Almaty, Kazakhstan  
Honored with Gold Medal

Professional Experience

1998-2003 ETH Zürich (Swiss Federal Institute of Technology)  
Scientific Assistant at Power Systems Laboratory

1996-1998 ABB Power Generation Ltd., Baden, Switzerland  
Development and mathematical simulation of the  
steam turbine control

1995-1996 ABB Power Generation Ltd., Baden, Switzerland  
Trainee, Automation of processes and database  
development for documentation of the gas turbines