UNIVERSITY OF VAASA

FACULTY OF TECHNOLOGY

ELECTRICAL ENGINEERING

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MODELLING AND CALCULATION OF THE SHORT-CIRCUIT CURRENTS OF INVERTER-BASED FLEXIBLE ENERGY RESOURCES

Bachelor’s thesis in Technology for the degree of Bachelor of Science in Technology submitted for inspection, Vaasa 25.4.2016.

Instructor Kimmo Kauhaniemi

PREFACE

I received the topic for this Bachelor’s thesis from Professor Kimmo Kauhaniemi in January of 2016. This thesis has been written as a part of a larger international research project, FLEXe – Flexible Energy Systems, in which the responsibility for the research on the modelling of flexible energy resources belongs to Professor Kimmo Kauhaniemi.

I would like to thank Professor Kimmo Kauhaniemi for his guidance, this great opportunity and an intriguing research problem.

Vaasa 25.4.2016

Aleksi Koskela

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SYMBOLS AND ABBREVIATIONS

Greek symbols

κ	Factor for calculation of the peak short-circuit current
φ	Phase angle (°)
ω	Angular frequency (rad/s)

Symbols

$\underline{a}$	Phase shift operator
c	Voltage factor
cos φ	Power factor
C	Capacitance (F)
E	Equivalent voltage source (V)
f	Frequency (Hz)
i_p	Peak value of short-circuit current (A)
I	Electric current (A)
$\underline{I}_{(0)}$	Zero-sequence current (A)
$\underline{I}_{(1)}$	Positive-sequence current (A)
$\underline{I}_{(2)}$	Negative-sequence current (A)
I'_k	Transient short-circuit current (A)
I''_k	Initial short-circuit current (A)
I''_{kPF}	Initial short-circuit current of power-stations units with full size converter (A)
$I''_{kmaxPFO}$	Maximum initial short-circuit current without the influence of power station units with full size converter (A)
I_{skPF}	Maximum source current of an inverter (A)

j	Imaginary unit
k	Inverter maximum current factor
L	Inductance (H)
P	Active power (W)
Q	Reactive power (VAr)
R	Resistance (Ω)
R_{G}	Resistance of a generator (Ω)
R_{k}	Short-circuit resistance (Ω)
S	Apparent power (VA)
t	Time (s)
U	Voltage (V)
U_{n}	Nominal voltage (V)
v_{control}	Control signal of PWM scheme
v_{tri}	Triangular waveform of PWM scheme
V_{d}	Input DC voltage of an inverter
x_{d}''	Per-unit value of a distributed generator's reactance
X	Reactance (Ω)
X_{G}	Reactance of a generator (Ω)
X_{k}	Short-circuit reactance (Ω)
Z	Impedance (Ω)
$\underline{Z}_{(2)\mathrm{PF}}$	Negative-sequence impedance of a power station unit with a full size converter (Ω)
$\underline{Z}_{\mathrm{DG}}$	Impedance of a distributed generator (Ω)
Z_{ij}	Absolute values of the elements of the nodal impedance matrix (Ω)
$\underline{Z}_{\mathrm{k}}$	Short-circuit impedance (Ω)

$\underline{Z}_{\mathrm{L}}$	Line impedance (Ω)
$\underline{Z}_{\mathrm{T}}$	Impedance of a transformer (Ω)

Abbreviations

AC	Alternate current
CAD	Computer-aided design
CAES	Compressed air energy storage
CSI	Current source inverter
DC	Direct current
DG	Distributed generation
DSO	Distribution system operator
EDLC	Electro double-layer capacitor
ES	Energy storage
ESS	Energy storage system
FESS	Flywheel energy storage system
HV	High voltage
IBDG	Inverter-based distributed generation
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-gate bipolar transistor
LV	Low voltage
MV	Medium voltage
PF	Power station unit with a full size converter
PV	Photovoltaics

PWM	Pulse-width modulation
RMS	Root mean square
SCC	Short-circuit calculation
SMES	Superconducting magnetic energy storage
TEES	Thermoelectric energy storage
TSO	Transmission system operator
VSI	Voltage source inverter
VTT	Technical Research Centre of Finland
VFD	Variable frequency drive
WT	Wind turbine

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ABSTRACT

This thesis is written for University of Vaasa as a part of a research program FLEX^{e} – Flexible Energy Systems. The goal of this thesis is to illustrate the behavior of short-circuit currents when flexible energy resources are added to distribution or transmission networks via inverters and to find methods for the calculation of short-circuit currents in energy systems that incorporate high penetration of inverter-based flexible energy resources such as wind power or solar power.

This thesis was based on a literature survey and simulations made in PSCAD. The simulations were done using existing grid models developed by University of Vaasa and VTT. The purpose of the simulations is to provide further understanding to the behavior of short-circuit currents in networks containing flexible energy resources. In the literature survey part, scientific papers and IEC standards were referred to and a few reasonable methods to calculate short-circuit currents were found.

The results of the study showed that uniform, generally accepted methods for the calculation of short-circuit currents of inverter-based distributed generation do not yet exist in the literature. Three different methods for calculating short-circuits currents were reviewed in this thesis. The method presented in the second version of IEC 60909 standard is going to give the most accurate results, because it uses the information of nodal impedance matrix. However, it takes more computational effort to calculate it, so the two other methods presented are faster to calculate, but do not give as accurate results. Desired accuracy level determines which method is reasonable to use in a specific situation. The need for further development and standardizing was found for this subject, because the share of flexible energy sources in power grids is constantly growing and more accurate network calculations are needed for successful integration of these energy sources.

KEYWORDS: flexible energy resources, inverter-based distributed generation, short-circuit calculation, power system analysis

1 INTRODUCTION

This work was carried out in the research program Flexible Energy Systems (FLEXe) and supported by Tekes – the Finnish Funding Agency for Innovation. The aim of FLEXe is to create novel technological and business concepts enhancing the radical transition from the current energy systems towards sustainable systems. FLEXe consortium consists of 17 industrial partners and 10 research organizations. The program is coordinated by CLIC Innovation Ltd.

Sustainable energy system will be a complex combination of centralized and local generation combining a wide variety of energy resources including renewables and energy storages. Increasing the intermittent energy like wind and solar power will pose a challenge to the balance management of the power system. New solutions to increase flexibility are required at all levels of the energy system. In addition, future energy system must not only be sustainable, but also affordable and reliable.

The emphasis of this thesis is on principles for modelling of flexible energy resources for various planning tools. More precisely this thesis will focus on modelling and calculation of the short-circuit currents of inverter-based flexible energy resources. Some earlier research has been made, but this field of study is not yet widely researched thus comprehensive books focusing on the problematics of this subject do not exist.

This thesis will only focus on the technical aspects of the integration of flexible energy resources to the power grid, so economical viewpoints will not be considered in this paper. The FLEXe research program has many other tasks that will inspect the subject from other, such as financial viewpoints.

Due to the global climate change and depleting of fossil fuels, development of renewable energy sources have become more important nowadays. Furthermore, constantly growing demand of electricity increases the interest in distributed generation (DG) and flexible energy resources. The most common energy sources belonging to flexible energy resources are wind power, solar power, fuel cells, steam turbines, combustion turbines and microturbines (Short 2014: 797-800). Flexible energy resources do not solely consist of energy sources, but also energy storages (ES). Energy storages can be for example batteries, electrochemical double-layer capacitors (EDLC), regenerative fuel cells, compressed air energy systems (CAES), flywheel energy storage systems (FESS), superconductive magnetic energy storage systems (SMES) and thermoelectric energy storages (TEES) (Haitham, Malinowski & Al-Haddad 2014: 50-51; Sioshansi 2011: 42-46). Energy storage systems (ESS) and most of renewable energy sources require power electronic converters in order to be connected to the power grid. The basic functionalities of power electronic converters will be considered in the second chapter of this thesis.

Power system faults, for example short circuits and ground faults, cannot be totally eliminated from a transmission or distribution network. This leads to the fact that protection engineer must design his protection system to (Behnke & Ellis 2013):

- quickly detect the presence of the fault
- interrupt the flow of current to the fault in a manner that minimizes loss of load
- restore service to as much of the load lost as possible once the fault is cleared.

Computer simulation programs that utilize network models are important for short-circuit analysis, because several different faults in various fault locations and complex transmission networks can be simulated by them (Behnke & Ellis 2013). In the third chapter of this thesis, a network model developed by VTT and University of Vaasa in PSCAD computer simulation program is used to illustrate the behavior of short-circuit currents, when DG is added to the network.

An engineer can use the results of a simulation to determine the magnitudes of short-circuit currents in a transmission or distribution network so that various devices such as circuit breakers, reclosers and fuses could be designed to be of right size and work properly. Breaking capacity and thermal durability of these devices is important for adequate fault clearance. Short-circuit analysis also makes a foundation for coordination of protection relays, which maximizes the selectivity of the protection system i.e. only the faulted part of the network will be disconnected from the power grid and healthy parts of the grid will stay energized. (Behnke & Ellis 2013).

Uniform and standardized equations and calculation methods exist for conventional rotating generators, because they have been invented relatively long time ago (in the end of 19^{th} century). These are presented for example in standards published by International Electrotechnical Commission (IEC). Inverter-based energy resources are rather new and inverters behave in a totally different way during the fault situation than rotating generators. Comprehensive books and universally accepted equations and calculation methods do not yet exist and usually inverters have been described with a help of IEC Standard 60909 based models for asynchronous generators. A new standard considering power station units with full size converters published by IEC in 2016 is referred to in Chapter 4 of this thesis.

The goal of this thesis is to review different methods used today to calculate short-circuit currents in a transmission or distribution network that includes inverter-based distributed generation (IBDG). The behavior of inverter-based fault currents is also illustrated by referring to various scientific papers and by simulating a fault situation in a simple radial network containing DG and analyzing the simulation results.

2 POWER PROCESSORS AND CONVERTERS

The existing power grid can be considered as a hierarchical system where power plants are at the top of the chain and loads are at the bottom, resulting in a unidirectional electrical pipeline managed with limited information about the exchange among sources and end points. Along with the introduction of DG, conventional power systems consisting of few high power generators feeding distribution systems loads through a tree are being replaced by wide, complex and heterogeneous meshes, embedding a huge number of loads and generators and operating at different power levels and voltages. (Haitham et al. 2014: 50-51; Sioshansi 2011: 186). This is why the integration of renewable energy sources to the existing power grid emerges challenges in designing and calculation of the power grids. Short-circuit currents in the grid will be altered when DG is added especially to the upstream side of grid. The interfacing components, inverters, affect the short-circuit currents and therefore knowledge about inverters is a requirement to understand short-circuit currents in networks that include IBDG.

The task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally used for user loads. Power converter is a basic module of a power electronic system, which utilizes controlled power semiconductor devices to convert power to a desired form. It is useful to categorize the power processors by their input and output forms into four different groups (Mohan, Undeland & Robbins 2003: 3, 9-10):

1. Rectifiers: convert AC to DC

2. Inverters: convert DC to AC

3. Switch-mode converters or chopper converters: convert DC to DC

4. Cycloconverters: convert AC to AC

The power flow through the converter can also be reversible and the converter can then operate in rectifier and inverter modes as shown in Figure 1.

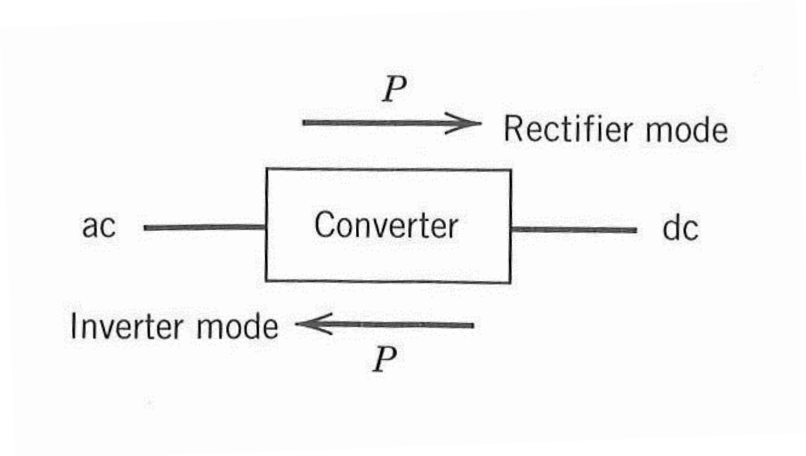

Figure 1. Different modes of a converter. (Mohan et al. 2003: 10).

The situations considered in this thesis include mainly inverters, because photovoltaic (PV) systems and energy storages are connected to grid by inverters. However, wind turbines (WT) generate AC power, so AC-AC converters, called also variable frequency drives (VFD), are usually used in wind power applications.

2.1 Switch-mode inverters

In this chapter the basic concepts of switch-mode inverters will be considered, which are usually voltage source inverters (VSI), where input is DC voltage. Another type of inverter is a current source inverter (CSI), where the input is a DC current source, but they are not discussed in this thesis because of their limited applications. (Mohan et al. 2003: 201). Voltage source inverter is preferred topology due to switching technology, cost, weight, size and voltage bus (Kauhaniemi, Rajkumar & Taikina-aho 2011: 9).

2.1.1 Pulse-width-modulated (PWM) inverters

The most common inverter type is pulse-width-modulated (PWM) inverter. In these inverters, the input DC voltage is smooth and the inverter controls the magnitude and the frequency of output by pulse width modulation at the inverter semi-conductor switches. In order to produce a sinusoidal output current waveform at a desired frequency, a sinusoidal control signal at the desired frequency is compared with a triangular waveform, as shown in Figure 2a. The frequency of the triangular waveform establishes the inverter switching frequency. (Mohan et al. 2003: 201, 203, 226).

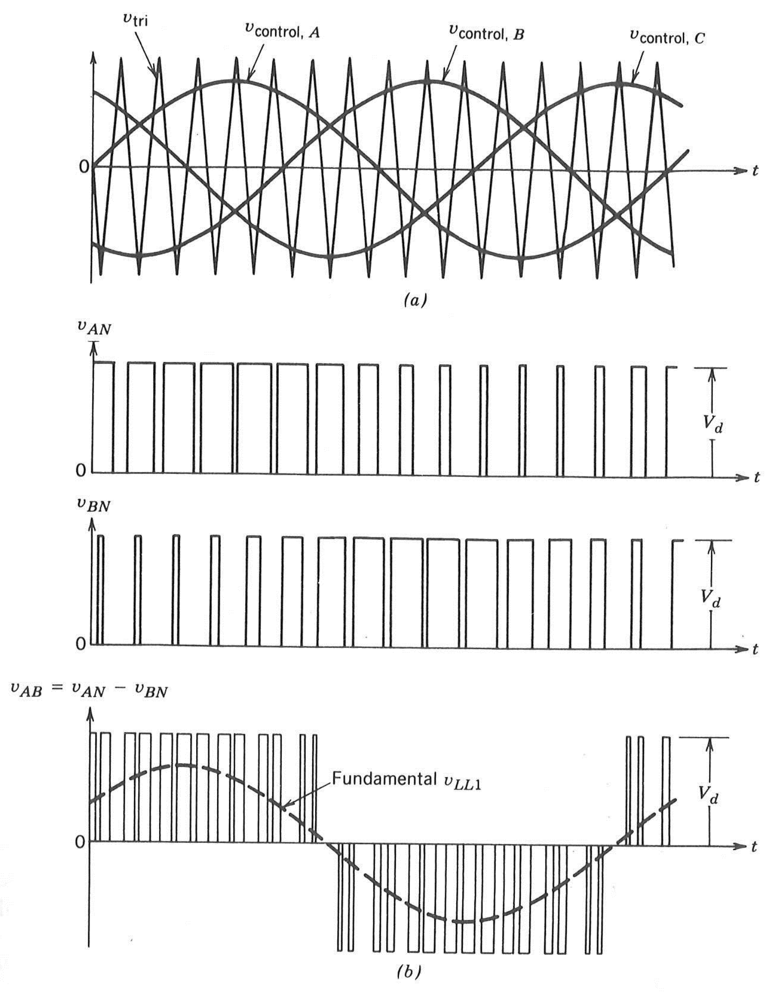

Figure 2. Three-phase PWM waveforms. (Mohan et. al 2003: 227).

A PWM scheme with unipolar voltage switching is used in Figure 2, as the DC voltage is switched between positive voltage V_d and 0. In bipolar voltage switching the DC voltage is switched between positive voltage V_d and negative voltage $-V_d$. Unipolar voltage switching enables the voltage jumps at each switching to V_d as compared to $2V_d$ in bipolar voltage switching. (Mohan et al. 2003: 203-217). From Figure 2 it can be seen, that when the triangular waveform v_{tri} is greater than control voltage $v_{control}$, output voltage is zero, and when v_{tri} is smaller than $v_{control}$, output voltage is V_d. Line-to-line voltage between phases A and B can be seen in Figure 2b.

2.1.2 Three-phase grid-tie inverters

Switch-mode DC-to-AC inverters are used in applications, which require sinusoidal AC output whose magnitude and frequency can both be controlled. The DC voltage is obtained by rectifying and filtering the line voltage, most often by diode rectifier circuits. The rectified voltage is then smoothened in the filter capacitor parallel to rectifier. The capacitor also works as an energy storage element between the rectifier and the inverter, so instantaneous power input does not always have to match the instantaneous power output. (Mohan et al. 2003: 9, 200). This is useful especially in wind power applications, because the frequency and magnitude of input voltage is varying.

The grid-tie inverter shown in Figure 3 uses active rectifier instead of diode rectifier circuit to rectify the line voltage. Active rectifiers use active switch components, for example insulated gate-bipolar transistors (IGBT) parallel to diodes to rectify the line voltage, so they are also capable of transferring power to both directions, which makes them better interfacing components for DG implementations than conventional diode rectifiers. One important advantage of active rectifier compared to diode rectifier is more sinusoidal supply current and the possibility to control the power factor so that the output voltage and current are lined up and the phase angle is very close to the phase angle of power grid. However, active inverters are very expensive and they require a LCL filter, which filters the harmonics of the line current and works as an energy storage between the network feeder and the inverter (Lappeenranta University of Technology & Tampere University of Technology 2010: 46-47).

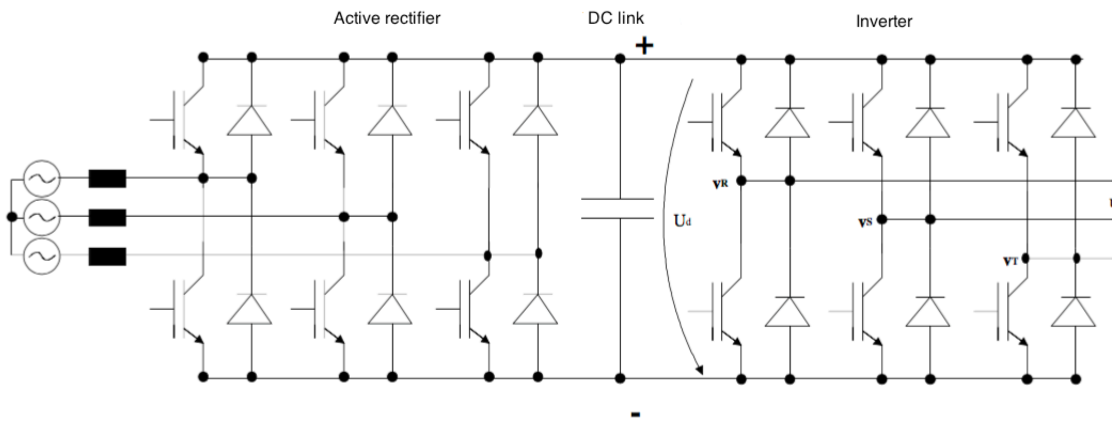

Figure 3. Grid-tie inverter with a DC link. (Jokinen 2016: 40).

Grid-tie inverters can be used with primary energy sources of DG, like photovoltaic (PV) systems, wind turbines (WT) and microturbines. WT can be connected directly or via gearbox to the generator and further to an inverter shown in Figure 3 and the output could be then connected via a step-up transformer to the power grid. PV systems can be connected to the DC link, because PV systems generate DC. However, a DC-DC converter should be added between the DC link and the grid-tie inverter to step up the output DC voltage of the PV system to a suitable voltage level (Kauhaniemi et al. 2010: 11). If the voltage levels rise too much during the times of high production, supplying reactive power to the grid might be necessary to keep the voltage inside allowed limitations. Active rectifier can also control DC voltage level actively, so DC link voltage can be kept almost constant.

2.2 Control of the inverter

The possibility of energy production using clean technologies like wind turbines and PV systems is very attractive, but the control of these systems is very demanding due to the uncertainty in the availability of input power. Moreover, the increased amount of DG systems connected to the utility grid can create instability in the power systems. (Rodriguez, Timbus, Teodorescu, Liserre & Blaabjerg 2007).

DG units require power electronics interfacing and different methods of control. In grid-connected mode it should give steady-state decoupled active power *P* and reactive power *Q* control and proper behavior under connecting, disconnecting and reclosing operations. (Keyhani, Marwali & Dai 2010: 106).

Unlike the conventional synchronous generator, the response of inverter-based distributed generators to a short circuit is very fast and dependent on the voltage and current control of the inverter. (Tu & Chaitusaney 2012).

2.2.1 Inverter control modes

Due to intermittency and uncontrollable factors affecting the output of renewable energy sources, it is necessary that the power output of the grid inverter is somehow controlled. For an inverter there are three control modes (Kauhaniemi et al. 2011: 13):

- Constant current (*I* control)

The inverter is configured to supply constant current by controlling the values of d-axis and q-axis currents, id and iq, to be equal to reference values idref and iqref.

- Constant reactive and active power control (*PQ* control)

The inverter is configured to supply constant active and reactive power by controlling id and iq to produce active and reactive power equal to Pref and Qref, respectively.

- Constant voltage and active power control (*PV* control)

The inverter is configured to supply constant active power keeping its terminal voltage also constant.

The first control mode can be considered as the basic control method, which usually is set to be the inner loop of the control system while the other two are set to be the outer control loop (Kauhaniemi et al. 2011: 13). In the inverter used in the simulations of next chapter, *I* controller is used as the inner loop and *PQ* controller is used as the outer loop of the control system.

3 BEHAVIOR OF SHORT-CIRCUIT CURRENTS OF FLEXIBLE ENERGY RESOURCES

The methods of calculating short-circuit currents when there is IBDG integrated to the power grid are considered in this thesis. Before considering the response of DG inverters to AC system faults, it is good to first understand how the short-circuit currents behave when the power grid consists of just conventional rotating generators and loads. The calculation of short-circuit currents has an impact on the selection of components when building or renewing power grids. Studying short-circuits is also essential for determining relay settings (Keller & Kroposki 2010: 36).

3.1 Short-circuit current of a synchronous generator

In a three-phase system the largest possible fault current is caused by three-phase short-circuit without a resistance. The magnitude of the short-circuit current with a conventional big generator is usually 10-40 times the rated load current. Protection automation has to break the circuit fast enough so that the devices would not be damaged.

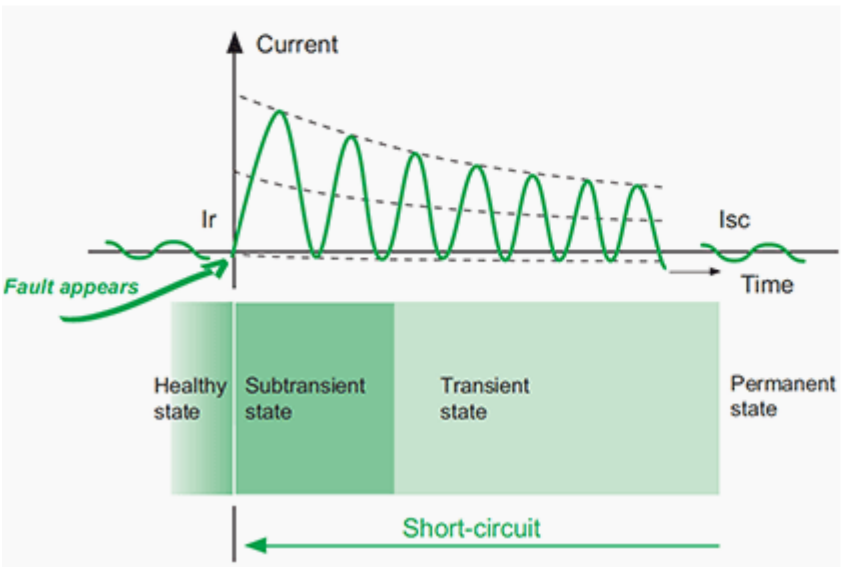

Figure 4. Short-circuit current of a synchronous generator in an asymmetric short circuit. (Csanyi 2014).

The different parts of a short-circuit current of a synchronous generator in an asymmetric short-circuit can be seen from Figure 4. An average duration for subtransient state is only about 10 ms, but it contains the highest instantaneous value of the short-circuit current i_p. The breaking capacity of circuit breakers should be determined by this peak short-circuit current. Transient state lasts roughly 250 ms and it sets the protection equipment's thermal constraints.

Synchronous generators are able to feed rather large sustained fault current while inverter based systems may be controlled so that their output is limited to much lower currents. The traditional grid protection strategy depends on high fault currents which trigger the overcurrent relays. The thermal capacity of an inverter is typically limited to 2-3 times the rated current, so single inverters cannot provide high contributions to the total current. However, the aggregate contributions of many small units, or a few large units, can alter the short circuit levels enough to cause overcurrent protection miscoordination. This can affect the reliability and safety of the distribution system. (Kauhaniemi et al. 2011: 25-6). Higher fault currents from the upstream side of the power grid may increase the total fault current over the maximum limit set to reclosers on the feeder. Too high fault currents may cause damage to reclosers and fuse operation will also be affected. Fuses will clear sooner than they are designed, which has an impact on the reliability of the feeder. Relatively accurate short-circuit models are needed to assess DG fault contribution during the subtransient and transient periods. (Baran & El-Markaby 2005).

3.2 Short-circuit currents of inverter-based energy resources

Inverters do not behave in the same way as conventional generators, because they do not have rotating mass and inductive characteristics that rotating machines have. Inverters are also controlled in a different way than rotating machines and they respond to fault situations in a different time, which also affects the fault current characteristics of inverters. Keller and Kroposki characterized the inverter's response in a fault situation by simulations and short-circuit tests with an actual inverter. (Keller & Kroposki 2010: 19).

Keller and Kroposki (2010: 21-24) found out that the magnitude of an inverter's short-circuit current can be much higher than the rules in literature imply, even up to five times inverter's rated current. Furthermore, the time that fault current stays on can be much shorter than it is implied in literature. The time of fault current in the case of their test was only 1,6 ms, so protective relays may be thinking that the contribution belongs to the subtransient part of a short-circuit current of a rotating generator (Kauhaniemi et al. 2011). However, the subtransient short-circuit currents in the case of rotating generators are much higher than the currents inverters can produce, thus the fault current could be ignored. Additionally, the semiconducting components of inverters could be damaged when currents of five times the rated current will apply. However, many inverters cannot produce currents that high, because they have efficient current limiters, which limit the current usually to 100-200 % of the rated current. The magnitude of an inverter's fault current is mostly dependent on the rated values provided by the manufacturer. In the next chapter simulations are presented to provide further understanding to the subject.

3.3 Simulations

In this chapter simulations are presented in PSCAD, which is a general-purpose, time domain simulation tool for studying transient behavior of electrical networks. The goal of these simulations is to illustrate the behavior of the short-circuit currents in transmission and distribution networks including flexible energy resources. In these simulations existing simulation models developed by University of Vaasa and VTT were used. All rights of the simulation models belong to their respectful owners. The models used in this chapter originate to a collection of models of distribution networks and distributed generators from earlier DG related projects. The model library was provided to me by Professor Kimmo Kauhaniemi.

3.3.1 Model used in the simulations

A model based on a MV overhead line grid was used in these simulations. The grid model, which is seen in the Figure 5, depicts characteristic Finnish medium-voltage transmission grid of overhead lines. The parts of the grid are:

1. Supplying network
2. Primary transformer
3. Feeder 1
4. Feeder 2
5. Background network

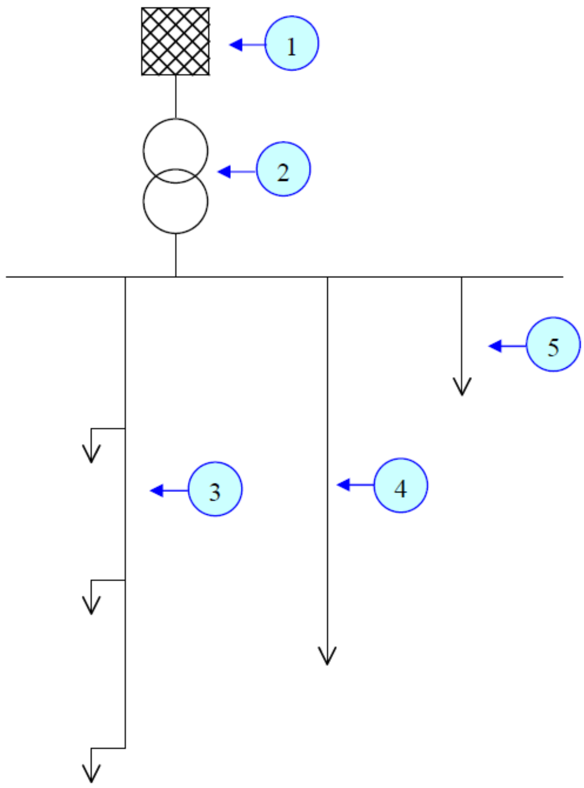

Figure 5. Structure of the medium-voltage transmission grid model. (Kauhaniemi & VTT 2007).

The PSCAD model consists of equivalent source representing the 110 kV supplying network, 110 kV bus, 110/21 kV primary transformer, earthing transformer, 20 kV bus and three feeders on 20 kV bus.

The supplying network is modeled as a voltage source using voltage source model, where desired short-circuit power and *R*/*X*-ratio can be defined directly. The model has also an integrated controller, which can be used to fine tune the voltage.

The rated power of the primary transformer in these simulations is 16 MVA and its vector group is YNd11, so the transformer has wye HV winding and delta LV winding and HV lags LV by 30º.

The grid model is modular, so it has several slots where DG stations can be added. In this simulation, an inverter based generator unit was added to feeder 1 to a connection place, which is located 35 km from the start of the feeder. This can be seen from Figure 6. Total length of the feeder 1 is 50 km. The inverter model used in the simulations is imported to the grid model from another file, wherein the operating principle of the inverter is explained. Rated power of the inverter is 2,3 MVA and rated voltage is 400 V. Start-up time of the inverter is set to be 0,5 seconds and power factor cos φ is 0,95. The maximum current of the inverter can be adjusted by a controller at the model. In this simulation a limit 120 % of the rated current is used.

3.3.2 Three-phase short-circuit on a feeder

Fault type, fault location and the starting time of the fault can be determined with three different controllers in the model. First a three-phase short-circuit was caused on feeder 1 through a fault resistance of 10 Ω at fault location 1, which is shown in Figure 6 with red arrow. Fault was set to begin at time t = 1,0 s, so the starting time of the inverter (0,5 s) is taken into account. Therefore the transients belonging to start-up phase have faded out and the model is in steady state.

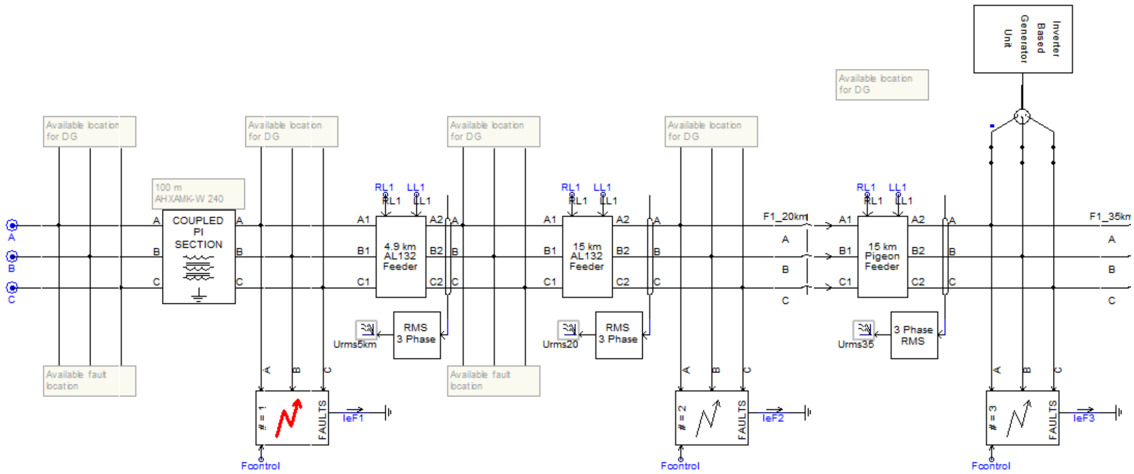

Figure 6. Schematic diagram of feeder 1.

From Figure 7 it can be seen that when the inverter starts at *t* = 0,5 s, the current of the inverter has an inrush current of 4,110 kA, which is 112,5 % of the steady state current during healthy state, 3,645 kA.

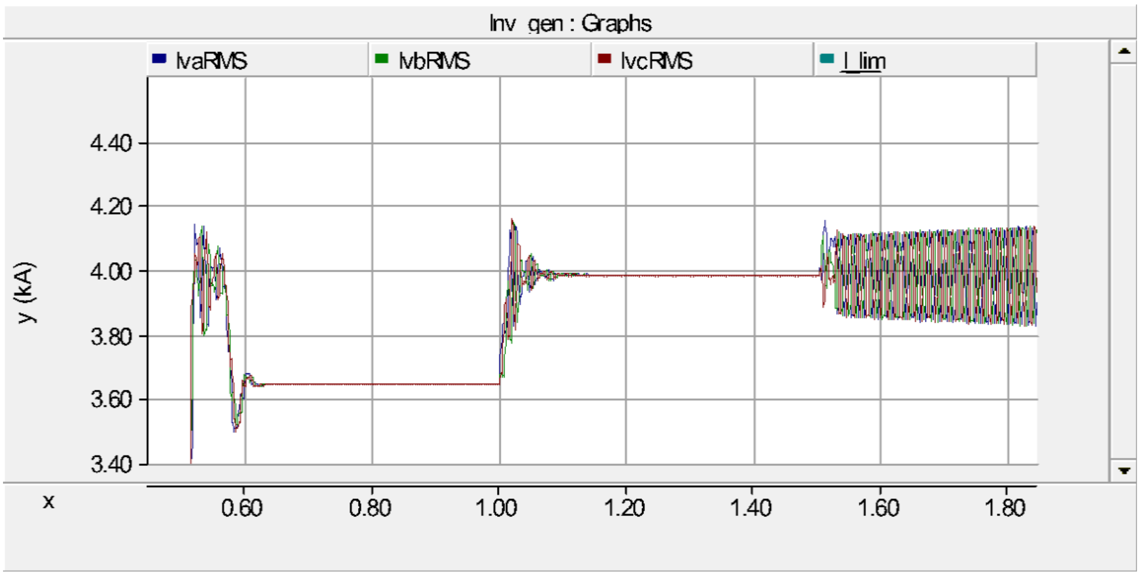

Figure 7. Inverter current during start, healthy state and fault state.

The fault is induced to the system at *t* = 1,0 s, when a transient can be seen at the inverter current. The maximum short-circuit current of the inverter seen in the Figure 7 is 4,144 kA, which is 114 % of the steady state current at healthy state. Then the controller compensates the fault current to a steady value of 3,984 kA, which is 109% of the steady state current at healthy state. After t =1,5 s the overcurrent relays at the beginning of the feeder operate and the measured inverter current starts to oscillate.

From Figure 8 it can be seen that the phase voltages at the inverter terminals will fall when the fault occurs. The maximum values of phase voltages before the fault are approximately 296 V, so RMS values are approximately 209 V. After the fault, maximum values of phase voltages drop to 200 V and RMS values drop to 141 V. This means that the voltage sags to 67,6 % of the nominal voltage. For example VFDs, inverters and AC motors are affected by the voltage sags. The higher away from the fault the inverter is, the higher is the retaining voltage at the inverter. Because fault location 1 is at the start of the feeder 1, there is a 35 km distance between the fault location and the inverter, thus the voltage sag is not so severe, as it is in the case of Figure 9.

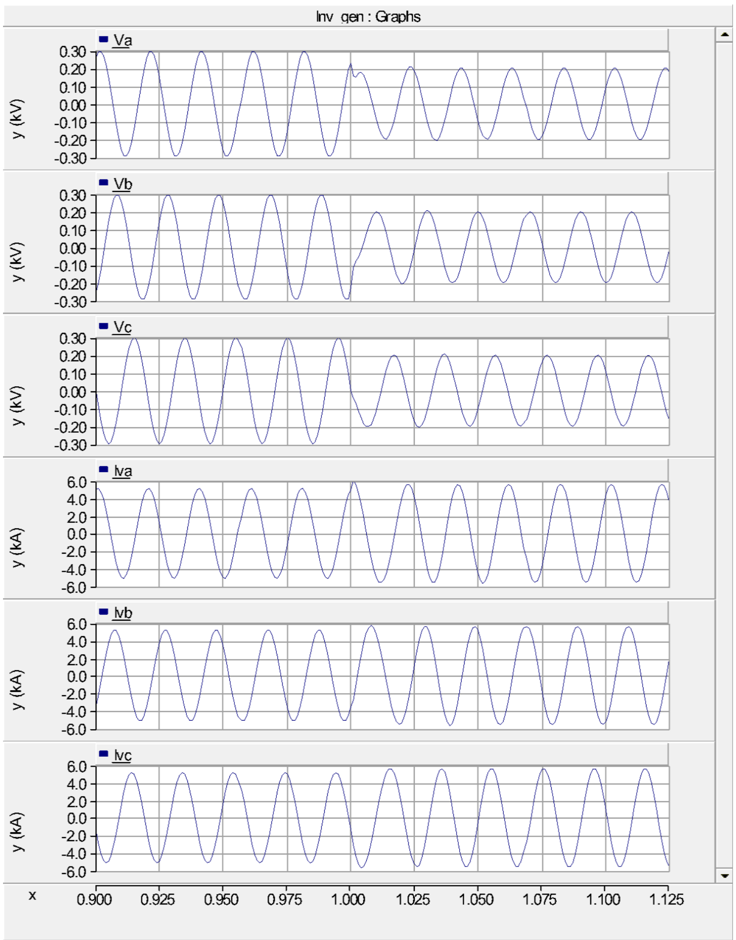

Figure 8. Phase voltages and currents at inverter terminals before and during the fault, when fault is located 35 km away from the inverter.

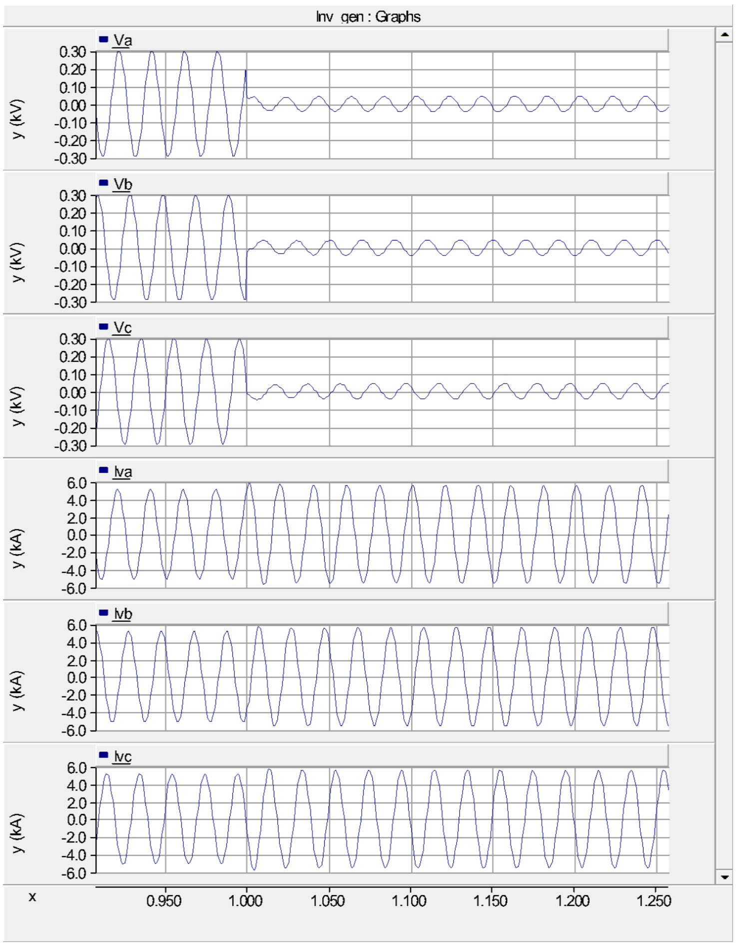

Figure 9. Phase voltages and currents at inverter terminals before and during the fault, when fault is located right at the inverter location.

Figure 9 shows the phase voltages and currents at inverter terminals when fault is located right at the inverter, at fault location 3, which can be seen from Figure 6. From the graphs of phase voltages it can be seen that they have significantly steeper decrease as in the situation of Figure 8. Now the maximum values of phase voltages drop to 44 V and RMS values drop to 31 V. This is only 14,9 % of the voltage before the fault, so very little voltage is retained at the inverter. However, the current does not rise relatively to the voltage, because the current limiter limits the current to maximum of 120 % of the nominal current. This means a significant drop in the active power of the inverter.

Inverter cannot ride through voltages that low, which means that it is really probable that the inverter will drop out. Typical trip level for undervoltage is 50 % of the nominal voltage, so in the case of Figure 9, inverter would stop the power delivery to the grid. Power electronic converters are sensitive to overvoltages and overcurrents, so easiest way to avoid harmful effects during grid fault is to disconnect the DG unit from the grid. If too many DG units drop out due to voltage sags, the grid would lose a significant amount of power generation and stability problems might appear. When DG is increased in the network and higher percentage of the power generation in the grid comes from DG stations, fault ride-through is required from DG stations also (Kauhaniemi et al. 2011: 16, 23).

4 SHORT-CIRCUIT CURRENT CALCULATION

The analysis of fault situations is an essential part of the design of transmission and distribution systems. The most common faults are short-circuits and earth faults. Short-circuits are faults between two or more phase connectors without a link to the ground, whereas in earth faults the ground is always included in the fault current circuit. The causes for faults are for example overvoltage, which can be caused by lightning strikes or some internal reasons in the power grid, malfunction or misoperation of devices due to mechanical defects or the decrease of insulating capacity of some grid components. (Elovaara & Haarla 2011: 166).

Programs, which are used to calculate short-circuit currents in conventional radial distribution networks, cannot be simply used to calculate short-circuit currents in inverter-based networks, because they do not take the behavior of inverters into account. (Margossian, Sachau & Deconinck 2014).

Various methods for calculating the short-circuit currents are overviewed in this chapter. Short-circuit calculations (SCC) are a standard component of power system analysis software like DIgSILENT PowerFactory and the calculations are far easier to compute with software than by hand.

Static SCCs are necessary for transmission system operators (TSO) and distribution system operators (DSO) for network planning and operation purposes. In network planning, the studies primarily focus on the maximum and minimum short circuit currents. Maximum short-circuit current determines the capacity and rating of the electrical equipment as minimum short-circuit current determines settings of the protection devices. SCCs are used in situations where a fast assessment of the grid state is needed and full dynamic simulations cannot be performed. (Chen, Lund, Zamastil, Akhmatov, Abildgaard & Gellert 2012).

The calculations introduced in the IEC 60909 International standard are often used in the situations when the majority of power in the grid is produced by synchronous generators. The IEC 60909 International standard provides the methodology to calculate fault currents in three-phase AC systems up to 550 kV of 50 or 60 Hz nominal frequency. The second edition of IEC 60909-0 also includes the calculation of short-circuit currents when distributed generation is added to the power grid.

Two common numerical methods used to calculate short circuit currents are superposition method and equivalent voltage source method. However, superposition method gives the short circuit current only in relation to one assumed amount of the load and it does not always lead to the maximum short-circuit current in the system. Equivalent voltage source method is developed from superposition method and gives better results.

4.1 Methods introduced in IEC 60909

4.1.1 Equivalent voltage source method

For analyzing different circuits it is reasonable to learn a technique, which represents an arbitrary circuit as a simple equivalent circuit. The original system can contain tens of thousands of components, whereas after the simplifications the circuit contains significantly less components. (Valtonen & Lehtovuori 2011: 59). According to Thévenin's theorem, any one-port network can be reduced to a single voltage source and single impedance, together called Thévenin equivalent (Johnson 2003).

The calculation method used in IEC Standard 60909 determines the short-circuit current in a fault location *F* by applying an equivalent voltage source *E* according to Equation 1 to the short-circuit location, while all other sources are ignored and network components are replaced by their internal impedances (IEC 2016: 43):

$$E = \frac{c \cdot U_n}{\sqrt{3}}. \tag{1}$$

In Equation 1, c is the voltage factor, which varies between c_{min} and c_{max}. U_n is the nominal system voltage at the fault location. Voltage factor usually varies between 0,95 and

1,10 in low voltage systems (100-1000 V) and between 1,00 and 1,10 in medium (> 1 kV – 35 kV) and high voltage (> 35 kV) systems according to Table 1.

Table 1. Variation of voltage factor *c* at different voltage levels. (IEC 2016: 22).

Nominal voltage U_n	Voltage factor c_{max}	Voltage factor c_{min}
100-1000 V (Low voltage)	1,05	0,95
> 1 kV – 35 kV (Medium voltage)	1,10	1,00
> 35 kV (High voltage)	1,10	1,00

In the calculation of the maximum short-circuit currents, voltage factor *c* can be assumed to be c_{max} and in the calculation of the minimum short-circuit currents *c* is assumed to be c_{min}.

4.1.2 Symmetrical components

Calculation of the short-circuit current values from balanced and unbalanced short circuits in three-phase AC systems can be simplified by the use of symmetrical components. Using this method, the currents in each line conductor are found by superposing the currents of three symmetrical component systems: positive-sequence current $\underline{I}_{(1)}$, negative-sequence current $\underline{I}_{(2)}$ and zero-sequence current $\underline{I}_{(0)}$. If line conductor L1 is to be taken as a reference, the currents $\underline{I}_{L1}$, $\underline{I}_{L2}$ and $\underline{I}_{L3}$ can be determined by (IEC 2016: 22):

$$\underline{I}_{L1} = \underline{I}_{(1)} + \underline{I}_{(2)} + \underline{I}_{(0)} \tag{2}$$

$$\underline{I}_{L2} = \underline{a}^2 \cdot \underline{I}_{(1)} + \underline{a} \cdot \underline{I}_{(2)} + \underline{I}_{(0)} \tag{3}$$

$$\underline{I}_{L3} = \underline{a} \cdot \underline{I}_{(1)} + \underline{a}^2 \cdot \underline{I}_{(2)} + \underline{I}_{(0)} \tag{4}$$

$$\underline{a} = -\frac{1}{2} + \mathrm{j}\frac{1}{2}\sqrt{3}, \tag{5}$$

where $\underline{a}$ is a phase shift operator. Each of the three symmetrical component systems has its own impedance. (IEC 2016: 22).

Symmetrical components are needed when calculating short-circuit currents of unbalanced faults, because single-phase equivalent circuits cannot be used in the case of e.g. two-phase short-circuits or line-to-earth short-circuits. They are also needed when the short-circuit impedances of power stations with full size converters are determined.

4.1.3 Short-circuit impedance of power station units with full size converters

Power station units with full size converter (PF), for example wind power station units and PV station units are modelled in the positive-sequence system by a current source. The source current depends on the type of short-circuit and is provided by the manufacturer of the converter. In case of unbalanced short-circuits the negative-sequence impedances $\underline{Z}_{(2)\mathrm{PF}}$ depend on the design and control strategies of the converter, which are also provided by the manufacturer. However, power station units with full size converters can be neglected if their contributions are not higher than 5 % of the initial short-circuit current without the contribution of these power station units. (IEC 2016: 35).

4.1.4 Three-phase initial short-circuit current

The short-circuit current in the circuit presented in Figure 10 can be calculated by Equation 6 with the equivalent voltage source E and the short-circuit impedance $Z_\mathrm{k} = |R_\mathrm{k} + \mathrm{j}X_\mathrm{k}|$ (IEC 2016: 43):

$$I''_\mathrm{k} = \frac{E}{Z_\mathrm{k}} = \frac{c \cdot U_\mathrm{n}}{\sqrt{3} \cdot Z_\mathrm{k}} = \frac{c \cdot U_\mathrm{n}}{\sqrt{3}\sqrt{R_\mathrm{k}^2 + X_\mathrm{k}^2}}, \tag{6}$$

where R_k is the short-circuit resistance and X_k is the short-circuit reactance.

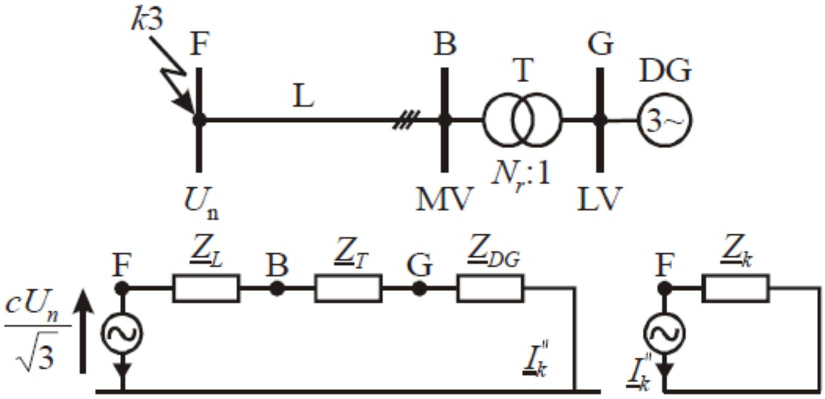

Figure 10. Equivalent circuit of a network containing DG during a fault situation. (Tristiu, Bulac, Costunas, Toma, Mandis & Zabava 2015).

In Figure 10 the first picture describes the transmission network in a situation, where conventional network feeder is replaced with a DG station. In Figure 10 $\underline{Z}_{\mathrm{DG}}$ is the impedance of the DG station, $\underline{Z}_T$ is the impedance of the transformer corrected with a correction factor κ_T and $\underline{Z}_L$ is the impedance of the line conductor. $\underline{Z}_k$, the equivalent short-circuit impedance of the transmission network at the fault location F, is all those impedances summed together. The network is described as in the Thevenin's theorem in last circuit diagram of Figure 10, where only equivalent voltage source and equivalent impedance exist in the circuit. Now the short-circuit current $\underline{I}_k''$ can be calculated by the means of Equation 7 (Tristiu et al. 2015):

$$\underline{I}_k'' = \frac{E}{\underline{Z}_k} = \frac{c \cdot U_{\mathrm{n}}}{\sqrt{3} \cdot (\underline{Z}_{DG} + \underline{Z}_T + \underline{Z}_L)}. \tag{7}$$

If power stations units with full size converter are to be considered, then the maximum initial short-circuit current shall be calculated as follows (IEC 2016: 43):

$$I''_{\mathrm{kmax}} = \frac{1}{Z_{\mathrm{k}}} \frac{c_{\mathrm{max}} \cdot U_{\mathrm{n}}}{\sqrt{3}} + \frac{1}{Z_{\mathrm{k}}} \sum_{j=1}^{n} Z_{ij} \cdot I_{\mathrm{skPF}j} = I''_{\mathrm{kmaxPFO}} + I''_{\mathrm{kPF}}, \tag{8}$$

where the sum of impedances Z_{ij} are the absolute values of the elements of the nodal impedance matrix of the positive-sequence system, $I_{\mathrm{skPF}j}$ is the rms value of the maximum source current (positive-sequence system) in case of three-phase short-circuit at the HV side of the unit transformer (given by the manufacturer), I''_{kmaxPFO} is the maximum initial short-circuit current without the influence of power station units with full size converter calculated by Equation 6 and I''_{kPF} is the contribution of the power station units with full size converter.

In order to calculate the initial short-circuit current by the means of Equation 8, it is required to calculate the nodal impedance matrix. In Z_{ij}, i is the short-circuit node and j are the nodes where power station units with full size converters are connected.

4.1.5 Peak short-circuit current

Furthermore, IEC 60909 defines the correction factor κ for calculation of the peak short-circuit current by following equation (IEC 2016: 50):

$$\kappa = 1{,}02 + 0{,}98e^{-3\frac{R}{X}}, \tag{9}$$

where R and X are the real and the imaginary part of the equivalent short-circuit current impedance Z_k at the short-circuit location. With κ calculated, the peak short-circuit current i_{p} can be calculated as follows (IEC 2016: 49):

$$i_{\mathrm{p}} = \kappa\sqrt{2}I''_{\mathrm{k}}. \tag{10}$$

The factor κ shall lead to the highest possible instantaneous value of the short-circuit current, therefore it is assumed that the short-circuit starts at zero voltage and i_{p} is reached in approximately 10 ms (in 50 Hz systems) after the beginning of the short-circuit. However, this applies only for branches with conventional generators and there is a different method for calculating the peak short-circuit current for power stations with full size converters. The peak short-circuit current for power stations with full size converters is determined by (IEC 2016: 50):

$$i_{\mathrm{p}} = \sqrt{2}I''_{\mathrm{kPF}}. \tag{11}$$

Now the total peak short-circuit for multiple-fed short-circuits can be calculated as a sum of currents calculated in Equations 10 and 11 (IEC 2016: 51):

$$i_{\mathrm{p}} = \kappa\sqrt{2} \cdot I''_{\mathrm{kmaxPFO}} + \sqrt{2} \cdot I''_{\mathrm{kPF}}. \tag{12}$$

4.1.6 Minimum steady-state short-circuit current

According to IEC 60909, the steady-state short-circuit currents of power station units with full size converter I_{kPFmax} and I_{kPFmin} are to be provided by the converter manufacturer. (IEC 2016: 61).

4.2 Power converter interfaced units

Information about inverter technology indicates that the fast current controllers applied and the limited overcurrent capability of the converters result in fault current contributions generally not exceeding 200 % of the rated current. Therefore the short-circuit currents provided by power converter interfaced units could be calculated with an equation (Boutsika & Papathanassiou 2008):

$$I''_{\mathrm{k}} = k \cdot I_{\mathrm{rG}}, \tag{13}$$

where k is a constant determining the upper limit of the inverter's short-circuit current, usually 1,5–2,0 and I_{rG} is the rated current of the inverter. The constant current representation of Equation 13 differs from the equivalent impedance of IEC 60909. One issue of the method presented in Equation 13 is that it does not take the phase angle of the current into account. If a power system analysis software uses vector summation of individual short-circuit current contributions, it is proposed that the contribution of power converter interfaced units is simply added algebraically to the total fault level of all sources, which will provide a result slightly on the safe side. (Boutsika & Papathanassiou 2008).

However, if the share of the DG in a grid gets greater, the short-circuit currents calculated by the means of Equation 13 are not going to give accurate results. The method presented in Equation 13 can be used if only small amounts of DG are added to the conventional grid, but as the power grids become more meshed, more accurate methods have to be used.

4.3 Backward and forward sweep in arborescent network

Methods for power systems analysis software to calculate short-circuit currents when flexible energy resources are added to the network are desired by researchers. Tristiu and others (2015) have developed a new and efficient algorithm for short-circuit calculation in networks with DG. The algorithm consists of two steps: a forward sweep, in which the aggregated impedances between each bus and the neutral point are calculated, and the backward sweep, in which the short-circuit currents flowing in the network branches are determined. The developed algorithm uses IEC 60909 standard as a starting point, so the fault is replaced by an equivalent voltage source introduced in the standard.

The network is described with a tree topology seen in Figure 11, where all branches can be approached using a simple algorithm, starting from any bus taken as reference. If n_0 is taken as a reference bus, the branches can be approached from the reference bus towards the terminal buses or from the terminal buses towards the reference bus, as is shown by the arrows in Figure 11.

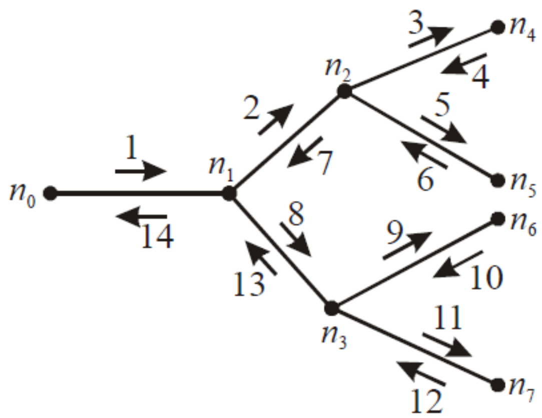

Figure 11. Network buses in an arborescent network. (Tristiu et al. 2015).

When a short circuit occurs in an arborescent network, no loops are formed, thus the network can be separated to upstream area and downstream area as is shown in Figure 12. Upstream area is located between the supplying network bus and the fault point, so the short-circuit current contains contributions from the supplying bus and DGs located at the upstream area. Downstream areas are located between the fault point and the end points, so the contribution to the short-circuit currents from these areas are solely from DGs.

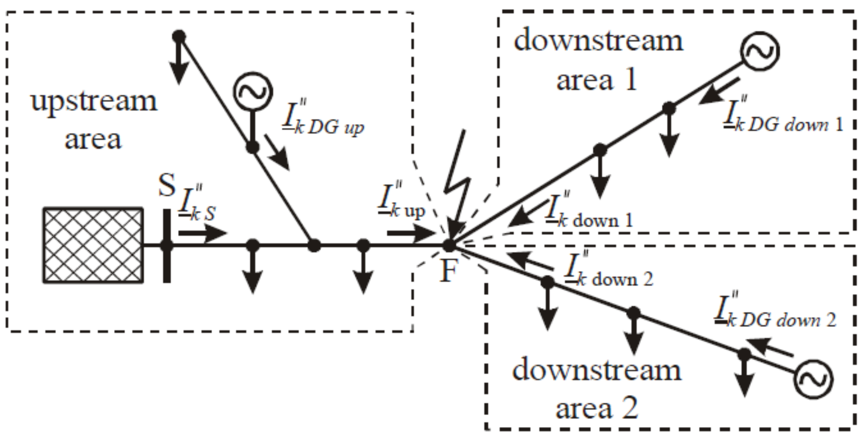

Figure 12. Network separated to upstream and downstream areas. (Tristiu et al. 2015).

In order to calculate the short-circuit currents using the equivalent voltage source method, the load current is neglected, the DGs and the supply source are replaced by equivalent impedances and equivalent voltage source E is placed to the fault current location.

The current at the short-circuit location can be calculated with Equation 7. The equation is applied for each network area and the fault point can be taken as a reference point for approaching different parts of the network as is shown in Figure 11.

Tristiu and others (2015) included a case study in their paper, where numerical calculation was performed on a 20 kV IEEE 33-bus network as shown in Figure 13.

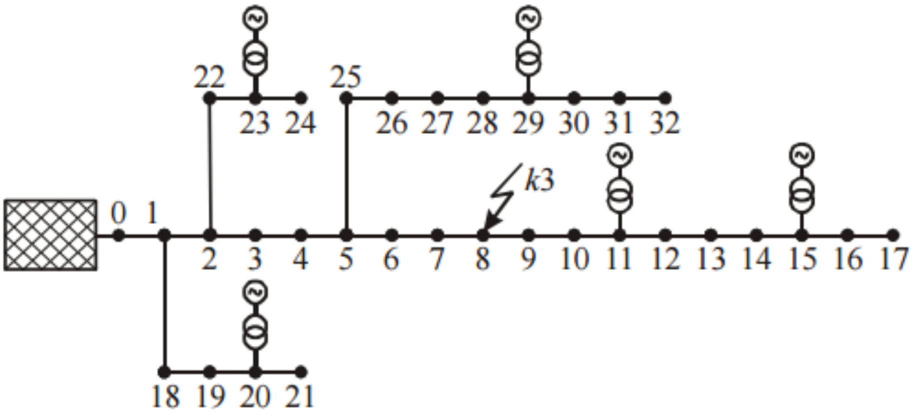

Figure 13. IEEE 33-bus distribution network system with 5 DG stations. (Tristiu et al. 2015).

In Figure 13, five distributed generators are connected to buses 11, 15, 20, 23 and 29 with following parameters: nominal apparent power S_N = 950 kVA, nominal voltage U_{nG} = 690 V, power factor cos φ = 0,9, x_d'' = 18 % and R_G/X_G = 0,15. When short-circuit occurs at bus 8 as is shown in Figure 13, the equivalent circuit can be constructed as in Figure 14.

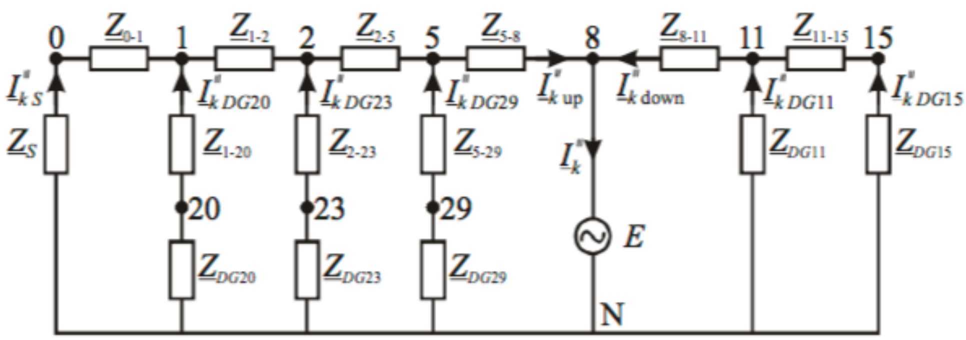

Figure 14. Equivalent circuit for short-circuit calculation. (Tristiu et al. 2015).

The equivalent circuit in Figure 14 takes into account the impedances of all buses in the grid.

Impedances for different areas are calculated in backward sweep, combining the impedances of different branches in the network. Then in the forward sweep, the short-circuit currents at different areas of the network can be calculated using Equation 3. Currents in the upstream and downstream areas can be then summed together for the total short-circuit current at the fault location. (Tristiu et al. 2015). The algorithm is very simple to implement and only basic rules for combining series and parallel impedances, Ohm's and Kirchhoff's laws and equivalent voltage source method of IEC 60909 standard are needed.

This method provides a fast way to calculate the short-circuit impedances and currents in a transmission or distribution network. The calculation of short-circuit impedances of inverter-coupled generators is dependent on parameters provided by inverter manufacturer, for example the upper limit of current limiter and rated current of the inverter.

5 CONCLUSIONS

The goal of this thesis was to review methods of calculating short-circuit currents in power grids where flexible energy resources have been added to the grid through power inverters. Simulations were also presented to illustrate the behavior of short-circuit currents in a MV network consisting an inverter-coupled wind turbine. Additionally, some methods of improvement are considered for the existing methods for the static calculation of short-circuit currents.

Many computer calculation programs and CAD-programs use Thevenin's method according to standard IEC 60909 for calculations of short-circuit currents. The first version of IEC 60909 published in 2001 does not include the contribution of power station units with converters to the short-circuit currents, so modern meshed networks including more and more IBDG cannot be accurately modeled with software using the old standard. The second version of the standard published in 2016 includes the contribution of power station units with full size converters to the short-circuit current. To calculate the short-circuit current contributions from power station units with full size converters, the maximum source current must be given by the inverter manufacturer and the nodal impedance matrix must be calculated.

Tristiu and others (2015) have recently developed a new algorithm, that is suitable for calculating short-circuit currents in a network of tree-like topology. It is not necessary to calculate the nodal admittance or impedance matrix with this algorithm as opposed to more laborious calculation methods, so this method is efficient and saves computational effort. The algorithm can be implemented in software programs, which are used to study integration of distributed generators into transmission or distribution networks (Tristiu et al. 2015). However, the algorithm assumes that there are not any loops created in the transmission or distribution networks, which is not always the real situation. Therefore, this algorithm can be implemented only in networks using a tree-like topology.

From simulations in Chapter 3 it could be seen that the short-circuit current of an inverter has a transient at the moment when the fault occurs, and then the short-circuit current stabilizes to a constant value, which is dictated by the controller of the inverter. The short-circuit current of an inverter could be split into two parts: the transient part and the steady-state part, which both depend on the current controller of the inverter. The contribution of the transient part depends on the accuracy and effectiveness of the controller.

Boutsika and Papathanassiou (2008) have proposed a method, which takes into account the rated current of the inverter and a constant, which represents the limit set by the current controller of the inverter. The constant can be determined so that the results will be at the safe side, but it is not always economically reasonable. This method does not take the phase angle of the current or the transient part of the short-circuit current into account, so further development for this method would be needed. However, the authors state in the end of the article that the standards of IEC and IEEE for short-circuit current calculations need to be revised to include the effect of DG resources and standardize their treatment. The new version of standard IEC 60909 was published after this article, so the standardizing of the short-circuit calculations of inverter-based distributed generators is ongoing.

An interesting topic for future research would be to develop an equation for the transient part short-circuit current of an inverter according to the step response of the controller. Combined with the maximum source current provided by the inverter manufacturer, fairly accurate short-circuit calculations for inverter-based generators could be made.

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