# Motivation / Introduction:

*Motivation to write the thesis is determined be recent experience of unexpected phenomena that occurs in first high-power HVDC connected off-shore AC grid including wind power plant. In this power electronics dominated grid converters go into resonance between each other causing oscillations and instabilities in the internal network. These problems were not considered during planning period. Due to future plans of development of many off-shore wind farms, to avoid problems for future hardware, new methods of investigation and analysis should be developed or current ones should be extended.*

*Problem expansion:*

*In contrast to the continental European grid, there is not enough resistive loads present in the network dominated by converters, therefore the resonance is not damped well enough. Moreover, in the offshore WPP the collection grid from turbines consist of long cables which have much higher capacitance than regular overhead line. That switches the resonance frequencies to the lower levels where the other harmonics are present and can be amplified.*

*The purpose of the thesis is to analyse some available methods to detect harmonic resonances in off-shore wind farm grids and couple this study with stability analysis based on Nyquist stability criterion. Since the quality of theoretical study is significantly determined by the quality of utilized model and its elements, more accurate approach to model power converters’ impedance is used.*

# Theoretical introduction:

## Basics about harmonics

Generation of electricity in power system is usually at the frequency constant level of either 50Hz or 60Hz. Waveforms produced by rotating generator is practically sinusoidal and in this shape they should be delivered to every customer. However when sinusoidal waveform is applied to nonlinear load the resulting current is not purely sinusoidal. The current which is not perfectly sinusoidal leads to not perfectly sinusoidal voltage drop due to system impedance. Hence, the voltage distortion at load terminals is produced. The problem of presence of these distortions is not new in the power system. However the devices responsible for producing distorted waveforms and devices suffering from presence of the distortion have changed down the years.

A distorted, non-sinusoidal waveform can be expressed as a sum of so-called harmonic components. Harmonic component in power system is a perfectly sinusoidal waveform that has frequency equal to integer multiple of the fundamental frequency:

where is an integer (harmonic order) and is fundamental frequency (usually 50 Hz   
or 60 Hz). If is not an integer, such a waveform is called interharmonic component.

As aforementioned, any sinusoidal waveform can be expressed as sum of its harmonic components. Exemplary distorted current waveform for fundamental frequency and 3rd 5th and 7th harmonics is expressed as follows:

where are peak RMS values of fundamental component and harmonic components and are possible phase shifts of each harmonic.

Concerns for harmonics rises from power quality requirements. Power quality requirements are introduced to prevent from negative effects on electrical equipment which are sensitive to poor power quality. Poor power quality leads to damages of equipment, in other words, causes great money losses for industry. Moreover, certain types of equipment, if exposed to distorted waveforms, lead to further generation of harmonics. [Das]

## Harmonics Indices

There are two most common indices to describe content of the harmonics in the signal as one number: Total Harmonic Distortion (THD) and Total Demand Distortion (TDD). THD, which usually relates to voltage waveforms, is defined as RMS values () of the harmonics expressed relatively to fundamental components ():

where is the harmonic order and is maximum harmonic order to be considered. For most application, it is sufficient to consider harmonic order range up to 25th harmonic, but most standards recommend up to 50th [Das].

Since THD of current waveform can be misleading when load is low and can result in very high THD value, RMS values of harmonic currents can be related to rated or maximum current magnitude rather than to fundamental current (TDD):

This reflects distortion in more intuitive way since the electrical power supply systems are design to withstand rated (or maximum) values, while relation to fundamental components when load is far lower from rated value can give impression of much more significant distortion.

In the presented study these indices are also applied to the three-phase systems since for all cases the three-phase balanced system is considered. If the system is not balanced some averaging can be carried out [Das].

## Sources of distorted waveforms (harmonics)

As mentioned before the sources of harmonic distortions have changed down the years. In early power systems harmonic distortions were mainly caused by saturation of transformers industrial arc furnaces and other arc devices like electric welders. On the other hand, the main concern was the effect of those distortions on electric machines, telephones and on increased risk of failure from overvoltage. [Rosa]

Generally speaking, harmonics in power systems are produced due to many phenomena, for example, ferroresonance, magnetic saturation, subsunchronous resonance, and nonlinear and electrically switched loads. These days, harmonic emission from nonlinear loads dominates. [Das,ch1]

In transformers, harmonics appear as result of saturation, switching, high-flux densities, winding connections and grounding. Also, energizing a power transformer generates a high order of harmonics and a DC component [Das].

In rotating machines, the construction elements and their limitations of both generators and motors like: armature windings, phase windings, teeth, phase spread etc. affects EMF in the phase windings, therefore rotating machines are also not pure linear elements. Even synchronous machine generates deviated voltage at its terminal, however the voltage is almost sinusoidal.

In presence of system capacitance, some inductive elements like transformers or reactors can lead to so-called ferroresonance phenomena, due to nonlinearity and saturation of reactance. This cases short current surges that generate overvoltages. Moreover, presence of capacitance in sinusoidal circuits can magnify existing harmonics (from other sources) by creating resonant condition. More about harmonic resonance in Section XXXX.

### Harmonics from power electronics elements

Above classical power system elements described above, static power electronic elements are the main source of harmonics in the power system. We can include in this group devices like: power converters, rectifiers, inverters, diacs, triacs, GTO’s and adjustable speed drives [Das].

Among the power electronics devices, many of them are controlled with pulse width modulation (PWM). We can distinguish several techniques of PWM: single PWM, multiple PWM, sinusoidal PWM, modified sinusoidal PWM. Inverters which use PWM can be divided into three groups: VSI (voltage source inverters), CSI (current source inverters) and ZSI (impedance source inverters).

These elements usually emit so-called characteristic harmonics which are those produced by power electronic converters during normal operation [Das]. They are still integer multiply of fundamental frequency. Static power electronic devices also produce some non-characteristic harmonics when some non-ideal condition of control occurs (for example unbalanced PWM signal). Then, harmonics emitted will be unbalanced, also interharmonics can appear. Since mitigation of harmonics is usually designed for characteristic harmonics, the non-characteristic harmonics can cause significant problems.

In the study cases of the thesis, VSI (voltage source inverters) are used in the considered wind power plant. VSI’s use switching devices like GTO, IGBT, MTO which have both turn off and turn on control. Because of this, much more accurate control comparing o CSI is possible, also including power flow control. Further details about used elements are provided in Section XXXX.

Beyond elements of high power, there are also many home appliances that are very non-linear and produce harmonics. These are: fluorescent lights, variable speed air conditioning systems, PCs, microwaves, induction heaters etc.

The harmonics from Wind Power Plants are becoming very important in the power system these days due to increasing number of these sources. The main subject of this thesis is to analyse harmonic created in the Wind Power Plants and emitted to the power system, including resonance analysis of these harmonics in Wind Power Plants inner grid. Further details about Wind Power Plants (Wind Farms) as a source of harmonics in Section XXXX.

## Harmonic resonance

Harmonic resonance is an important factor affecting the system harmonic levels. Harmonic waveform generated in other part of the grid can be magnified many times due to this phenomenon [Das]. Most of the networks are considered inductive, therefore, in principle, the resonance very often depends on the capacitive elements. Depending on the type of the grid these are usually capacitor banks, cables, overhead lines, compensators etc. Since harmonic resonance either amplify existing harmonics or creates new, the negative effects of this phenomenon are very similar to the effects caused by harmonics described   
in Section XXX. Moreover, it can overload the capacitor and may result in nuisance fuse operation causing severe amplification of the harmonic currents resulting in waveform distortions, which has consequent deleterious effects on the power system components [Das].

As circuit theory says, resonance harmonics can occur in series RLC or parallel RLC circuits (the connection type between L and C elements). The resonance frequency depends on values of the inductance and capacitance. The smaller the size of the capacitor, the higher is the resonant frequency [Das]. This conclusion can be observed in the results presented in Section XX.

Major concerns about harmonic resonances [Das]: Maybe at the end?

* the resonant frequency is present in a grid (for example separated industrial grid or inner collection grid of WPP) and depends very strongly on topology of considered network,
* expansion, disconnection of some parts of the network may bring out a resonant condition not existing before (for example switching on the capacitor for power factor improvements),
* even when some elements are designed to prevent from harmonic resonance, after any modification of the topology, immunity from resonant conditions cannot be guaranteed.

The resonance problem in power system is a serious potential problem [Das]. It leads to many negative (shut-downs, failures). It may appear unexpected at certain operating condition of the power system. Moreover, it can also appear partially or disappear with no negative effect. Due to this problems, prevention may require long-term online measurements to establish the disturbing source in the system [Das]. The thesis describes some methods for monitoring the resonance in the grid and identification of an element responsible for certain emission.

### Series AC resonance

The simple series connection of resonant element is presented in the Fig. XX.

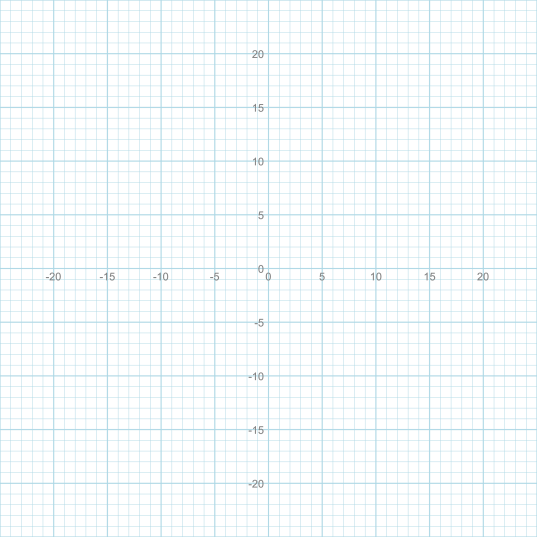


The impedance of such a circuit is as follows:

The series resonance occurs at certain resonant frequency , when the impedance is minimum i.e.:

What leads to:

Exemplary impedance magnitude and angle plots of the system from Fig. XX are plotted at Fig. XX.

 magn and ang

Since the impedance is minimum, the current can reach very high values:

Thus, we can see that the current is limited only by resistance. In the pure case the currents tends to infinity and if is very small, current can be high.

### Parallel AC resonance

The parallel resonance occurs in parallel RLC circuit (Fig. XX) when the impedance tends to maximum i.e.:



Thus, the resonant condition is:

Then again, the resonant frequency is as follows:

#### Tank circuit

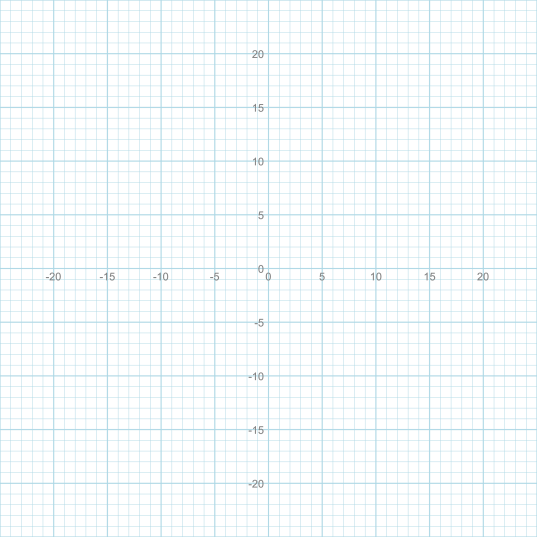
More practical LC circuit i.e. with inductor modelled with non-zero value of resistance and capacitor modelled without resistance is called Tank circuit [Das]. Fig. XX presents such a circuit.



In this circuit the aggregate admittance seen from the left side is as follows:

In other form:

The plot of impedance of the system is presented in the picture:

magn and ang

In the circuit with zero-resistance (lossless circuit), resonance occurs if impedance of inductor equals impedance of capacitor i.e. when the circuit behaves as short-circuited. In this case, resonance occurs in similar situation, even though the resistance stays unchanged in the circuit. In other words resonance occurs when power factor of admittance above equals zero:

That gives resonant frequency:

Moreover, as distinct from the series resonance, where resonance can occur from any value of resistance, in this case resonance occurs only if following equation is true:

In other words, resonance cannot occur if:

### DC resonance

### Factors affecting harmonic resonance [Das]

Some factors impacting harmonic resonance are the following:

• Synchronous and asynchronous machines and loads in the power system will

absorb some of the generated harmonics and change the resonance points. Their

correct modeling is an important factor.

• The harmonic impedance of the utility source must be ascertained and

accounted for. It is not merely given by the three-phase, short-circuit current,

when harmonic sources are present.

• The shunt power capacitors are not recommended to be applied in the presence

of load-generated harmonics. These must be turned into harmonic filters after

a careful study and applied at an appropriate location in the power system.

• Secondary resonance can occur when the shunt capacitors are applied at multivoltage

level in a distribution system. This is an important consideration. When

a capacitor bank on the high side of distribution is switched, overvoltages of the

order of four to five times can occur on the capacitor bank, which is in service

at a lower voltage.

The load resistance plays an important role in the system resonance

(Fig. 9.5(b)). The impedance modulus and sharpness of the tuning of the ST

filters vary with resistance.

The motor loads should be appropriately modeled (Chapter 14). These appear

primarily inductive at harmonic frequencies.

The presence of single-phase loads must be considered.

The harmonic mitigation and passive filter designs should be properly applied.

Application of single-tuned or band-pass filter does not eliminate harmonic

resonance, but merely shifts the resonant frequency. A proper choice of passive

filter type has to be exercised (Chapter 15).

Harmonic analysis for transmission systems requires rigorous modeling. Also

the transmission systems undergo changes and the limitation of the computer

models and practical conditions apply (Chapter 14).

Resonant conditions may not be experienced all the time. A resonant condition

can vanish with a system change and vice versa.

Online measurements over a period of time are required to capture a resonant

condition.

• Subharmonic resonance is discussed in Chapter 5.

## Effects of harmonics

The harmonic resonance in a power system cannot be tolerated and must be avoided. The magnified harmonics will have serious effects on equipment heating, harmonic torque generation, nuisance operation of protective devices, derating of electrical equipment, damage to the shunt capacitors due to overloading, and can precipitate shutdowns.

## Nabe and Akagi instantaneous power theory

# Methods of analysis (Analysis methods of harmonics propagation)

The phenomenon of harmonic resonance seems well understood in the literature, however tools available to analyse it are very limited [Xu 2005]. Method of frequency scan (frequency sweep) is the most general and popular method to identify the resonance frequencies in the network [ref 2 in Xu, 2005]. However the method is limited. A resonance is between two elements (capacitive and inductive) in the system. Networks usually consists of many elements, therefore the result of frequency sweep does not indicate which elements exchange energy between each other, causing resonance.

The method of Harmonic Resonance Modal Analysis (HRMA) was developed to face this problem [Xu,2005]. This method involves only analysis of parallel resonance which is more dangerous in the power system. From HRMA buses that excite a particular resonances can be identified. Thus, we can conclude which components are involved in the resonance. Moreover, the method gives clues where the resonance can be observed more easily and how far the resonance can propagate in the system.

## Fourier Analysis

## Frequency Sweep

Frequency Sweep (or Frequency Scan) analysis is a characterization of the system equivalent impedance at a bus in the system as a function of frequency [Bradt 2012]. As the result, curve of impedance in frequency domain is obtained. The peaks in the curve suggest frequencies when parallel resonance occurs (very high impedance at certain frequency) while dips indicate the frequencies when series resonance occurs (very low impedance at certain frequency).

In Wind Power Plants often frequency scans are done at various grid locations or at the collector bus [Bradt 2012]. The magnitude of computed impedances depends also on the level of equivalent voltage used in the calculations. However, the single value of identified peak impedance does not determine if the resonance occurs. For harmonic problems, there must also be a sufficient level of harmonic source voltages or currents at or near the resonant frequency to excite the resonance [Bradt 2012]. Also, the impedance value itself has to be analysed in particular case to identify the value that can cause harm. To do this, the best way is to obtain specific data by measurements, but also data provided by manufacturers of devices in the network.

## Harmonic Resonance Modal Analysis

The method is based on analysis of well-known admittance matrix of the network - . It focuses on the large elements of inverted . In the extreme case (very large elements) the admittance matrix tends to singularity and element of inverted tends to infinity, thus very high voltages can be produced, which is in principle parallel resonance.

The elements are identified on the basis of eigenvalues of matrixes. Since matrix becomes singular when even one of the eigenvalue becomes zero, the principle can be clearly used. Eigenvalues correspond to certain mode of harmonic resonance, therefore the study consists of identification of critical resonance modes. The equations describing the method including the identification of certain buses and elements are presented below.

The admittance matrix on the network is constructed for certain frequency . Admittance matrix fulfils equation:

where: is the network admittance matrix is the nodal voltage and is the nodal current injection. All matrix values are at frequency .

To investigate if approaches singularity, the theory of eigen-analysis is applied. According to [Bellman, 1970], matrix can be decomposed into (index is neglected in the next equations for simplicity):

where is the diagonal eigenvalue matrix and and are the left and right eigenvector matrices.

Defining as the modal voltage vector and as the modal current vector, the equation can be derived:

or

where has the unit of impedance and is named modal impedance . From matrix equation (XX), one can easily identify the “location” of resonance in the modal domain due to corresponding modal currents and voltage [Zhenyu Huang 2005]. It is not related to or caused by a particular bus injection since it is in modal domain. Thus, the smalles eigenvalue is called the critical mode of harmonic resonance and its left and right eigenvectors are the critical eigenvectors.

The modal currents are a linear projections of the physical currents in the direction of the first eigenvectors. Also the physical nodal voltages are related to the modal voltages by: . More details in [Zhenyu Huang 2005]. In summary, the critical eigenvectors characterize the excitability of the critical mode (right critical eigenvector) and observability of the critical mode (left critical eigenvector) [Zhenyu Huang 2005]. The excitability and observability of modes are characterized with respect to the location. It is possible to combine the excitability and observability into a single index according to the theory of selective modal analysis [Perez-Arriaga 1982]:

The diagonal elements of the above matrix characterize the combined excitability and observability of the critical mode at the same bus. The definition [Zhenyu Huang 2005] is:

where is the bus number and is the mode number.

From these calculation on the basis of admittance matrix, after the process, it is obtained: the set of participating factors for each bus for each critical mode, so the modes when the modal impedance is the highest, which occurs for certain frequency at certain number of mode. The participation factors of all buses sum up to 1, therefore the comparison between buses is simple.

#### Critical Modes and Resonance Condition – comparison between FS and HRMA

As mentioned, resonant conditions identified in this method depends on the value of eigenvalue, which is very small if resonance occurs. This results in very high modal impedance. As seen from comparison with frequency scan impedance curves, the sharp peaks occur for the same frequencies. One has to remember that in frequency scan method, the impedance curves are seen from the certain point in the grid, while in HRMA the impedance curves are divided into modes, which does not correspond to the physical buses, even though the number of modes and the number of buses is the same.

Moreover the values of maximum impedances at peak point from both methods are different. The reason is again due to comparison between “real” impedance and “modal” impedance. Modal impedance should be investigated referring to every specific case in order to identify the threshold, above which the harmful resonance is produced. In this thesis, values of interests identified by both methods are the frequencies when resonances occurs.

# Harmonics in WPP

Wind Power Plants due to intermittency of the wind, are usually supported by great number of power electronic converters which enable effective operation of WPP. These non-linear devices are sources of significant amounts of harmonics in Wind Farms.

Harmonics produced by converters first of all are introduced into inner grid of WPP. Before any waveform produced by wind turbines and converted by wind turbines converters is introduced into the power system (through point of common coupling - PCC - between WPP and external grid), it is exposed to dangerous phenomenon of harmonic resonance in inner grid of WPP.

Internal harmonic resonance depends essentially on the elements that the inner grid consists of (including possible HVDC link converter) and the way of their connection (topology). It contributes to amplification of existing harmonics and is able to create new harmonic components.

External emission of harmonics (to the power system) from Wind Power Plants first of all depends on **(1) converter topology, (2) applied harmonic filters and (3) short-circuit current at PCC [Das]. These three features has to be completed by the above problem of (4) internal harmonic resonance** in the wind power plant inner grid.

If the wind farm is connected by HVDC link, then the emission of harmonics to the external grid depends on the DC/AC conversion at the PCC behind HVDC connection.

For harmonic resonance problems, there must also be a sufficient level of harmonic source voltages or currents at or near the resonant frequency to excite the resonance [Bradt 2012].

*Main focus of this thesis is understanding and description harmonic resonance appearing in inner grids of Wind Power Plants. Moreover, stability issues due to the harmonic resonance are put forward. As mentioned in Section XXXX, the analysis of these problems has recently become very important due to serious problems observed in first HVDC connected offshore wind farm during its first years of operation. For future implementation of HVDC connected offshore WPP the problem is currently investigated.*

## Converter topology

Topology of the converter is partially determined by the electrical machine that is used in wind turbine to generate electricity. According to the level of power that flows through a converter, full scale converter can be distinguished. It provides control over total power produced in generator. On the other hand, there are also Wind Turbine application where only part of the power produced can flows through converter. The ratings of the converter, so also its costs, are reduced, however control of the power produced in wind turbine is limited.

Within the full-scale converters, the most popular utilized in these days in wind turbines are: 2-level converters, 3-level NPC converters, multi-level converters, also matrix converters and tandem converters [Review, Pham 2013+].

Secondly, when it comes to the scale of the wind farm, as stated in [Das], the greater the number of turbines the lower is the magnitude of the harmonics and subharmonics, especially of the lower order.

*In this study, only models of full rate wind turbine converters are considered with some minor exception of networks with direct connections of SCIG to the collector grid. On the other hand, HVDC link converter is modelled with respect to principles described in the Section XXXX.*

## Applied filters

The two main methods for controlling harmonics in WPP are avoiding producing of harmonics and implementing filters to mitigate them [Bradt 2012]. To avoid the production of harmonics, network of WPP has to be designed properly, however implementation of harmonic filters anyway can be necessary due to topology changes or even very insignificant modifications which change resonance levels. The designing of filters should be based on measurements and simulations in order to control resonance properly.

Second method - implementation of filters - is the most common approach to the harmonic resonance [Bradt 2015]. The design and implementation of filters is not considered in this study, however the method presented of HRMA is vital for identification of the buses which are potentially more appropriate for filters installation.

## Short circuit current at PCC

From the grid side, the short circuit level at the point of application is also not fixed. It varies with operational condition in the grid. The weaker the external grid, the more it varies usually, therefore the resonant frequency can float around. These fluctuations are not considered in the thesis.

## Internal WPP resonance

The phenomenon of electrical resonance is described in section XXXX. As mentioned, if the resonance is not properly controlled, it leads to failures, instabilities, shut-downs or even damage of components. If the internal grid of WPP is separated from external grid for example by HVDC connection, electrical behaviour of the WPP grid can be different from the main grid.

In such a grid there is no rotating mass that establishes physical binding of power and frequency [BorWin1, 2015]. Thus, the frequency of internal WPP and the infeed from the WTs can be completely controlled by converters. Moreover, every converter has its own control schemes that can have a bandwidth of several hundred hertz. Thus, converters are able to amplify oscillations which are in the system [BorWin1, 2015].

The modelling of the converters is described in the Section XXXX.

*The resonance in Wind Power Plant is the main reason of the instability in first HVDC connected offshore WPP, described in motivation of the thesis part (section XXXX). This problem was not considered during the planning phase of the wind farm and should be extended.*

# Stability of WPP

In VSC converters the bandwidth of control signals are several times of the fundamental frequency. Such high-frequency control introduces dynamics above fundamental frequency, creating potential for HF instabilities and resonances that are not present in CSC [Liu, Sun 2014]. Since the VSC does not need reactive power support, it has higher controllability, also ability of black start the system, this type of converter is getting more popular in new Wind Farms.

*In the offshore WPP Bard Offshore 1 VSC converters are utilized. However the problem of grid resonances caused by these converters was not considered during planning phase of the WPP. Therefore, stability problems due to converters interactions were not considered [BorWin1].*

As stated in [Sun 2011] and [Liu,Sun 2014] converters could go into resonance with the grid if the grid impedance exceed the input impedance of the converter. On the basis of this statement, the analysis of stability is performed. This could happen due to more advanced nonlinear power electronics included in the converters. This problem does not occur between, for example, synchronous generators since power electronic elements influence in these elements is limited. The problem of converter impedance non-linear behaviour is described in Section XXXX.

## Harmonic stability

The new stability criterion based on Nyquist stability criterion is described in [Sun 2011] and is still under development [BorWin1]. The main advantage of this method is that it does not require all details about converter which are intellectual property of manufacturers and could be right choice at the planning phase of an investment. Only frequency dependent impedances of converter are needed [BorWin1].

In contrast to EMT simulations and eigenvalue analysis only relatively simple stability criterion is developed. Thus, this method is very fast and can evaluate new topology if any switching action occurs [BioWin1]. The simplicity is achieved by aggregation of all wind farms with their controllers into one element. Then, the aggregated system is evaluated by Nyquist stability criterion that provides information about gain and phase margin. As mentioned, the manufacturers have to provide only frequency dependent impedance of their generation unit (converter), including passive elements impedance and impedance changes due to active controls [BioWin1]. Moreover, the frequency dependent impedance can be measured or calculated from analytic model, using EMT-tools.

## Stability criterion

With the proper data and assumptions described above, the stability problem can be explained for very simple grid.



where the current depends on both frequency dependent impedances:

In the last form the system can be expressed in as loop gain:



Hence, the system is stable if the source has a zero and the load an infinite output impedance. For stability the expression has at least to be below 1 to for all frequencies [Sun 2011].

The problem with the model above is the point division between and . The best point of division is still under investigation [BioWin1]. In this study the network is divided behind the HV transformer from the HVDC link point of view.

## Results of Nyquist criterion

Calculated curves for positive and negative impedance can be plotted at the in a Bode diagram. From Bode diagram, each intersection has to be investigated. For each intersection, phase margin has to be calculated. If it is below 30 the system can be instable [BioWin1].

…………………

# Modelling of elements

## Transformers:

For harmonics modelling of transformers in electrical grid models for very high frequencies a generally not necessary. For higher frequencies resistance increases, while the leakage inductance reduces [Das,ch12]. In this study, two-winding transformer will be represented simply by its impedance as follows:

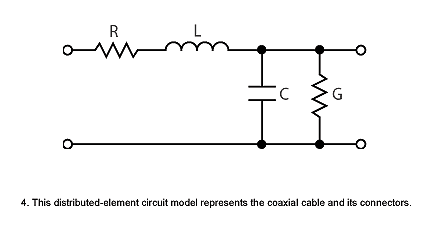
where and corresponds to fundamental frequency resistance and reactance and factor takes account of skin effect and eddy currents effect at higher frequencies.



## Cables

Modelling of cables is important in harmonic analysis since they are very significant source of capacitance in considered grids. For harmonic frequencies up to 3000Hz the resistance of cables will increase. The slight effect of decrease in inductance and shunt capacitance can be ignored [Das,ch12]. PI models are considered as appropriate for frequency scan analysis, but not for transient analysis.

Usually, exact frequency-dependent model is obtained by Finite Element analysis [Das,ch12], however in this study exact methods of cable models are not considered. Elements of Pi model of the cables is described by:



## Filter reactor

Filter reactors modelling is important since it significantly affects the tuning of whole system. Resistance of the filters at high frequencies can be calculated as follows:

– for aluminium reactors

– for copper reactors

In the models presented, resistance of LCL filter and resistance of phase reactor is assumed to be neglected (equals zero).

## Power converters

Modelling of power converters is the most challenging within all elements. Power converters devices are very nonlinear and their impedance behaviour strongly depends on many factors. The exact model should be derived on the basis of control codes, ideally also on the basis of measurements on the real device.

Control codes are very unique and never published by the manufacturers. They are their intellectual property and thus the determination of the exact frequency is very difficult [BorWin1, 2015]. There are also more simple approaches to face the problem of converter modelling. The principles presented below are considered for frequency domain analysis. EMT (electromechanical transient) analysis is not considered.

### Current Source and Voltage Source

It is common to model converters be either current or voltage source. As stated in [BorWin1], current sources should be only used if the **grid impedances are similar.** Otherwise it leads to very inaccurate harmonic current values and wrong results. Therefore, voltage sources should be modelled instead and the input impedance should be considered.

What important is for both approaches in frequency domain analysis is the fact that, according to circuit theory, ideal voltage source internal resistance is zero (short-circuit). On the other hand, the ideal current source internal resistance is infinite (open-circuit).

### Frequency dependent impedance model

The approach developed in [Liu Sun 2014] and [Liu Sun 2013] of frequency dependent impedance of converters in introduced to this study and described below.

The assumed converters modelled are: 2-level VSC Wind Turbine DC/AC inverter and the same type of HVDC AC/DC rectifier.

For the control purposes, wind turbine converter is controlled as current source. Reactive power supply and voltage regulation of the model is not considered. A phase-locked loop (PLL) is included in the model for AC bus synchronisation.

## HARMONIC LINEARISATION!!!! BODE PLOTS!!!! Other nyquist criterion

# Harmonics and power quality regulations

It is worth of mentioning that harmonics are not the only problem of power quality in power system. Power quality includes more electromagnetic phenomena which can be categorized on the basis of duration (from nanoseconds, like lightning strokes) to steady state disturbances (e.g. harmonics and interharmonics) [Das].

# Temporary planning and cost

# Environmental impact

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